Recent Trends in Civil Engineering and Built Environment Vol. 3 No. 1 (2022) 1752-1764

RTCEBE

Homepage: http://publisher.uthm.edu.my/periodicals/index.php/rtcebe
e-ISSN :2773-5184

A Review of Geopolymer Bricks and Concrete Containing fly ash and Palm oil Fuel ash

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DOI: https://doi.org/10.30880/rtcebe.2022.03.01.195
Received 4 July 2021; Accepted 13 December 2021; Available online 15 July 2022

Abstract: The production of conventional bricks and concrete will involve the emission of greenhouse gases. Fly ash (FA) and palm oil fuel ash (POFA) as the industrial byproduct or waste material are potentially to be used to replace the ordinary Portland cement (OPC)-made construction materials through the process of geopolymerization. This study was conducted to review the physical properties, microstructure and performance (compressive strength and water absorption) of eco-friendly bricks and concrete made from FA and POFA through geopolymerization. The comprehensive literature review was conducted to review all the related online articles and journals to achieve the objectives of this study. The keywords were used to filter the journals found in order to obtain the most related journals with this study. All the studies would be summarized according to the geopolymer product, waste material used, alkali activator, specimen size, curing condition, conducted test and author. FA and POFA were proved as one of the alternatives to substitute OPC content in bricks and concrete because the geopolymers produced complied with the standard requirement to be used in the construction industry. The study would provide a first idea to the engineers in the construction field to use the eco-friendly geopolymer bricks and concrete made by FA and POFA instead of ordinary Portland cement.

Keywords: Fly Ash, Palm Oil Fuel Ash, Geopolymer

1. Introduction

As the world population increases, the demands of building materials like bricks are getting higher. The conventional bricks made by the fire clay and ordinary Portland cement negatively impact the environment due to its highly energy intensive and its large carbon footprint. The production of conventional bricks involves emission of greenhouse gases by 5-7%. There are many researches and studies conducted to reuse the waste materials in the production of bricks to protect our environment

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and conserve sustainable development. The bricks made from waste material are ideally cheap, light, environmental-friendly and most importantly, its material properties still comply with the standard [1]. The usage of concrete is high enough to be the second place in the whole world before water. The advanced technology of concrete was well-developed in terms of design and execution procedure [2]. Ordinary Portland Cement (OPC) as the most used binder to produce the concrete had left us some environmental issues such as the emission of carbon dioxide during the manufacturing of OPC due to the calcination of limestone and fossil fuel combustion. As the demand for OPC increased every year, the studies were conducted to find other alternatives to replace the OPC usage [3].

The aim of this study is to review the physical properties, microstructure and performance of bricks and concrete containing FA and POFA through geopolymerization. The related and trusted journals and articles are explored through the internet. All the online papers would be filtered for the studies within recent years (2011-2021) to ensure the research is up to date with the latest science and technology developed. This study would provide a first idea to the engineers in the construction field to use the eco-friendly geopolymer bricks and concrete made by FA and POFA instead of OPC. The idea to use waste materials to partially or fully substitute the raw material in the production of construction materials would encourage a cleaner and sustainable construction practice.

2. Fly Ash

2.1 Physical Properties

By visually, FA is grey in colour. It is abrasive, mostly alkaline and refractory in nature. Pozzolans works well as the admixture with FA combined with water and alkali activator to form cementitious products at ambient temperature. For producers of thermal electricity, FA is a waste material produced during the generation of electricity while for the cement industry. FA is described as fine, powdery particles predominantly round or spherical in shape, either solid or hollow and mostly glassy in nature. The angular particles are found in the carbonaceous material in FA. The particle size distribution of bituminous coal FA is similar to silt which is less than 0.075mm or No. 200 sieve. The specific gravity of FA is between 2.1 to 3.0 while its specific surface area is between 170 to 1000 m^2/kg. The colour of FA could be gray or black which depends on the unburnt carbon left in the FA [4].

2.2 Chemical Properties

There are four types of coal which are anthracite, bituminous, sub-bituminous and lignite. The FA is classified according to the type of coal that produced it. The main components of bituminous coal FA are silica, alumina, iron oxide, and calcium, with different amounts of carbon which can be measured by loss on ignition (LOI). Lignite and sub-bituminous have high concentration of calcium and magnesium oxide which make them have lesser concentration of silica, iron oxide and carbon when compared with bituminous coal FA [4]. Table 1 showed the normal range of the chemical constituents of bituminous coal FA, lignite coal FA and sub-bituminous coal FA.

Table 1: Components of oxides respectively in bituminous, sub-bituminous and lignite coal FA [4]

Component (wt%)	Bituminous	Sub-bituminous	Lignite
SiO_2	20-60	40-60	15-45
Al_2O_3	5-35	20-30	10-25
Fe_2O_3	10-40	4-10	4-15
CaO	1-12	5-30	15-40
MgO	0-5	1-6	3-10
SO_3	0-4	0-2	0-10
Na_2O	0-4	0-2	0-6
K_2O	0-3	0-4	0-4
LOI	0-15	0-3	0-5

3. POFA

3.1 Physical Properties

POFA includes large particles of carbon, intact palm oil fibre and some greyish colour particles. The physical properties of POFA were shown in Table 2. The physical properties of POFA are affected by the burning temperature and other conditions. The higher the amount of unburned carbon, the darker it looks. If further burning until all carbon is removed, the colour of POFA will be grey. The particle size of unground POFA is larger than ground POFA. In terms of shape, the particle shape of unground POFA is spherical and porous while the particle shape of ground POFA is irregular and angular due to its crushed particles [5].

Table 2: Physical Properties of POFA [6].

Physical Properties	POFA
Specific gravity	2.42
Particle retained on 45um sieve	4.98
Median particle d_{10} (1.69um)	1.69
Median particle d_{50} (14.58um)	14.58
Blaine fitness (cm^2/g)	4935
Surface area (cm^2/g)	7078
Soundness (mm)	3.0

3.2 Chemical Properties

The chemical properties of POFA differ from the burning condition of palm oil such as temperature and burning quantity. The chemical properties of material to produce the cement can affect the performance of concrete such as workability. There is about 43% to 71% of the silicon dioxide component in POFA that gives it good pozzolanic properties to produce high performance concrete [5]. Awal & Abubakar, [6] had conducted review research for the chemical composition of ground POFA. Table 3 showed the chemical composition of ground POFA. The combination of its chemical composition in POFA makes it a good material to substitute OPC to produce a better product.

Table 3: Chemical Composition of POFA [6]

Chemical composition	% in POFA
SiO_2	59.62
Al_2O_3	2.54
Fe_2O_3	5.02
CaO	4.92
MgO	4.52
K_2O	7.52
Na_2O	0.76
P_2O_5	3.58
Cl	0.34
SO_3	1.28
LOI	8.25
$SiO_2 + Al_2O_3 + Fe_2O_3$	67.18
Residue on 45 µm sieve	4.98

4. Geopolymer Bricks

Muduli *et al.*, [7] used different ratios of $Na_2O/(Al_2O_3+SiO_2)$ as a manipulation variable to study the crushing strength of FA-based geopolymer bricks under atmospheric curing and hot air curing. The $Na_2O/(Al_2O_3+SiO_2)$ ratio of 0.078 achieved the highest compressive strength of 43 MPa under atmospheric curing. The micrograph showed that sodium formed a crystalline structure which strengthened the alumino-silicate geopolymer and became a more complex and stronger product.

Ferone *et al.*, [8] had conducted a study to produce the geopolymer brick by using the weathered coal FA. The weathered FA is categorized into dry FA and wet FA. The performance of dry FA is adequate for manufacture of geopolymer based low temperature products while the wet FA without any activating solution would result in high water content in the product and bad mechanical performance in terms of unconfined compressive strength (UCS) at any curing condition. Furthermore, the curing condition of 60 degree Celsius could strongly improve the mechanical strength of geopolymer brick made by weathered FA even only for 24 hours of curing time. When curing under room temperature, the unreacted spherical fly ash particles could be seen clearly and porosity voids could be spottedt from the micrographs. He strongly suggested considering the water content of FA for mix design of geopolymer bricks.

In the study of Kalombe *et al.*, [9] it was proved that the increased concentration of NaOH could increase the strength of geopolymer bricks. Besides, the curing temperature did not affect the strength development, but it was recommended to cure the geopolymer bricks under low temperature for a short period. The water content had a significant effect on the hardening process of geopolymer to act as a transport mechanism for the dissolution of silicate and alumina to form N-A-S-H gel. In terms of water absorption, an increase in alkalinity could decrease the water absorption and produce low porosity geopolymer bricks.

According to Jandhyala *et al.*.. [10] phosphogypsum-based geopolymer bricks could be used for bearing application as its highest compressive strength was up to 12.5 MPa. When mixed with FA, the density of geopolymer bricks could achieve the lowest water absorption of 17.72% when 9% of phosphogypsum was mixed. The geopolymer bricks made by phosphogypsum and FA have low porosity, high acid resistance, high durability and low water absorption. It could contribute to the construction sector as it can reduce the total cost of the building structure and ideally be used in water retaining structures.

Opiso *et al.*, [11] had utilized the FA and POFA to produce the geopolymer bricks. The result showed that FA and POFA were feasible to be used in the production as the brick specimen could achieve the compressive strength of 7.58 MPa and 7.7 MPa. As shown in micrographs, the gel-like structures and unreacted FA particles were observed.

75% FA and 25% GGBS was the optimum composition to produce the geopolymer bricks with the highest compressive strength (51.6 MPa) and the lowest water absorption (6%) [12].

Table 4 showed the summary of geopolymer bricks comprehensive literature review in terms of waste material used, alkali activator, specimen size, curing condition, test conducted and references.

Table 4: Summary of geopolymer bricks comprehensive literature review.

No.	Waste Material	Alkali activator	Specimen size (mm)	Curing condition	Test conducted	References
1.	FA	$Na_2O/(Al_2O_3+SiO_2)$ = 0.025 to 0.078	230 x 110 x 75	Atmospheric curing for 25 days	Crushing strength	[7]
2.	Weathered coal dry FA and wet FA	$Na_2SiO_3/NaOH$ = 2.5	30 (diameter) x 60 (height)	Cured under room temperature and 60°C for various of duration	Compressive strength,	[8]
3.	FA	$Na_2SiO_3/NaOH$ = 2,5	100 x 100 x 100	Cured at 60°C or 80°C for 24 hours	Compressive strength, water absorption, carbon emission	[9]

Table 4: Summary of geopolymer bricks comprehensive literature review (continued)

No.	Waste Material	Alkali activator	Specimen size (mm)	Curing condition	Test conducted	References
4.	Phosphogypsum and FA	$Na_2SiO_3/NaOH$ = 1.0	90 x 92 x 192	Cured in 70-75°C for 12 hours	Compressive strength, water absorption, acid reaction	[10]
5.	FA, mine tailing, POFA, powder activator	Sugar mill lime sludge/NaOH = 0.5	50 x 50 x 50	Cured at ambient temperature for 14 days	Compressive strength	[11]
6.	FA, GGBS	$Na_2SiO_3/NaOH$ = 2.5	230 x 110 x 75	Cured at curing tank for 28 days	Compressive strength, water absorption, acid resistance	[12]

5. Geopolymer Concrete

The increase in addition of foaming agent into the mixture of geopolymer concrete could significantly decrease its performance in all aspects. The micrographs showed great numbers of pore found at the interface of concrete which was contributed by the foaming agent [13].

The addition of POFA up to 20% and 40% into the oil palm shell geopolymer concrete could decrease its density and compressive strength respectively. The increase of strength gain in ambient temperature curing was higher than the oven curing over time. It was recommended to use 20% of POFA and the alkaline solution to binder ratio of 0.35 to produce the highest compressive strength concrete [14]

To compare the geopolymer concrete that added superplasticizer and water alone into the mixture, the addition of water was actually enough to increase the compressive strength of concrete while the superplasticizer had only minimal effect on the strength of concrete. The micrograph showed the bond within the concrete was stronger when the water was added alone if compared to water and plasticizer added together [15].

In terms of compressive strength, density, porosity and water absorption, the FA and foam-contained geopolymer concrete performed better when cured at 60°C compared to room temperature. The microcracks were observed at the surface of concrete that cured under 60°C which could increase the porosity and water absorption and decrease the strength [16].

Lavanya & Jegan, [17] showed the downside of geopolymer concrete as the overall performance would drop over time when exposed to acid. The OPC concrete became a better alternative as its compressive strength, density and water absorption were better than geopolymer concrete.

Wardhono *et al.*, [18] had compared the performance of geopolymer concrete between alkali activated slag and low calcium fly ash geopolymer concrete up to 540 days. The FA concrete showed a constant improvement in strength and water absorption over time while slag geopolymer concrete became weaker over time. The maximum compressive strength achieved by FA geopolymer concrete was 33.2 MPa. The micrograph showed a crack-free FA geopolymer concrete at 540=day.

Sasui *et al.*, [19] proved that geopolymer concrete with the alkali activator consisted of Na_2SiO_3 and NaOH could perform better in terms of compressive strength, final setting time, porosity and water absorption if compared with the alkali activator consisted of NaOH alone. The micrograph showed the increasing Si/Al ratio and led to formation of the Si-O-Si bond which was stronger.

Yong *et al.* [20] studied that POFA geopolymer concrete could achieve 87% of 28-day compressive strength in just 3 days. The addition of foam decreased the concrete strength and increased the water absorption. The micrograph showed the concrete was denser and more homogenous at 28-day due to higher degree of gel formation and dissolution of the binder.

The external heat during the curing process of geopolymer concrete could boost its compressive strength at both early age and final age. The increase in the concentration of NaOH as the alkali activator could improve the strength of concrete. The content of OPC in the concrete could reduce the microcracks at the surface of the concrete as OPC could utilize any excessive water from the geopolymerization process [21].

Angulo-ramírez & Valencia-saavedra, [22] discovered that geopolymer concrete produced by the combination of GGBS and FA achieved higher compressive strength and lower water absorption if compared with conventional OPC concrete. The micrograph showed the dense compacted geopolymer concrete mixed with GGBS and FA.

According to Mahmoud *et al.*, [2] the addition of Si and NaOH concentration in the mixture within the required limit could boost the compressive strength of the geopolymer concrete. Same theory applied to superplasticizer as 2.5-3.5% content would increase the void in the concrete. The study proved that the long rest period before curing could increase the strength of concrete. The concrete that cured under high temperature had higher strength. As everything stated above was fulfilled, the maximum compressive strength achieved was 50.4 MPa. The microstructure of geopolymer concrete was denser than OPC concrete when it was produced correctly.

The addition of just a little bit of graphene oxide about 0.6% at 14 molarity concentration of NaOH could boost the compressive strength of geopolymer concrete and perform better in terms of voids and density. Higher concentration of NaOH and the addition of graphene oxide resulted in denser composite of concrete [23].

Different curing methods of geopolymer concrete would eventually achieve the similar strength at 28-day but the difference could be spotted at the early age of 3-day and 7-day. The manufactured sand was more suitable to be used as the fine aggregate to achieved higher strength if compared with mining sand and quarry dust [24].

Kabir *et al.*, [25] produced the POFA, metakaolin and BBGS-contained geopolymer concrete with 100% palm oil clinker (9-14mm) as coarse aggregate which achieved 42 MPa compressive strength. The water absorption of concrete increased with the size of course aggregate. In fact, the micrograph showed the denser microstructure of concrete with 100% palm oil clinker as coarse aggregate.

Table 5 showed the summary of geopolymer concrete comprehensive literature review in terms of waste material used, alkali activator, specimen size, curing condition, test conducted and references.

Table 5: Summary of geopolymer concrete comprehensive literature review

No.	Waste Material	Alkali activator	Specimen size (mm)	Curing condition	Test conducted	References
1.	FA, GGBS	Na_2SiO_3/NaOH	40 x 40 x 40, 70 x 70 x70	Cured in the curing machine for 7 days	Compressive strength, density, thermal conductivity, water absorption, fluidity	[13]
2.	POFA, oil palm shell	Na_2SiO_3/NaOH = 2.5, 0.55, 0.35	100 x 100 x 100	Cured at 65°C and ambient temperature for 48 horus	Compressive strength, tensile strength	[14]

Table 5: Summary of geopolymer concrete comprehensive literature review (continued)

No.	Waste Material	Alkali activator	Specimen size (mm)	Curing condition	Test conducted	References
3.	POFA	Na_2SiO_3/NaOH = 2.5	50 x 50 x 50	Cured at 60±5°C for 24 hours	Compressive strength	[15]
4.	FA, foam	Na_2SiO_3/NaOH = 2.5	50 x 50 x 50	Cured at 60°C and room temperature for 24 hours	Compressive strength, water absorption, porosity, density	[16]
5.	FA	Na_2SiO_3/NaOH = 2.5	150 x 150 x 150	Cured at ambient temperature until the age of testing	Compressive strength, water absorption, density	[17]
6.	FA	Na_2SiO_3/NaOH = 2	100 (diameter) x 200 (height)	Cured at 80°C for 24 hours	Compressive strength, tensile strength, flexural strength, elastic modulus, water absorption, water permeability	[18]
7.	FA, GGBS	Na_2SiO_3/NaOH = 1.5	50 x 50 x 50	Cured at 60°C for 24 hours	Final setting time, compressive strength, porosity, water absorption, volume of impervious portion	[19])
8.	POFA	Na_2SiO_3/NaOH = 2.5	100 x 100 x 100	Cured at 65°C for 48 hours	Compressive strength, water absorption, sorptivity	[20]
9.	FA	Silica fume/NaOH =0.75	75 (diameter) x 152 (height)	Cured at various temperature for different duration	Compressive strength	[21]
10.	FA, GGBS	Na_2SiO_3/NaOH = various ratio	76.2 (diameter) x 76.2 (height)	Cured at various temperature until the age of testing	Compressive strength, water absorption	[22]
11.	FA	Na_2SiO_3/NaOH = 2.4	-	Cured at various temperature for different duration	Compressive strength, shrinkage	[2]
12.	POFA	Na_2SiO_3/NaOH	50 x 50 x 50	Cured at 80°C for 24 hours	Compressive strength, void, density	[23]
13.	POFA	Na_2SiO_3/NaOH = 2.5	100 x 100 x 100	Cured at 65°C and ambient temperature at 2 hours	Compressive strength, split tensile strength, flexural strength, elastic modulus	[24]
14.	POFA, GGBS, metakaolin, oil palm shell, oil palm clinker	Na_2SiO_3/NaOH = 2.5	100 x 100 x 100	Cured at 65°C for 24 hours	Elastic modulus, ultrasonic pulse velocity, water absorption, sorptivity, density, workability, compressive strength.	[25]

6. Discussion on Previous Study

According to the study of Muduli *et al.*, [7] the geopolymer mixture was solidified due to the reaction of SiO_2 and Al_2O_3 with alkali (Na_2O) governing the geopolymerization process. The geopolymer bricks were strong and compacted as the dissolution and polymerization of Al and Si and formed the crystalline structures of sodium assisted cross linked alumino-silicate geopolymer phases. The presence of Cl and SO_4^{2-} anions in the alkali activator could enhance the geopolymerization process. According to the SEM (scanning electron microscope) micrograph shown in Figure 1, it showed the microstructure of weak bonded geopolymer due to low concentration of alkali activator. Hence, the structure of geopolymer would be weak and less compacted while there are some unreacted FA particles observed. From the SEM analysis, high content of Al, Si and Ca were observed as they were the main reason for the formation of geopolymers.

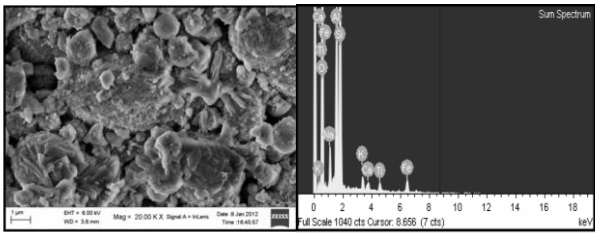


Figure 1: SEM micrograph of FA geopolymer [7]

The addition of wet ash into the geopolymer mixture would result in low compressive strength and low density due to its water content. Therefore, wet ash was not suitable to be used as the binder in the geopolymer while dry coal fly ash was potentially to produce a better geopolymer with proper curing. Figure 2 showed the microstructure of coal FA geopolymer when cured at room temperature and elevated temperature respectively. It was less compacted and unreacted FA particles could be observed clearly. The study proved that the geopolymer could be more compacted with a longer curing time. In the case where the geopolymer cured at room temperature, the microstructure of geopolymer was compacted because of the higher SiO_3/Na_2O molar ratio in the alkali activator [8].

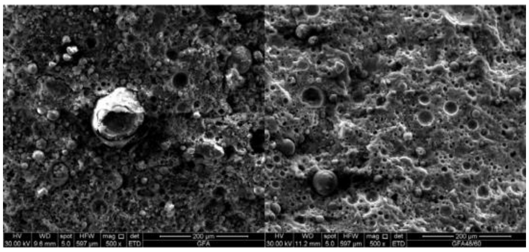


Figure 2: The microstructure of coal FA geopolymer cured at room temperature and elevated temperature respectively [8]

The geopolymer with the foaming agent did not work that well and some treatments were needed. Therefore, Xu *et al.*, [13] studied the addition of foam stabilizer into the mixture. Figure 3 showed the treated sample of geopolymer foam with obvious pores on its surface. By adding the foam stabilizer H_2O_2 (hydrogen peroxide), it could improve the density, thermal conductivity, pores, compressive strength and fluidity. The SEM micrographs were shown at Figure 4 with magnification of 135x and

3700x. It could be seen that the structure of geopolymer foam was very porous. These large pores indicated how weak the geopolymer foam was. The microcracks could be observed at the same time.

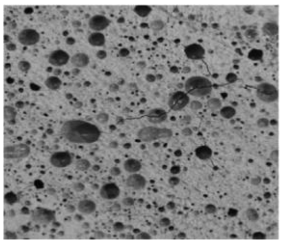


Figure 3: The surface appearance of geopolymer foam [13]

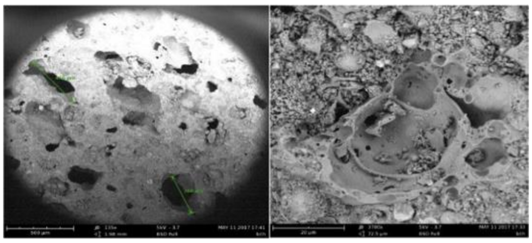
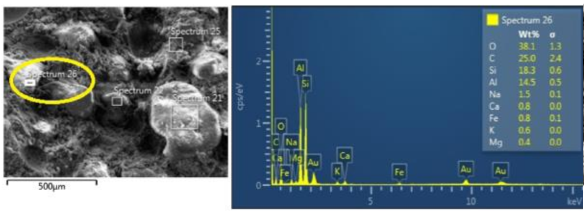


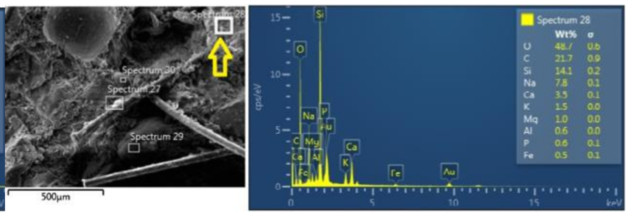
Figure 4: The SEM micrographs of geopolymer foam with the magnification of 137x and 3700x respectively [13]

In the study of Yong *et al.*, [14] he found the best content of POFA in oil palm shell geopolymer concrete mixture to produce the highest compressive strength (20%) and density (40%) geopolymer. The density of geopolymer increased over the curing time. This is due to longer time of pozzolanic activity within the mixture to harden and undergo the process of dissolution, condensation and polymerization of Al and Si.

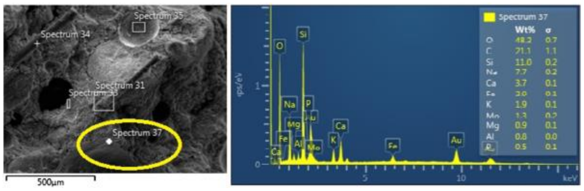
Salami *et al.*, [15] concluded that addition of water into POFA geopolymer could increase the compressive strength of geopolymer better than the addition of superplasticizer and both. Figure 5a-c showed the SEM micrographs of geopolymer with water; superplasticizer; and both water and superplasticizer. The microstructure of all the samples were quite compacted and uniform. In the case where only water was added, the water content added could be more than 10% or else the compressive strength of geopolymer would drop.



(a)



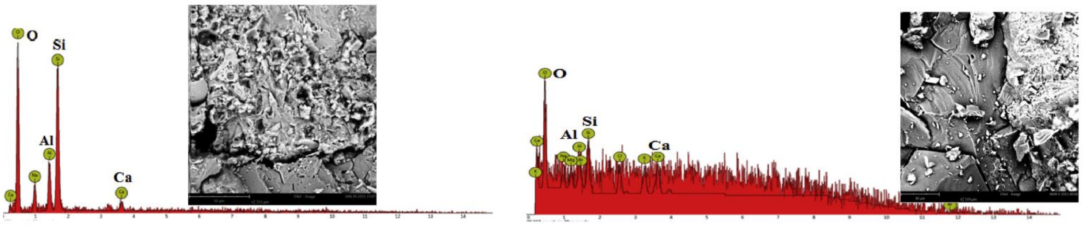
(b)



(c)

Figure 5: The SEM micrograph of geopolymer added with specific content. (a) superplasticizer and water. (b) water. (c) superplasticizer [15]

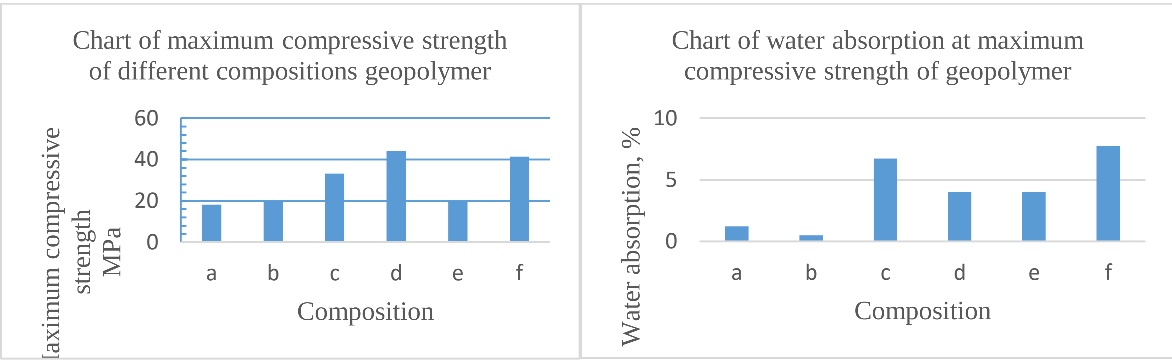
According to Kabir *et al.*, [25] the density (1955-2172 kg/m^3) of POFA geopolymer concrete with the mixing of palm oil clinker and oil palm shell coarse aggregate was complied with the standard requirement of lightweight concrete (<2200 kg/m^3) stated in Eurocode. 6 different compositions of aggregates were studied. The density and compressive strength of geopolymer concrete differed with the different size of coarse aggregates added into the mixture. Figure 6a showed the micrograph of POFA geopolymer concrete with 100% of palm oil clinker coarse aggregate and Figure 6b showed the micrograph of POFA geopolymer concrete with 50% of palm oil clinker and 50% of oil palm shell as the coarse aggregate. The study proved that the types and sizes of coarse aggregate could significantly affect the microstructure of geopolymer.



(a) (b)

Figure 6: The SEM and EDS micrograph of POFA geopolymer concrete with specific content. (a) 100% of palm oil clinker coarse aggregate. (b) 50% of palm oil clinker and 50% of oil palm shell as the coarse aggregate.

Figure 7a and 7b showed the maximum compressive strength and water absorption of different compositions of geopolymer. The compositions of geopolymer are: (a) FA with foaming agent concrete, (b) FA concrete, (c) FA with aggregate concrete, (d) 15% FA, 85% GGBS concrete, (e) POFA concrete, (f) 20% metakaolin, 45% GGBS, 45% FA with POFA as coarse aggregate concrete.



(a) (b)

Figure 7(a) Maximum compressive strength of different compositions geopolymer, (b) Water absorption at maximum compressive strength of geopolymer

To compare two charts shown in Figure7a-b, it could be seen that different studies achieved different results in terms of compressive strength and water absorption. In most cases, the content and materials used in the geopolymer are not the only factor to affect these two parameters.

Beside the type of binders used, the concentration of NaOH solution, curing method, specimen size and shape [17] and even the minor detail in the studies could make a big difference. It is difficult to determine the compressive strength and water absorption of FA/POFA-contained geopolymer just based on the journal reviews. The geopolymers with high compressive strength would also have low water absorption and high density as its binder particles reacted in high degree and compacted well.

According to the studies of Wardhono *et al.*, [18] and Yong *et al.*, [20] longer curing time of geopolymer would definitely produce the result of better performance of geopolymer in terms of compressive strength and water absorption. The geopolymer had the ability to develop high strength at the early stage.

Moreover, in the studies of Kabir *et al.*, [25] and Sasui *et al.*, [19] it could be observed that geopolymers with a single type of binder did not work as well as the geopolymers with combinations of different binders such as GGBS. It is because other binders are used as an agent to strengthen the geopolymer with its unique characteristic and chemical composition. On the other hand, the geopolymer with the addition of a foaming agent did not improve the performance but the final product did serve for the other structural purposes such as non-bearing concrete and bricks [16].

According to the studies of Angulo-ramírez & Valencia-saavedra, [22] and Islam *et al.*, [24] FA and POFA as the waste material and main binder of geopolymer showed great potential to be used in the construction industry. The geopolymer had a similar or higher performance than the OPC concrete when every step in the geopolymerization process was done right. For example, the method of curing, concentration of alkali activator and the composition of binder.

Meanwhile, Mahmoud *et al.*, [2] studied that FA-based geopolymer did not perform better than OPC concrete. In this case, there are lots of alternatives to be used as shown in the studies of Amri *et al.*, [23] Islam *et al.*, [24] and Assi *et al.* [21]. The addition of other materials such as graphene oxide and GGBS could effectively increase the strength of thr geopolymer.

In conclusion, POFA and FA is the future environment-friendly alternative to substitute OPC in the construction industry because its geopolymer produced is still complied with the standard requirement of construction material and its sustainability value is undeniable.

7. Conclusion

The physical properties, microstructure and performances of FA-contained and POFA-contained bricks and concrete produced through geopolymerization were reviewed in this study. There are many factors to consider before manufacturing the geopolymer products as their performances are highly dependent on them. The physical properties and microstructure of geopolymers with compacted, dense and crack-free surface indicate their good performance in terms of compressive strength and water absorption. The use of geopolymer is a big step in sustainable development without causing tremendous damage to mother nature. The awareness is needed in town planners, architects, engineers, and builders to consider the reutilization of waste material but not create more of them.

Some recommendations for further studies are made as follow:

i. The laboratory experiment could be carried out to determine the compressive strength and water absorption of geopolymers containing POFA and FA.
ii. More combinations of waste materials are mixed into the geopolymer mixture and tested.
iii. More additives such as water and superplasticizer could be mixed into the geopolymer mixture together with POFA and FA to investigate and compare its performance with other studies.
iv. The geopolymer contained POFA and FA could be used to produce concrete beam and column to determine its safeness, strength and performance such as deflection, vibration, fire resistance and many others.

Acknowledgement

The authors would also like to thank the Faculty of Civil Engineering and Built Environment, Universiti Tun Hussein Onn Malaysia for its support.

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