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Effect of incorporation POFA in cement mortar and desired benefits: a review

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Abstract. Palm oil fuel ash (POFA) is a by-product waste material more economical and environmentally friendly, resulted from production palm oil products. Lack of enough information on the advantages of POFA in the concrete production in various proportions was the main cause to select this work. This paper presents the advantages of POFA as a partial cement replacement in concrete production. This study recommends that researchers and academics should show more experimental works in order to illustrate the desired benefits from POFA as cement replacement, thus mitigate of environmental impacts.

1. Introduction

South-east Asia countries produces increasing quantity of palm oil products due to its location on the regional area [1, 2]. They depend on the agriculture industry to promote their economic because of receiving abundant rainfall throughout the year which made they suitable for plantation [3]. Production of palm oil represent the most proportion of vegetable oil production in the world which was more than 60 million tons in 2012, whereas the percentage of palm oil was more than 35% of the total vegetable oil in the same year [2, 4]. Malaysia and Indonesia contribute to the largest production of palm oil in the world which was more than 80% of the total production, just 10% of the palm oil used to cover the local demand and 90% has been exported [5, 6]. The cultivation of palm oil was cover 54,000 ha in Malaysia in 1960, and increased dramatically to 5.39 million ha in 2014, while in Indonesia the cultivation of palm oil was the largest which was 5.39 million ha in 2014, Therefore palm oil tree is a backbone for growth economic of both countries Malaysia and Indonesia. In 2011, the production rate of palm oil was 48% in Indonesia, 38% in Malaysia, and 3% in Thailand [7-9]. Increasing the production of palm oil lead to generate huge quantity of waste materials such as palm oil fuel ash (POFA) that has high content of silica and also poses threats to the surrounding environment if it is not used any other application of industries. Malaysia's production of POFA is up to 3 million tons in 2007, while Thailand's production of POFA about 0.1 million ton in the same year [10].

The cement industry is also facing problems in terms of increasing consumption of electricity and high cost to produce the quantity needed to meet the market requirements. Reducing emission of CO_2 is the main concern for scientists, academics and researchers to produce alternative materials of cement in the concrete production [11]. The increase of cement content in the concrete automatically reflected in the increase of the construction cost [12] thus, the increase in the cement production will result to rise in the consumption of electrical energy, besides rise the CO_2 emission, which causes an environmental issues can be no treatment in the future [12, 13]. Many researchers studied adding POFA as a partial replacement of cement to obtain high compressive strength [14, 15] due to the high silica content enabling it to be good pozzolanic material. As POFA contain a high quantity of silica in their chemical composition, it has been used to replace cement partially in order to produce durable and high strength for concrete produced [16]. In the recent years and after concrete technology development, innovations has been conducted by reducing the use of ordinary Portland cement in concrete by replacing it with huge amounts of palm oil fuel ash and fly ash [17]. Generation of CO_2 to the atmosphere due to cement production causes an undesirable environment impact which increases the global warming. Therefore, many studies were conducted to replace cement partially with suitable supplementary cementitious materials such as POFA, fly ash, silica fume, metakaolin and other pozzolanic materials in order to reduce the cement production and mitigate it impacts on the environmental conditions [18]. This paper will highlight the advantages acquired due to incorporation of POFA in various percentages to the concrete as cement replacement partially. Heat of hydration, compressive strength, resistance to the acid, resistance to the chloride, and resistance to the sulfate will be presented as in figure 1. The study will emphasize on the similarity and difference faces in the results obtained from the previous studies. Therefore, this study will contribute to the body of knowledge on the impacts of adding various percentages of POFA particles to the cement as replacement, and their advantages desired of POFA to improve the concrete properties.

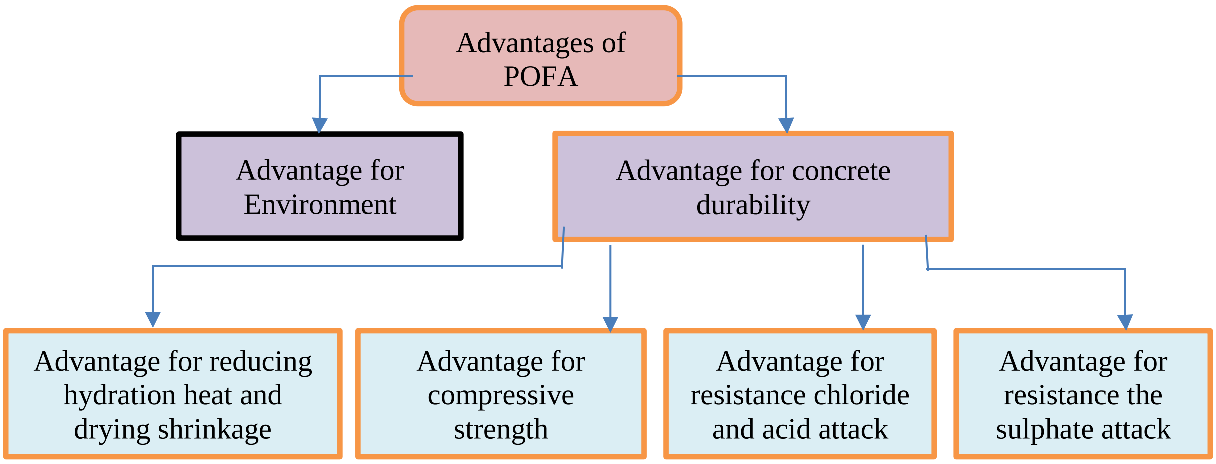


Figure 1. Advantages of POFA to concrete.

2. Advantages of concrete containing POFA for durability properties

The previous researchers proved that incorporation of POFA in the concrete added many advantages to the concrete properties especially in the durability aspect. Improving the microstructure and density of hardened concrete can be achieved by adding micro and Nano POFA as cement replacement in the concrete mix which result to improve the pozzolanic reaction as well [19]. Ability of POFA to produce further amounts of C-S-H gels due to the pozzolanic activity and used it as filler in concrete mixture led to improve the durability and mechanical properties of the hardened concrete [20-22]. Fine particles of POFA can be increase the pozzolanic activity in the concrete mix, reduce quantity of calcium hydroxide, improve fresh concrete properties, Improve durability and mechanical properties [23, 24]. The higher content of silica in the POFA particles has effect on the pozzolanic reaction to produce further C-S-H gels, and make the concrete produced denser and durable [25]. Four properties within the concrete durability will be discussed in the next subsections to show the impact of POFA in enhancing their properties namely, Heat of hydration, compressive strength, resistance to the acid, resistance to the chloride, and resistance to the sulphate.

2.1 Advantages to reduce hydration heat and drying shrinkage

The hydration heat released from the fresh concrete containing ash is due to two reasons, the first reason is due to release hydration heat of cement, the second reason is due to hydration heat released by the admixture reactions [26]. Hydration process of cement compounds accompanied by heat generation resulting from the reaction of different compounds in cement with mixing water, this heat is form of energy to reach on the stable state [21, 27]. Research by Lim et al. [25] proved that the decarbonation process of POFA is due to decomposition of the calcium carbonate between temperature 400 and 600 ^{o}C as in Fig. 2. The hydration heat of GPOFA and UPOFA mortar were similar somewhat, but they totally different on the reading of the cement hydration heat during the initial reading.

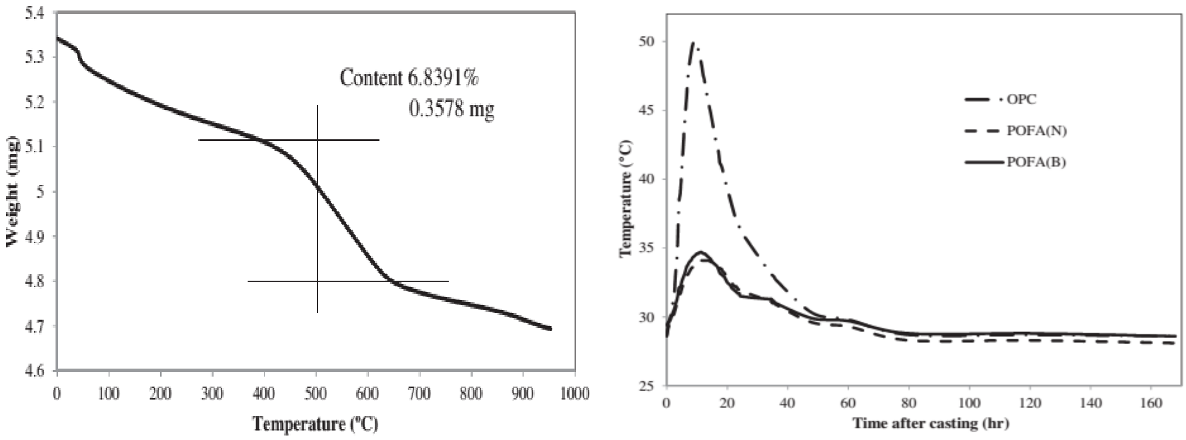


Figure 2. TGA results for POFA and B hydration heat of OPC, GPOFA, and UPOFA [25].

Absorption of water of the polymer-filled composites is identified by various factors, such as duration of immersion in water, composition of the composites, and processing techniques [28]. Besides that Tay et al. [29] proved that there is no significant impacts of POFA addition on the water absorption, segregation, drying shrinkage, density, and soundness of cement [29]. Awal et al. [21] who conducted study to find out effect of replacement 30% POFA by cement on the concrete on the hydration heat of cement, noted that delay in the final setting time more than in control sample, and the peak temperature acquired by incorporation 30% POFA in concrete mix is less than control sample. Also, Awal et al. [30] reported that concrete with 50, 60, and 70% POFA as cement replacement has a significant impact to reduce the hydration heat of concrete samples and delay to access to peak point in hydration heat as in Fig. 3.

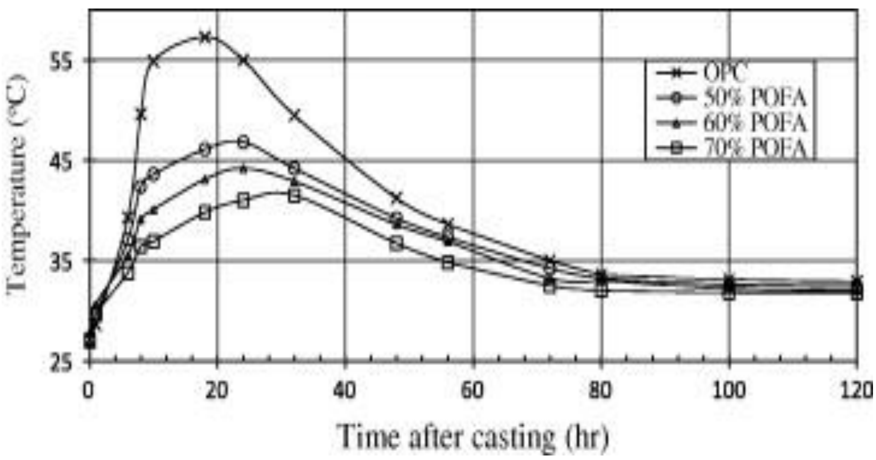


Figure 3. Development of hydration heat over the curing time [30].

Drying shrinkage is the main cause to occurrence of cracking, excessive deflection, stress re-distribution, pre-stress losses, and ingression of water and aggressive chemicals [31, 32]. Farzadnia et al. [33] conducted study on the 30% POFA as cement replacement in concrete mix, it was noted that drying shrinkage will be reduced by 7.5 % within 28 days due to add Nano silica to the concrete mix.

2.2 *Advantages for compressive strength*

The compressive strength for concrete containing POFA, flexural and tensile strength in same direction were comparable to the control concrete sample below the percentage of replacement less than 50% [34-36]. But, the replacement percentage of cement 50% by fineness POFA, the compressive strength was 90% of the control sample value. This is due to the high fineness of POFA particles and high surface area which assist to improve chemical reactivity [30]. Although the cement replacement by industrial waste will improve the compressive strength relatively, but replacement quantity more than 50% will decrease the compressive strength and other properties in concrete mortar due to level of pozzolanic reaction [37]. Therefore percentage of cement replacement by waste material is limited [38]. Lim et al. [25] proved that ultrafine POFA (UPOFA) has compressive strength value more than OPC and GPOFA at 28 days which was 105 MPa for UPOFA and 84 MPa for GPOFA. The high strength is due to the pozzolanic activity of fineness particle size of UPOFA and less carbon content. As in Fig. 4, UPOFA has better compressive strength value than both OPC and GPOFA.

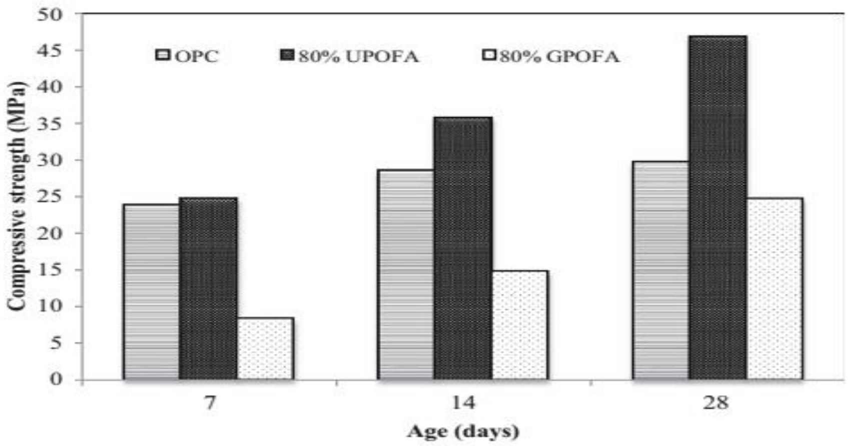
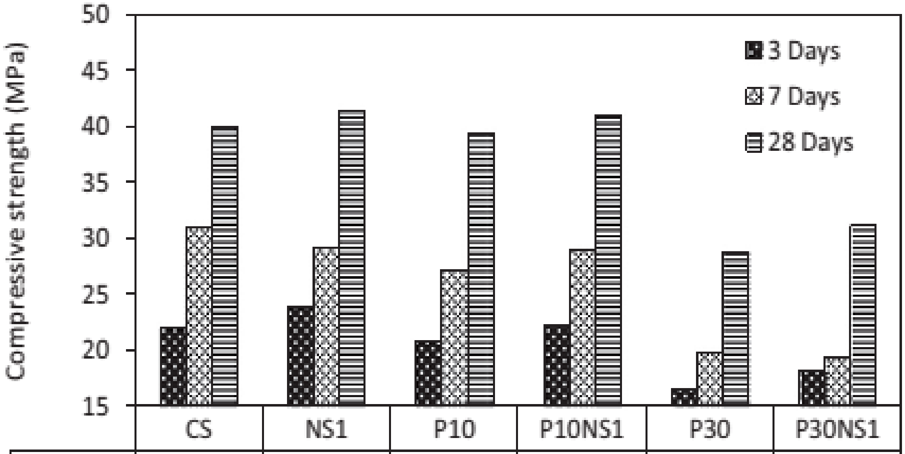


Fig. 4. Compressive strength of concrete made of OPC, GPOFA, UPOFA [25].

Although, adding more quantities of waste material to the concrete may lead to decrease compressive strength and decline other characteristics but some researcher noted that the nanoparticles based waste materials give better performance if used as cement replacement [39, 40]. Farzadnia et al. [33] evaluated influence adding Nano silica on the concrete containing POFA as cement replacement on the short-term drying shrinkage at 28 days and proved that the compressive strength will increase with adding Nano silica by 15% in the duration between 7 and 28 days of curing as in Fig. 5. In terms of preparation concrete in HPC, the highest compressive strength has been achieved with 20% POFA as cement replacement at 28 days and 550 kg/m3 was ranging between 60–86 MPa [15, 41]. In order to produce high strength concretes (HSC) by using POFA as cement replacement, Sata et al. [15] used water/ binder ratio of 0.28 and 560 kg/m^3 as binder content, the level of POFA replacement was 10%, 20% and 30% to produce concrete with compressive strength at 28 days 77.5, 81.3, 85.9, and 79.8 MPa respectively.



	CS	NS1	P10	P10NS1	P30	P30NS1
3 Days	22.0	23.8	20.8	22.2	16.4	18.1
7 Days	31.1	29.2	27.1	29.0	19.8	19.4
28 Days	40.0	41.4	39.4	41.0	28.8	31.2

Figure 5. Compressive strength of concrete samples at age 3,7,and 28 days [33].

Also, Tangchirapat et al. [14] said that the compressive strength of concrete containing POFA as cement replacement by 0%,10%, 20%, and 30% with water/binder ratio 0.32 and binder content amount 550 kg/m^3, the compressive strength at 28 days was 58.5, 59.5, 60.9 and 58.8 MPa respectively. Table 1 show the effect of POFA as cement replacement on the concrete properties by the previous studies.

Table 1. Effect of POFA as cement replacement on the concrete durability

Ref.	Replacement rate	Effect of cement replacement by POFA on the concrete properties
[14]	10%, 20%, 30%	Compressive strength at 28 days was 60.9 MPa for concrete with 20% POFA, while the control sample was 58.5 MPa only.
[15]	10%, 20%, 30%	The compressive strength will increase with the curing age which was more than the control sample by 85.9 MPa for 20% POFA.
[42]	60%, 80%, 100%	60% and 80% POFA as cement replacement appear high compressive strength at later age more than cement control due to the pozzolanic reaction between (SiO_2) from POFA and Ca $(OH)_2$ from process of cement hydration.
[43]	20%, 40%, 60%	Improve the compressive strength in later age of curing
[44]	20%, 40%, 60%	Achieve high compressive strength more than 90 MPa in 28 days, gain about 8% in 90 days with 60% POFA as replacement of OPC.
[44]	60%, 80%, 100%	The concrete samples were produced by POFA achieved 90% of the compressive strength in the normal concrete sample at 28 days.

2.3. Advantage for resistance chloride and acid attack

Chloride penetration, sulfate attack, and carbonation are three factors effect on the durability directly due to exposure to the external aggressive environments [45-47]. The concrete components break down when exposed on the acids attack, the dissolution of calcium hydroxide is the most pronounced [48]. The pozzolanic behavior and particles fineness of POFA made it has a unique resistance for aggressive chemical materials such as chloride penetration, sulfate, acid and other materials, in addition to limit the expansion resulted due to the alkali-silica reactivity [49]. POFA particles increase the resistance of concrete to the chloride ion penetration and acid environment [23, 34]. The high strength concrete HSC containing UPOFA in their composite has been used to protect the concrete from aggressive environment due to the delay in the migration time and chloride ion penetration needed to corrosion of reinforced concrete [44]. The results in Fig. 6 illustrated that the chlorine penetration rate values in concrete is rising at the first three days of curing age, because of weak microstructural density, however for long time up to 90 days there is reducing in the value of penetration rate if compared with OPC.

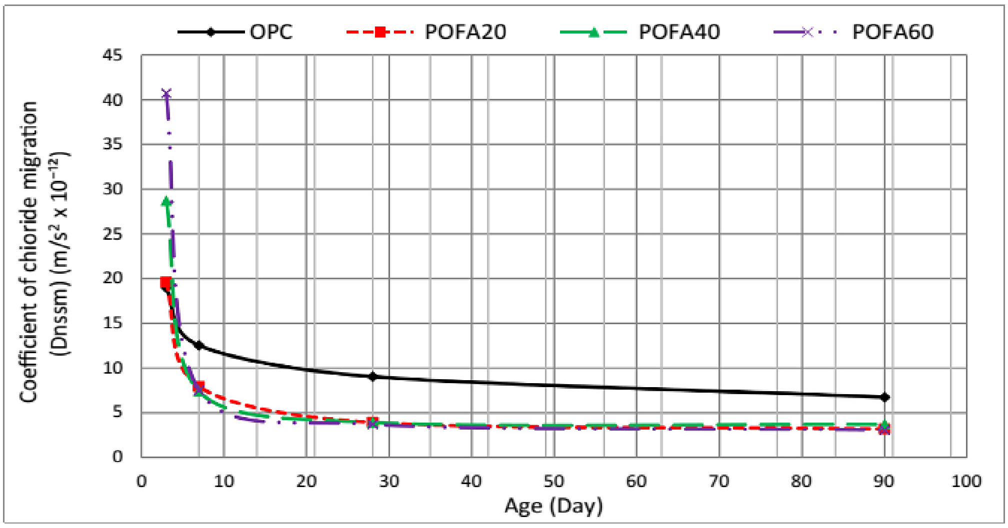


Figure 6. Impact of UPOFA in concrete on the chloride migration [44].

Besides to that, many researchers proved that inserting POFA as cement replacement partially to prepare concrete has lots benefits such as improving and enhancing the resistance of concrete against acid and chloride penetration [50, 51]. POFA is one of the geopolymer materials that have significant properties such as resistance of acid and sulphate attack, low shrinkage, low creep, and improve compressive strength [52].

2.4. Advantage for resistance the sulphate attack

POFA is one of the geopolymer binders and has been used as alternative to cement in concrete production because of ability to resistance of acid and sulphate attack, and enhance the compressive strength in the concrete [53]. Many researchers proved that POFA can be produced through grinding process to obtain fine particles with high surface area and good pozzolanic activity making it effective partial cement replacement material that improve compressive strength and resistance to sulphate attack [53, 54]. Salami et al. [55] used POFA as a binder cementitious material with 100% and Engineered Alkaline-activated Cementitious Composite (EACC) to produce concrete has resistance to sulphate attack. The concrete samples were immersed in three different solutions: 2.5% magnesium sulphate + 2.5% sodium sulphate solution, 5% magnesium sulphate solution, and 5% sodium sulphate solution. The study concluded that there was losing in the alkalinity of the POFA-EACC mortar samples in the first few days of exposure these samples to the sulphate solutions.

3. Conclusion

In this study, the advantages of POFA has been illustrated in the concrete mix especially regarding durability characteristics, hydration heat and drying shrinkage, compressive strength, resistance to chloride and acid, and resistance to the sulphate attack. POFA has good properties to enhance and improve the concrete durability especially with finer particles which called ultrafine POFA, due to have high content of silica thus tend to be high pozzolanic behaviour. In order to benefit from the POFA advantages in the concrete manufacturing, further experimental studies should be conducted to show the potential benefits beyond incorporation of POFA in the concrete mixtures.

References

[1] B. Wicke, R. Sikkema, V. Dornburg, and A. Faaij, "Exploring land use changes and the role of palm oil production in Indonesia and Malaysia," *Land use policy,* vol. 28, pp. 193-206, 2011.
[2] S. B. Hansen, R. Padfield, K. Syayuti, S. Evers, Z. Zakariah, and S. Mastura, "Trends in global palm oil sustainability research," *Journal of cleaner Production,* vol. 100, pp. 140-149, 2015.
[3] K. H. Mo, U. J. Alengaram, and M. Z. Jumaat, "A review on the use of agriculture waste material as lightweight aggregate for reinforced concrete structural members," *Advances in Materials Science and Engineering,* vol. 2014, 2014.
[4] Y. L. Chiew and S. Shimada, "Current state and environmental impact assessment for utilizing oil palm empty fruit bunches for fuel, fiber and fertilizer–A case study of Malaysia," *Biomass and bioenergy,* vol. 51, pp. 109-124, 2013.
[5] E. Olanipekun, K. Olusola, and O. Ata, "A comparative study of concrete properties using coconut shell and palm kernel shell as coarse aggregates," *Building and environment,* vol. 41, pp. 297-301, 2006.
[6] B. S. Thomas, S. Kumar, and H. S. Arel, "Sustainable concrete containing palm oil fuel ash as a supplementary cementitious material–A review," *Renewable and Sustainable Energy Reviews,* vol. 80, pp. 550-561, 2017.
[7] M. F. Awalludin, O. Sulaiman, R. Hashim, and W. N. A. W. Nadhari, "An overview of the oil palm industry in Malaysia and its waste utilization through thermochemical conversion, specifically via liquefaction," *Renewable and Sustainable Energy Reviews,* vol. 50, pp. 1469-1484, 2015.
[8] M. Gatto, M. Wollni, and M. Qaim, "Oil palm boom and land-use dynamics in Indonesia: the role of policies and socioeconomic factors," *Land Use Policy,* vol. 46, pp. 292-303, 2015.
[9] O. Sulaiman, N. Salim, N. A. Nordin, R. Hashim, M. Ibrahim, and M. Sato, "The potential of oil palm trunk biomass as an alternative source for compressed wood," *BioResources,* vol. 7, pp. 2688-2706, 2012.
[10] P. Chindaprasirt, S. Homwuttiwong, and C. Jaturapitakkul, "Strength and water permeability of concrete containing palm oil fuel ash and rice husk–bark ash," *Construction and Building Materials,* vol. 21, pp. 1492-1499, 2007.
[11] H. Abdel-Gawwad and S. Abo-El-Enein, "A novel method to produce dry geopolymer cement powder," *HBRC Journal,* vol. 12, pp. 13-24, 2016.

[12] E. Worrell, L. Price, N. Martin, C. Hendriks, and L. O. Meida, "Carbon dioxide emissions from the global cement industry," *Annual review of energy and the environment*, vol. 26, pp. 303-329, 2001.
[13] M. N. Fardis, *Innovative materials and techniques in concrete construction: ACES Workshop*: Springer Science & Business Media, 2011.
[14] W. Tangchirapat, C. Jaturapitakkul, and P. Chindaprasirt, "Use of palm oil fuel ash as a supplementary cementitious material for producing high-strength concrete," *Construction and Building Materials,* vol. 23, pp. 2641-2646, 2009.
[15] V. Sata, C. Jaturapitakkul, and K. Kiattikomol, "Utilization of palm oil fuel ash in high-strength concrete," *Journal of Materials in Civil Engineering,* vol. 16, pp. 623-628, 2004.
[16] A. A. Awal and M. W. Hussin, "The effectiveness of palm oil fuel ash in preventing expansion due to alkali-silica reaction," *Cement and Concrete Composites,* vol. 19, pp. 367-372, 1997.
[17] A. A. Awal and I. Shehu, "Performance evaluation of concrete containing high volume palm oil fuel ash exposed to elevated temperature," *Construction and Building Materials,* vol. 76, pp. 214-220, 2015.
[18] P. Monteiro, *Concrete: microstructure, properties, and materials*: McGraw-Hill Publishing, 2006.
[19] M. A. A. Rajak, Z. A. Majid, and M. Ismail, "Morphological characteristics of hardened cement pastes incorporating nano-palm oil fuel ash," *Procedia Manufacturing,* vol. 2, pp. 512-518, 2015.
[20] M. Safiuddin, M. Abdus Salam, and M. Z. Jumaat, "Utilization of palm oil fuel ash in concrete: a review," *Journal of Civil Engineering and Management,* vol. 17, pp. 234-247, 2011.
[21] A. A. Awal and M. W. Hussin, "Effect of palm oil fuel ash in controlling heat of hydration of concrete," *Procedia Engineering,* vol. 14, pp. 2650-2657, 2011.
[22] S. Bamaga, M. A. Ismail, Z. Majid, M. Ismail, and M. Hussin, "Evaluation of sulfate resistance of mortar containing palm oil fuel ash from different sources," *Arabian Journal for Science and Engineering,* vol. 38, pp. 2293-2301, 2013.
[23] M. Aldahdooh, N. M. Bunnori, and M. M. Johari, "Development of green ultra-high performance fiber reinforced concrete containing ultrafine palm oil fuel ash," *Construction and Building Materials,* vol. 48, pp. 379-389, 2013.
[24] W. Kroehong, T. Sinsiri, and C. Jaturapitakkul, "Effect of palm oil fuel ash fineness on packing effect and pozzolanic reaction of blended cement paste," *Procedia Engineering,* vol. 14, pp. 361-369, 2011.
[25] N. H. A. S. Lim, M. A. Ismail, H. S. Lee, M. W. Hussin, A. R. M. Sam, and M. Samadi, "The effects of high volume nano palm oil fuel ash on microstructure properties and hydration temperature of mortar," *Construction and Building Materials,* vol. 93, pp. 29-34, 2015.
[26] X.-Y. Wang and H.-S. Lee, "Modeling the hydration of concrete incorporating fly ash or slag," *Cement and concrete Research,* vol. 40, pp. 984-996, 2010.
[27] A. M. Neville, *Properties of concrete* vol. 4: Longman London, 1995.
[28] H. Ramakrishna, S. P. Priya, and S. Rai, "Effect of fly ash content on impact, compression, and water absorption properties of epoxy toughened with epoxy phenol cashew nut shell liquid–fly ash composites," *Journal of reinforced plastics and composites,* vol. 25, pp. 455-462, 2006.
[29] J.-H. Tay, "Ash from oil-palm waste as a concrete material," *Journal of Materials in Civil Engineering,* vol. 2, pp. 94-105, 1990.
[30] A. A. Awal and I. Shehu, "Evaluation of heat of hydration of concrete containing high volume palm oil fuel ash," *Fuel,* vol. 105, pp. 728-731, 2013.
[31] S. Tongaroonsri and S. Tangtermsirikul, "Effect of mineral admixtures and curing periods on shrinkage and cracking age under restrained condition," *Construction and Building Materials,* vol. 23, pp. 1050-1056, 2009.
[32] A. Itim, K. Ezziane, and E.-H. Kadri, "Compressive strength and shrinkage of mortar containing various amounts of mineral additions," *Construction and Building Materials,* vol. 25, pp. 3603-3609, 2011.

[33] N. Farzadnia, H. Noorvand, A. M. Yasin, and F. N. A. Aziz, "The effect of nano silica on short term drying shrinkage of POFA cement mortars," *Construction and Building Materials*, vol. 95, pp. 636-646, 2015.
[34] N. M. Altwair, M. M. Johari, and S. S. Hashim, "Flexural performance of green engineered cementitious composites containing high volume of palm oil fuel ash," *Construction and Building Materials*, vol. 37, pp. 518-525, 2012.
[35] N. Ranjbar, M. Mehrali, A. Behnia, U. J. Alengaram, and M. Z. Jumaat, "Compressive strength and microstructural analysis of fly ash/palm oil fuel ash based geopolymer mortar," *Materials & Design*, vol. 59, pp. 532-539, 2014.
[36] T. Deepak, A. Elsayed, N. Hassan, N. Chakravarthy, S. Y. Tong, and B. Mithun, "Investigation on properties of concrete with palm oil fuel ash as cement replacement," *International Journal of Scientific & Technology Research*, vol. 3, pp. 138-142, 2014.
[37] D. Lin, K. Lin, W. Chang, H. Luo, and M. Cai, "Improvements of nano-SiO 2 on sludge/fly ash mortar," *Waste management*, vol. 28, pp. 1081-1087, 2008.
[38] K. Lin, W. Chang, D. Lin, H. Luo, and M. Tsai, "Effects of nano-SiO 2 and different ash particle sizes on sludge ash–cement mortar," *Journal of Environmental Management*, vol. 88, pp. 708-714, 2008.
[39] M. M. Khotbehsara, E. Mohseni, M. A. Yazdi, P. Sarker, and M. M. Ranjbar, "Effect of nano-CuO and fly ash on the properties of self-compacting mortar," *Construction and Building Materials*, vol. 94, pp. 758-766, 2015.
[40] M. Sumesh, U. J. Alengaram, M. Z. Jumaat, K. H. Mo, and M. F. Alnahhal, "Incorporation of nano-materials in cement composite and geopolymer based paste and mortar–A review," *Construction and Building Materials*, vol. 148, pp. 62-84, 2017.
[41] V. Sata, C. Jaturapitakkul, and K. Kiattikomol, "Influence of pozzolan from various by-product materials on mechanical properties of high-strength concrete," *Construction and Building Materials*, vol. 21, pp. 1589-1598, 2007.
[42] M. W. Hussin, N. H. A. S. Lim, A. R. M. Sam, M. A. Ismail, M. Samadi, N. F. Ariffin, *et al.*, "Long Term Studies on Compressive Strength of High Volume Ultrafine Palm Oil Fuel Ash Mortar Mixes."
[43] M. M. Johari, A. Zeyad, N. M. Bunnori, and K. Ariffin, "Engineering and transport properties of high-strength green concrete containing high volume of ultrafine palm oil fuel ash," *Construction and Building Materials*, vol. 30, pp. 281-288, 2012.
[44] A. M. Zeyad, M. A. M. Johari, B. A. Tayeh, and M. O. Yusuf, "Pozzolanic reactivity of ultrafine palm oil fuel ash waste on strength and durability performances of high strength concrete," *Journal of Cleaner Production*, vol. 144, pp. 511-522, 2017.
[45] J. Zhang, C. Shi, Z. Zhang, and Z. Ou, "Durability of alkali-activated materials in aggressive environments: A review on recent studies," *Construction and Building Materials*, vol. 152, pp. 598-613, 2017.
[46] S. A. Bernal and J. L. Provis, "Durability of Alkali-Activated Materials: Progress and Perspectives," *Journal of the American Ceramic Society*, vol. 97, pp. 997-1008, 2014.
[47] M. Hossain, M. Karim, M. Hossain, M. Islam, and M. F. M. Zain, "Durability of mortar and concrete containing alkali-activated binder with pozzolans: A review," *Construction and Building Materials*, vol. 93, pp. 95-109, 2015.
[48] F. Pacheco-Torgal, J. Castro-Gomes, and S. Jalali, "Alkali-activated binders: A review: Part 1. Historical background, terminology, reaction mechanisms and hydration products," *Construction and Building Materials*, vol. 22, pp. 1305-1314, 2008.
[49] M. W. Hussin and A. A. Awal, "Influence of palm oil fuel ash on sulfate resistance of mortar and concrete," *Special Publication*, vol. 178, pp. 417-430, 1998.
[50] M. A. Lacasse and D. J. Vanier, *Durability of Building Materials and Components 8: Service life and durability of materials and components* vol. 1: NRC Research Press, 1999.
[51] P. Chindaprasirt, S. Rukzon, and V. Sirivivatnanon, "Resistance to chloride penetration of blended Portland cement mortar containing palm oil fuel ash, rice husk ash and fly ash," *Construction and Building Materials*, vol. 22, pp. 932-938, 2008.

[52] S. Wallah and B. V. Rangan, "Low-calcium fly ash-based geopolymer concrete: long-term properties," 2006.

[53] W. Tangchirapat, T. Saeting, C. Jaturapitakkul, K. Kiattikomol, and A. Siripanichgorn, "Use of waste ash from palm oil industry in concrete," *Waste Management*, vol. 27, pp. 81-88, 2007.

[54] C. Jaturapitakkul, K. Kiattikomol, W. Tangchirapat, and T. Saeting, "Evaluation of the sulfate resistance of concrete containing palm oil fuel ash," *Construction and Building Materials*, vol. 21, pp. 1399-1405, 2007.

[55] B. A. Salami, M. A. M. Johari, Z. A. Ahmad, and M. Maslehuddin, "Durability performance of Palm Oil Fuel Ash-based Engineered Alkaline-activated Cementitious Composite (POFA-EACC) mortar in sulfate environment," *Construction and Building Materials*, vol. 131, pp. 229-244, 2017.