Sustainable Structures
ISSN: 2789-3111 (Print); ISSN: 2789-312X (Online)
http://www.sustain-dpl.com/journal/sust
DOI: 10.54113/j.sust.2024.000050

REVIEW ARTICLE

Integration of fly ash and ground granulated blast furnace slag into palm oil fuel ash based geopolymer concrete: a review

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Abstract: The construction industry significantly depends on concrete due to its mechanical attributes and economy efficiency. The increase demand for building materials, particularly concrete, has resulted in overproduction of ordinary portland cement (OPC) and consequent significant release of carbon dioxide (CO_2) into the atmosphere. For addressing these issues, alternative innovative and sustainable materials, such as geopolymer concrete, which utilised waste materials as binding agents have been introduced, leading to a reduction in CO_2 emissions. Palm oil fuel ash (POFA) contains abundant silicates and aluminates, making it well-suited for use as binder in geopolymer concrete. On the other hand, POFA geopolymer concrete with high volume exhibits reduced early strength development, decreased workability, and an extended setting time. Therefore, this review paper emphasizes the need of including fly ash (FA) and ground granulated blast furnace slag (GGBS) into POFA-based geopolymer concrete. A notable result of the review is that the inclusion of aluminium oxide and iron (III) oxide in FA improves the chloride binding capability, resulting to a dense microstructure with high strength. In addition, the presence of calcium oxide in FA and GGBS enhances the creation of C-S-H, N-A-S-H, and C-A-S-H gels, resulting in a decrease in porosity and an enhancement of the fresh and mechanical characteristics. Furthermore, the use of FA improves the insulation and thermal efficiency of the geopolymer concrete. Therefore, integration of FA and GGBS in POFA geopolymer may enhanced the mechanical and durability qualities. Further study is required to optimize the composition of POFA, FA and GGBS in the mix, and researching new, cost-effective alkaline activators obtained from waste products offers another avenue for boosting the efficiency of geopolymer synthesis.

Keywords: Geopolymer; palm oil fuel ash; fly ash; ground granulated blast furnace slag; fresh and mechanical properties; alkaline activator

1 Introduction

Concrete is often used in the building sector because to its mechanical properties and economic efficiency [1]. Ordinary portland cement (OPC) is the predominant building material [2] but it contributes up to 7% of the worldwide carbon dioxide (CO_2) emission during the manufacturing process [3]. The manufacturing process of cement necessitates a substantial quantity of energy for the elevated temperature

Received: 1 April 2024; Received in revised form: 24 August 2024; Accepted: 28 August 2024

heating process in the cement kiln, leading to excessive CO_2 emissions [4]. Decreasing the use of cement is essential as a means of mitigating CO_2 emissions [5].

To mitigate the issues of the excessive emission of CO_2 and the high amount of waste materials, the cement and concrete industry has been working on several innovations and techniques. The development of geopolymer concrete is an innovative solution to address environmental concerns. Geopolymer concrete employs waste materials as a binder compound, lowering CO_2 emissions by eliminating the need for OPC in the production. Palm oil fuel ash (POFA), fly ash (FA), and ground granulated blast furnace slag (GGBS) are industrial waste products that include high levels of silicates and aluminates. These materials are considered sustainable pozzolanic precursor materials for geopolymer concrete. Geopolymer concrete can achieve almost similar properties to conventional concrete [6].

In recent decades, excessive amounts of waste products have been produced along with the rapid growth in urban population and the improper and illegal disposal of these waste materials presents significant challenges on ecology, health and land use [7]. POFA is a substantial byproduct resulting from the palm oil production process. The substantial volume of POFA is a consequence of the elevated demand for palm oil. Disposal through landfill might lead to enormous ecological and economic costs [8].

Previous research of Tangchirapat et al. [9] concluded that substituting OPC with POFA for up to 30% of the binder weight yields strength comparable to 100% OPC concrete. However, increasing the POFA content beyond this point results in a reduction of compressive strength [10], likely due to the higher water demand and lower pozzolanic reactivity of POFA. Additionally, many researchers have been utilizing POFA as a precursor material for geopolymers [11]. However, high volume of POFA in the matrix exhibits relatively low workability and strength, limit its application as a geopolymer. Hence, it is essential to allocate substantial focus towards enhancing POFA-based geopolymer. The addition of FA and GGBS which contain higher concentration of aluminium oxide and calcium oxide as compared to POFA, can benefit in enhancing the hydrolysis reaction during the geopolymerisation process. This, in turn, improves the durability and strength characteristics of POFA geopolymer concrete [12] [13].

Thus, this study explores the integration of both FA and GGBS to assess their impact on durability and mechanical properties. Numerous researchers have delved into the properties of geopolymer concrete utilising FA, POFA, and GGBS. This study, however, focuses on exploring the potential integration of both FA and GGBS into POFA-based geopolymer concrete, with the aim of offering insights applicable to the construction industry.

2 Constituents of POFA, FA and GGBS

The properties of materials play a key role in defining the eligibility for application in geopolymer concrete and improving the overall performance. The physical properties might be affected by various factors such as the material source and production process. The physical properties of POFA, FA and GGBS are tabulated in **Table 1**. Additionally, the chemical compositions of POFA, FA, and GGBS, as determined through X-ray fluorescence (XRF) in earlier studies, are presented in **Table 2**. The chemical composition of the material is essential because it will impact the geopolymerisation process.

Table 1. Physical properties of POFA, FA and GGBS [14] [15] [16]

Physical Properties	POFA	FA	GGBS
Particular shape	Irregular/angular	Circular/spherical	mostly spherical
Specific gravity	1.89 – 2.6	2.1 – 3.0	2.5 – 2.9
Specific surface area (m^2/kg)	707.8	170 - 3000	425 - 470
Colour	Grey	Light brown	White

2.2 Palm Oil Fuel Ash (POFA)

POFA is a type of waste material produced through the combustion of empty fruit bunches and palm oil kernels [17]; and possesses distinct characteristics. According to the study of Tan et al. [14], unground POFA exhibits a spherical and porous particle shape, whereas ground POFA resulting from a crushing

process has irregular and angular particles. The rate of alkali activation of POFA can be enhanced by increasing its fineness through grinding. According to Hamsan et al. [18], the specific gravity ranges from 1.89 to 2.6. Tan et al. [14] reported that the specific surface area of POFA is about 707.8 m2/kg. The colour of POFA is commonly grey and is dependent on the amount of unburnt carbon present, with a higher amount leading to a darker colour of POFA. **Fig 1**. illustrates the XRD result of POFA, where the peaks indicate the existence of crystalline phase of quartz, kyanite and gehlenite.

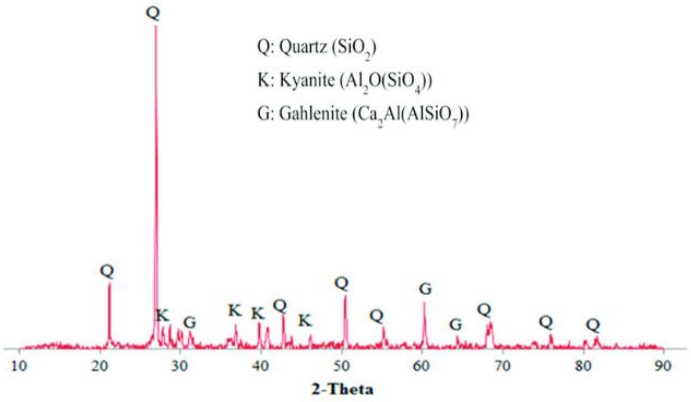


Fig. 1. XRD for POFA [35]

From **Table 2**, the presence of silicon dioxide (SiO_2) in POFA is the key factor contributing to its favourable pozzolanic characteristics, leading to the development of high-performance concrete [19]. The SiO_2 concentration by percentage for POFA is considerable high, ranging from 42.94% to 55.94%. The silica content will then undergo pozzolanic reaction with $Ca(OH)_2$ and form C-S-H gel for further strength development [20]. The Al_2O_3 concentration for POFA is low, which leads to lower setting time and strength development.

Table 2. Chemical composition of POFA, FA and GGBS (% by weight).

Material	Chemical composition (% by weight)								Reference
	SiO2	Al2O3	Fe2O3	CaO	MgO	SO3	Na2O	K2O	
POFA	54.98	3.27	3.96	10.77	5.02	4.09	0.40	9.50	[22]
POFA	42.94	2.22	0.69	5.19	4.55	6.10	0.49	22.45	[23]
POFA	55.94	1.85	1.53	8.1	8.11	1.77	0.156	8.78	[24]
POFA	51.81	2.76	3.20	5.70	3.978	1.28	0.76	3.23	[25]
POFA	64.3	4.3	3.2	10.4	5.9	1.3	1.3	8.8	[26]
FA	53.49	29.35	5.98	3.33	1.33	0.50	0.68	0.509	[24]
FA	29.32	12.96	15.64	25.79	2.94	7.29	2.83	2.93	[23]
FA	55.38	28.14	3.31	3.45	1.85	0.32	2.30	1.39	[27]
FA	56.00	18.10	5.31	7.24	0.93	1.65	1.21	1.36	[28]
FA	65.90	24.00	2.87	1.59	0.42	-	0.49	1.44	[29]
FA	47.90	25.70	14.70	4.11	1.36	0.19	0.81	0.67	[30]
FA	57.3	29.1	3.8	5.3	1.6	1.6	1.6	1.2	[26]
GGBS	30.35	14.62	0.35	32.79	6.38	-	0.27	0.38	[22]
GGBS	35.34	20.69	0.18	31.32	8.11	1.79	1.36	0.29	[31]
GGBS	18.90	6.43	0.74	66.90	1.41	1.97	-	0.67	[32]
GGBS	28.20	9.73	0.98	52.69	2.90	1.46	-	1.22	[33]
GGBS	36.50	9.95	0.38	43.38	6.74	-	-	0.35	[34]

Higher SiO_2 content leads to higher Si/Al content in POFA. This affects the chemical stability of the POFA geopolymer concrete in the air, where there are efflorescence develops on the surface of the geopolymer concrete surface owing to the greater free K^+ ions in the geopolymer matrix, which is critical for long term performance [21]. Additionally, due to the low Ca content in POFA, which ranging from 2.70%

to 10.77%, lead to longer setting time, and cause water content in the geopolymer evaporated and lead to risk of drying shrinkage.

2.3 Fly Ash (FA)

FA is a by-product of manufacturing processes, typically generated by pulverised coal in power plants [35]. Tan et al. [14] characterised FA as tiny particles, primarily circular or spherical, with the possibility of being solid or hollow and predominantly possessing a glassy composition. From **Table 1**, the carbonaceous material in FA contains angular particles ranging in size from 0.1 to 100 μm [15]. The specific gravity of FA ranges from 2.1 to 3.0, and the specific surface area is typically between 170 and 1000 m2/kg. From **Fig. 2**, the prominent peaks correlate to the crystalline phase of quartz and Mullite in FA.

The chemical composition of FA is indicated in **Table 2**, where the Al_2O_3 and SiO_2 concentration has a high proportion of 18.10% to 29.35% and 29.32% to 65.90% respectively. When FA reacts with alkaline activator, the Al_2O_3 and SiO_2 will experience dissolution and create the aluminate and silicate ions to form N-A-S-H gel. The presence of Al_2O_3 in FA acts as nuclei within the cement paste, thereby expediting the hydration reactions of the cement [12]. Moreover, the Al_2O_3 will enhance the chloride binding capacity. Consequently, the highly dense microstructure of Al_2O_3 will enhance the durability of the geopolymer mortar.

The presence of iron (III) oxide (Fe_2O_3), especially in FA, has the potential to benefit the compressive strength and durability of the geopolymer mortar [37]. This occurrence is attributed to the higher atomic diameter of iron than those of silica and alumina. Increasing iron concentration in raw materials may prolong the geopolymerisation reaction with the alkali solution resulting in the production of an iron silicate binder and subsequently improving the strength of the geopolymer mortar. Kaze et al. [38] concluded that the presence of ferrosilite along with sodium aluminosilicate gel in geopolymer mortar enhances durability.

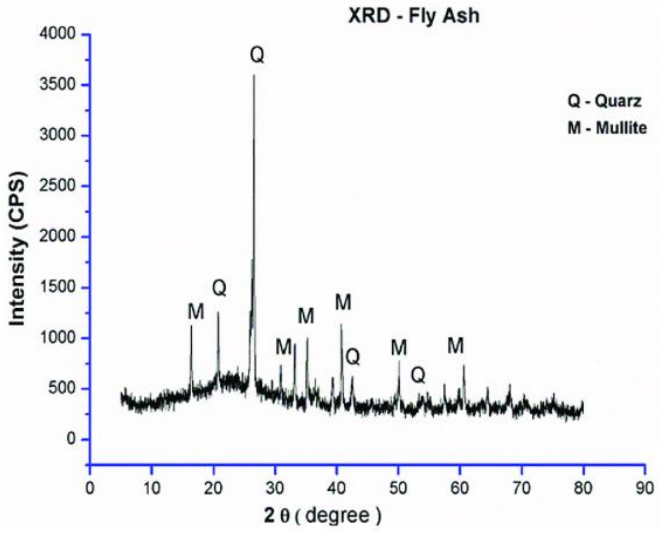


Fig. 2. XRD for FA [39]

2.4 Ground Granulated Blast furnace slag (GGBS)

GGBS is a form of industrial residue which can be employed to create eco-friendly cement and concrete, exhibiting favourable mechanical, thermal, and rheological characteristics [16]. It is a type of industrial by-product from the manufacturing of iron, which is mostly spherical [40], containing a high percentage of calcium, silica; and alumina [41]. This composition allows GGBS to potentially serve as a binder material similar to cement in the construction of concrete due to the cementitious and pozzolanic characteristics. The specific gravity of GGBS varies between 2.5 and 2.9, and its surface area is around 425 m2/kg to 470 m2/kg [16]. **Fig. 3** shows the XRD micrograph of GGBS, which has a comparatively broad

hump, suggesting the existence of strong amorphous phase in GGBS.

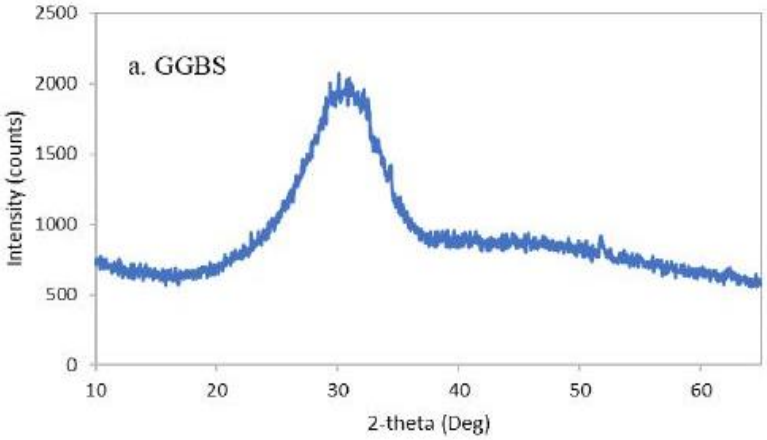


Fig. 3. XRD for GGBS [42]

When GGBS is activated by an alkali activator, it predominantly leads in the creation of C-A-S-H, N-A-S-H, and K-A-S-H gel type hydration products, which relies on the kind of alkali silicates or hydroxides utilized in the geopolymer [43]. From **Table 2**, the high propertion of calcium oxide (CaO) in GGBS from 31.32% to 66.90% facilitates the development of calcium silicate hydrate (C-S-H) and C-A-S-H gels in the geopolymer mortar. It can improve the compressive strength of the geopolymer mortar. The high concentration of CaO in GGBS may enable the geopolymer mortar to attain high mechanical strength [13]. The high calcium oxide in GGBS will react with the high silica concentration from both POFA and FA and lead to the creation of C-S-H and C-A-S-H gel.

In addition, the proportion of SiO_2 and Al_2O_3 in GGBS play a vital function in the geopolymer matrix. The SiO_2 serves as the source of silicate ions $(SiO_4)^{4-}$ ions, which are crucial for the formation of geopolymer matrix. Subsequently, it will chemically react with the $(AlO_4)^{1-}$ derived from Al_2O_3 leading to condensation and solidification. This process will then lead to th formation of a semi-crystalline structure [44]. Al_2O_3 plays a vital function in determining the strength characteristics and setting time of the geopolymer matrix [45].

Consequently, an increase in the amount of POFA in the mixture will lead to an elevated concentration of SiO_2. Increasing in the amount of both FA and GGBS, will result in higher concentration of Al_2O_3 and CaO in the matrix will be raised. Therefore, the addition of FA and GGBS to POFA-based geopolymer mortar has the potential to enhance its strength and overall characteristics.

2.5 Geopolymerisation mechanism of POFA with FA and GGBS

The chemical composition of the precursor materials is critical in defining the geopolymerisation mechanisms involving POFA, FA, and GGBS. Numerous studies have analyzed the chemical components of POFA, FA, and GGBS, as **Table 2** illustrates. The dissolution of aluminosilicates from POFA, FA, and GGBS occurs through hydrolysis by alkaline activators such as sodium hydroxide and sodium silicate, producing tetrahedral structures like aluminates intermediate species $[Al(OH)_4]^-$ and silicates $[Si(OH)_4]^{4-}$ [45]. Through the hydroxylation and polycondensation reaction of the precursor material, an amorphous 3-dimensional cross-link polysialate chain of Si-O-Al is formed [46]. In the polycondensation phase, the elevated calcium oxide content in GGBS interacts with the silica and alumina from both POFA and FA, resulting in the production of calcium silicate hydrate (C-S-H), sodium aluminosilicate hydrate (N-A-S-H), and calcium aluminosilicate hydrate (C-A-S-H) gels as reaction products [47]. The C-A-S-H gel will undergo absorption of Na+ ions into the structure, forming (N,C)-A-S-H [48]. Alkaline activation of materials including CaO, SiO_2, and Al_2O_3 results in a new reaction compound. The resulting compound is an extremely complex binder system, consisting of alkaline gels like C-A-S-H, which undergo further

polymerisation, and reorganization. The proposed mechanism of geopolymerisation of POFA with FA and GGBS is illustrated in **Fig. 4**.

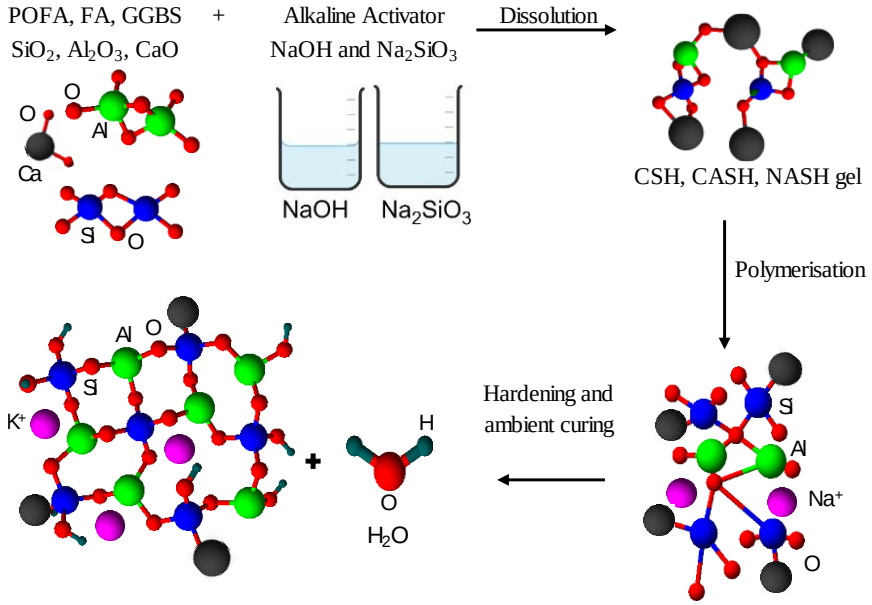


Fig. 4. Proposed geopolymerisation mechanism of POFA with FA and GGBS

3 Properties of Geopolymer Concrete Using POFA, FA, and GGBS

3.1 Setting Time

According to ASTM C150 the minimum initial setting time for geopolymer concrete is 45 min, with a maximum setting time of approximately 365 min [50]. According to Alsubari et al. [51], the initial and final setting time for POFA mortar are around 30 min and 600 min. Salih et al. [52] experimentally studied POFA geopolymer concrete with partial replacement of GGBS at ambient temperature. The study concluded that decreasing the amount of POFA in the mix resulted in shorter initial and final setting time. Additionally, the inclusion of GGBS in the mix further reduced these setting times, as the CaO content in GGBS accelerated the hydration reaction [53]. Similar to the study of Isa et al. [22], as GGBS was added to POFA geopolymer mortar, the flowability and setting time decreased. Compared with other mixtures, the mortar with a higher amount of GGBS is more difficult to compact.

Mulizar et al. [21] investigated the substitution of FA-based geopolymer concrete with POFA. As the percentage of POFA in the binder increased, the calcium content in the binder decreased due to the reduction in FA. This led to an increase in the setting time. Based on the previous experimental study of Monita et al. [54], when cured at ambient temperature, the setting time for POFA-based geopolymer concrete decreased; by contrast, the setting time increased when the mixture was cured at high temperature. The process of curing at high temperatures significantly improved the geopolymerisation of the POFA geopolymer concrete. The presence of OPC in the POFA geopolymer concrete resulted in a reduction in the setting time. This is due to the fact that the calcium content in OPC improved the rate of solidification and hardening of the concrete.

Wijaya et al. [55] examined the variables that impact the setting time of FA based geopolymer concrete and found that the CaO content significantly affects the setting time. As the CaO concentration rose, the setting time likewise increased. Similarly, Putra et al. [24] observed that the incorporation of FA with POFA, along with a higher alkali activator ratio and increased POFA content, resulted in longer setting times for the geopolymer mortar. The high K_2O content in POFA was identified as a factor contributing to this delay.

3.2 Workability

The workability of geopolymer concrete can be affected by several factors, including the shape of precursor materials. The irregular and angular shape of POFA contributes to the low workability of POFA geopolymer concrete. As the amount of POFA is increased, the slump decreases, resulting in reduced compaction and necessitating additional water. Additionally, the higher porosity of POFA particles retains water, reducing the amount of free water available for optimal workability.

The liquid-to-binder (L/B) ratio is a crucial factor in geopolymer concrete because it also affects workability. In a study by Kwek et al. [35], the experimental tests on the L/B content for POFA geopolymer concrete ranging from 0.5 to 0.85 revealed that the most ideal value of L/B ratio is 0.6. An increase in L/B ratio enhances flowability. However, owing to the irregular and highly porous characteristics of POFA, there is an increase in demand for alkali activator, potentially leading to uneven chemical reactions amongst binder materials.

Fig. 5 illustrates that the workability improves with a higher proportion of FA in the mixture, attributed to the spherical characteristics of FA. Conversely, introducing GGBS diminishes the flowability of POFA because of the comparably irregular shape of GGBS and POFA. Consequently, incorporating FA into POFA geopolymer proves advantageous for improving workability.

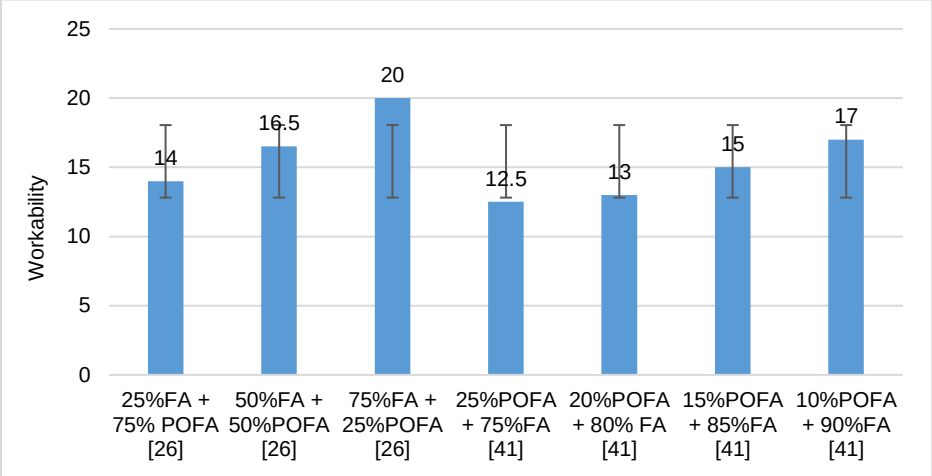


Fig 5. Previous study of workability on FA and POFA geopolymer [23] [53]

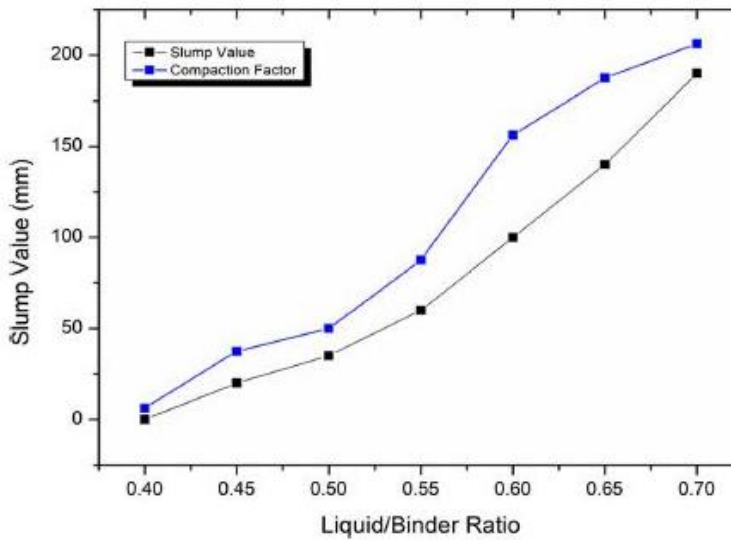


Fig. 6. Relationship between slump value and L/B ratio [56]

Verma et al. [56] investigated the effect of L/B ratio on the workability of geopolymer concrete. The findings depicted in **Fig. 6** demonstrate that workability improves with a higher L/B ratio for FA and GGBS-based geopolymer concrete. However, a higher L/B ratio also leads to a reduction in compressive strength, mirroring the relationship observed between the water-to-cement ratio and compressive strength in OPC concrete [57].

3.3 Compressive Strength

The mechanical properties of geopolymer are mostly reliant on the inherent characteristics of the precursor material [58]. **Table 3** shows an overview of previous studies and analysis on POFA, FA and GGBS geopolymer concrete in terms of sample size, AAR and L/B, curing regime, compressive strength at 7 and 28 days and references. **Fig. 7** shows the compressive strength of POFA, FA, and GGBS geopolymer concrete after 7 and 28 days of curing. According to Ranjbar et al. [59], the strength development of POFA based geopolymer mortar is slow. After 3 and 28 days, POFA-based geopolymer mortar achieves only 40% and 62% of its 112-day strength, respectively.

Table 3. Overview of an extensive literature analysis on POFA, FA and GGBS geopolymer concrete

Source Material	Sample Size	AAR and L/B	Curing Regime	Compressive Strength (MPa)		Reference
				7 days	28 days	
POFA 100%	50x50x50mm	2.5 / 1.32	Ambient	21	31.04	[51]
POFA 100% + GGBS 50%	50x50x50mm	2.5 / 1.32	Ambient	60.78	78.12	[51]
FA	-	0.4 / 0.7	Room temperature	15.4	-	[60]
FA 100%	230x110x75mm	0.4 / 0.5	Ambient	-	8.93	[61]
FA 75% + GGBS 25%	230x110x75mm	0.4 / 0.5	Ambient	-	25.22	[61]
GGBS 70% + FA 20% + POFA 10%	40x40x160mm	1.33 / 0.4	Ambient	36	98	[25]
FA 60% + GGBS 40%	190x90x90mm	2.5 / 0.4	Ambient	6	6.5	[62]
FA 40% + GGBS 60%	190x90x90mm	2.5 / 0.4	Ambient	7	7.75	[62]
POFA 40% + GGBS 60%	75x150mm (Cylinder)	0.5 / 0.4	Ambient	0.92	1.71	[22]
POFA 30% + GGBS 70%	50x50x50mm	0.4 / 0.4	65°C for 24 hrs and ambient	60	66	[63]
GGBS 50% + FA 25% + POFA 25%	50x50x50mm	0.4 / 0.4	65°C for 24 hrs and ambient	52	54	[63]
GGBS 30% + FA 70%	150x150x150mm	2.5 / 0.35	70°C for 24 hrs and ambient	14	24.8	[64]
GGBS 70% + FA 30%	150x150x150mm	2.5 / 0.35	70°C for 24 hrs and ambient	24.5	33.5	[64]

According to the research of Salih et al. [52], 100% POFA geopolymer cured at ambient temperature achieved 21MPa at 7 days and 31.04MPa at 28 days with a sample size of 50x50x50mm, as shown in **Table 3**. Under the same curing conditions, increasing the replacement of POFA with GGBS to 50% significantly improved the compressive strength to 60.78MPa at 7 days and 78.12MPa at 28 days as depicted in **Fig. 7**. However, the compressive strength of 100% POFA after 7 days was notably low at 21MPa. By contrast, the mix with 50% POFA and 50% GGBS exhibited much higher strength at 60.78MPa. This finding indicates that geopolymer concrete made solely with POFA may encounter a slowdown in early strength

development. In contrast, with the presence of GGBS, the CaO content rises, hence improving the porosity and further strengthening the POFA geopolymer mortar.

Isa et al. [22] found that at ambient curing condition, the compressive strength of POFA-based geopolymer mortar was enhanced with increasing GGBS content. The compressive strength of POFA-based geopolymer concrete increased by up to 73.38% compared to the control specimen that did not contain GGBS. **Fig. 7** illustrates that after 28 days of curing, 100% POFA achieved 7.5 MPa, whilst 60% POFA with 40% GGBS reached 28.17 MPa. With an increasing amount of GGBS in POFA-based geopolymer, the compressive strength of the mix increased [52]. Islam et al. [63] reported that geopolymer mortar with 30% POFA and 70% GGBS, activated at 65 ℃ for 24 hours and cured at ambient temperature, achieved compressive strengths of 60 MPa and 66 MPa at 7 and 28 days, respectively. This enhancement was due to the addition of GGBS in the geopolymerization process, which raised the CaO content and facilitated the formation of C-S-H gel. This led to a reduction in the porosity of the mix, thereby increasing the compressive strength of the POFA-based geopolymer concrete.

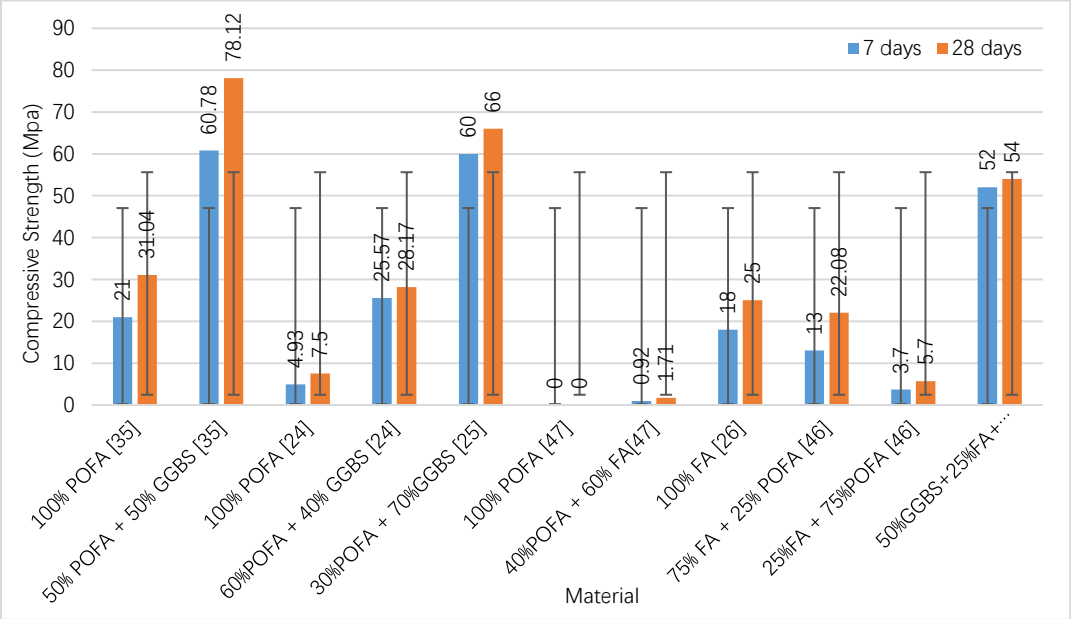


Fig. 7. Compressive strength of POFA, FA and GGBS geopolymer concrete at 7 and 28days [52] [22] [23] [65] [24] [63]

From the study of Depthan et al. [23], the 100% POFA geopolymer concrete exhibited very low compressive strength owing to the slow reaction process at ambient temperature. Incorporating 40% POFA with 60% FA resulted in improved compressive strength, reaching 0.92 MPa at 7 days and 1.54 MPa at 28 days. The presence of SiO2 and CaO in FA facilitated enhanced compressive strength and accelerated geopolymerisation, leading to the formation of C-S-H and N-A-S-H gels.

Ionescu et al. [65] found that FA geopolymer achieved 18 and 25 MPa at 7 and 28 days of curing, respectively, when activated at 75 ℃ for 24 h and ambient cured. In a study by Putra et al. [23] with similar curing conditions, a geopolymer mix with 75% FA and 25% POFA achieved the highest compressive strength at 13.7MPa (7 days) and 22.08MPa (28 days). Conversely, when the proportions were inverted to 25% FA and 75% POFA, the compressive strength decreased, measuring 3.7 MPa at 7 days and 5.7 MPa at 28 days. Husseien et al. [25] emphasised the influence of SiO_2-to-Al_2O_3 and CaO-to-SiO_2 ratios on geopolymer compressive strength. The CaO and Al_2O_3 content in FA significantly impacted the strength, with the chemical composition being more influential than physical properties. Including FA in POFA geopolymer concrete has the potential to strengthen it owing to the CaO and Al_2O_3 content, and the lower density of FA results in a lighter weight of geopolymer concrete.

In comparison with fly ash, GGBS replacement with cement yields higher strength given its higher alumina, CaO, and silica content [66]. Sole GGBS-based geopolymer achieves comparable strength properties and is more economically efficient [48]. Optimal strength is achieved with a composition of 70% GGBS and 30% POFA. However, further replacement of GGBS leads to a reduction in strength due to the dilution effects of increased unreactive silica. According to the findings of Islam et al. [63], the mixture comprising 50% GGBS incorporating 50% POFA exhibited greater strength than the mixture of 50% GGBS with 50% FA. Additionally, the composition of 50% GGBS with 25% POFA and 25% FA attained compressive strength up to 52 MPa and 54 MPa at 7 and 28 days, respectively. Therefore, incorporation of FA and GGBS to POFA based geopolymer concrete have the possibility to enhance the compressive strength.

3.4 Flexural and Split Tensile Strength

From the study of Isa et al. [22], the flexural strength of POFA geopolymer mortar was 0 MPa at day 3 of curing but gradually increased to 2.84 MPa at 28 days, as depicted in **Fig. 8**. This initial lack of strength on day 3 was attributed to the incapacity of the mixture to attain adequate strength to withstand flexural strength at an early stage. Nevertheless, comparison of mortars with and without GGBS, showed that the mortar containing GGBS exhibited higher flexural strength. The presence of CaO, accelerated the dissolution rate of aluminosilicate materials, resulting in a highly dense microstructure. This improvement contributed to an enhanced flexural strength of the geopolymer mortar.

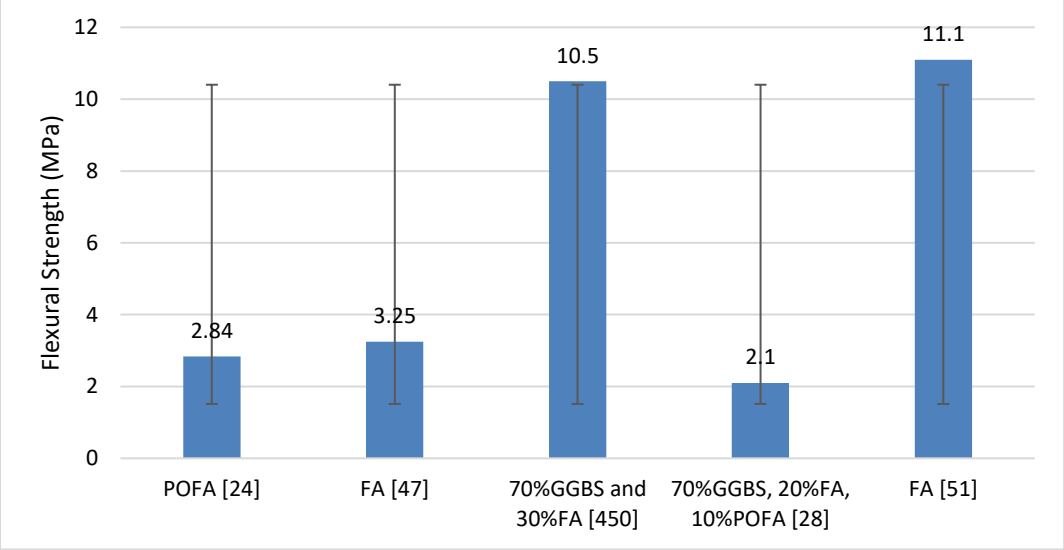


Fig. 8. Flexural strength of POFA, FA and GGBS geopolymer concrete [22] [65] [64] [26] [67].

For FA geopolymer mortar, the flexural strength was recorded at 3.25 MPa after 28 days, as illustrated in Fig. 8 [65]. Husseien et al. [26] found that as the FA content increased and the POFA content decreased, the flexural strength improved. The strength of the bond was significantly affected by the ratio of POF:FA, in which a rise in POFA content led to a drop in single-lap shear values. This outcome was associated with the rise in the SiO_2-to-Al_2O_3 ratio and the adverse effects of the reaction process, especially regarding the formation of C-S-H and C-A-S-H gels. In a study by Kumar et al. [67] on the flexural strength of FA geopolymer concrete, the concrete can attain a flexural strength of 11.10 MPa after 28 days of curing.

An increase in the content of GGBS in a geopolymer mix led to a corresponding increase in flexural strength. The highest flexural strength, reaching approximately 2.1 MPa, was achieved when the composition included 70% GGBS, 20% FA and 10% POFA. Bellum et al. [64] reported that the highest flexural strength, approximately 10.5 MPa at 28 days, was achieved when a mixture containing 70% GGBS and 30% FA was used.

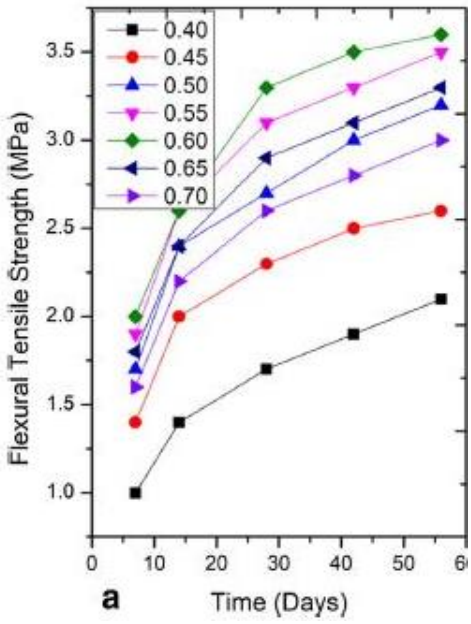


Fig. 9. Flexural strength of FA and GGBS geopolymer concrete [56]

In an investigation led by Ionescu et al. [65], the flexural strength of FA geopolymer mortar underwent a progressive increase with the passage of time during the curing process. This observed pattern aligns closely with the outcomes reported by Verma et al. [56], as visually depicted in Fig. 9. The graphical representation in Fig. 9 distinctly portrays a consistent upward trajectory of flexural strength in correlation with the duration of curing. Hence, the choice of precursor material and the L/B ratio have an impact on the flexural strength of geopolymer.

To determine the resistance of concrete against cracking, the split tensile strength is critically significant [68]. The development of tensile strength in POFA geopolymer concrete follows a similar pattern to that of compressive strength. According to the experimental study by Sata et al. [70], the ratio of splitting tensile strength to compressive strength for POFA geopolymer concrete is approximately 8% - 10%. Meanwhile, the increasing amount of POFA in geopolymer concrete decreases the split tensile strength, which is illustrated in **Fig. 10** [70]. This decrease may be due to weak bonding in POFA geopolymer, leading to a compromised interface zone. Moreover, the high-water absorption of POFA reduces the available free water necessary for proper hydration.

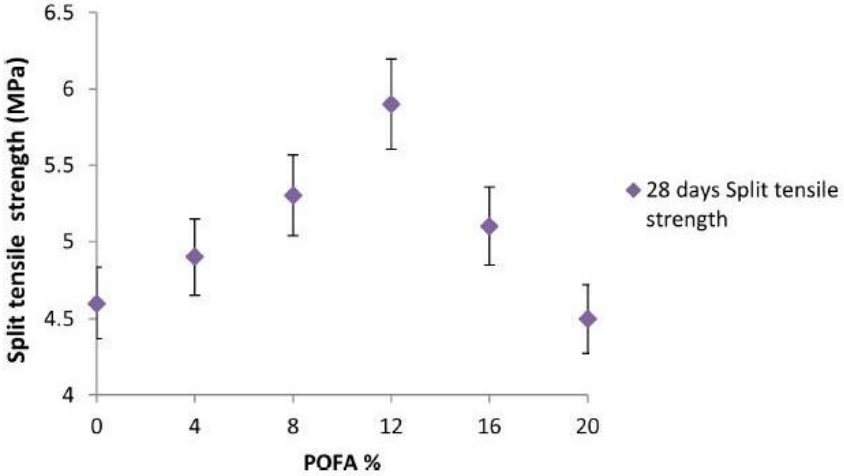


Fig. 10. Split tensile strength of POFA geopolymer concrete [67]

Therefore, to enhance the split tensile strength of POFA geopolymer concrete, inclusion of FA and GGBS can be advantageous. From the study of Sarvanan and Elavenil [71], FA and GGBS geopolymer concrete can show significant enhancement in the splitting tensile strength. The lower SiO2 in GGBS will result in higher reactivity in geopolymerisation hence enhance the splitting tensile strength. While high content of SiO_2 and low contents of CaO and Al_2O_3 will result in lower reactivity [72].

3.5 Water Absorption and porosity

The water absorption characteristics of geopolymer concrete play a crucial role in determining its durability. A reduced infiltration of water into geopolymer concrete is associated with increased durability and enhanced resistance to the natural environment. **Fig. 11** illustrates that, according to Isa et al. [22], the water absorption of the geopolymer concrete reduced as the curing age increase. For POFA geopolymer, the water absorption was 11.09%. The introduction of GGBS to geopolymer mortar resulted in a significant reduction in water absorption. Specifically, the water absorption of the geopolymer mortar decreased from 11.01% to 8.01% with GGBS inclusion ranging from 0% to 40%. Hence, incorporating GGBS into POFA geopolymer mortar has the potential to reduce porosity and, consequently, lower the water absorption rate.

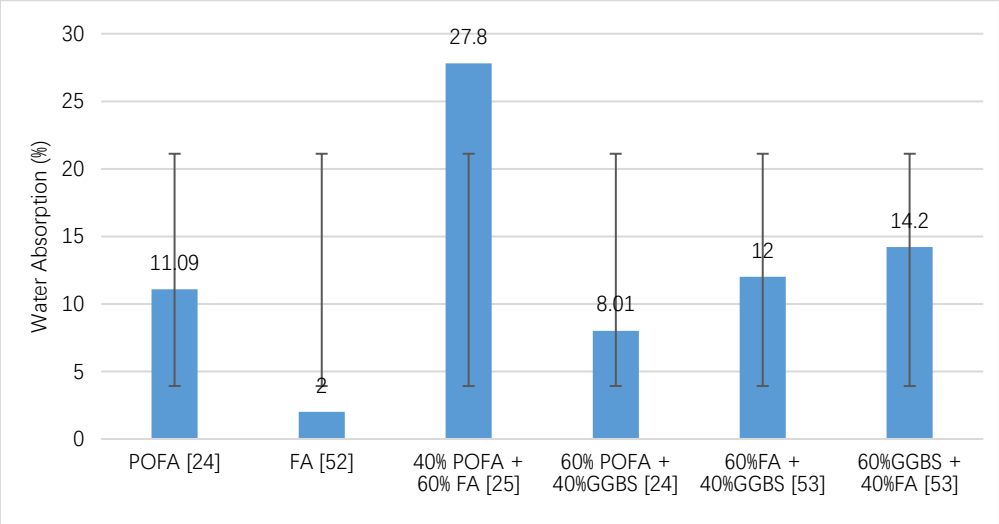


Fig. 11. Water absorption of POFA, FA and GGBS geopolymer concrete [22] [73] [23] [62]

From the earlier research by Ibrahim et al. [73], the water absorption of an FA geopolymer brick at room temperature reached 2%. Detphan et al. [23] incorporated 40% POFA with 60% FA, and the water absorption was reported to be approximately 27.8%. In an investigation conducted by Shilar et al. [62], the water absorption for a geopolymer mix consisting of 60% FA and 40% GGBS was approximately 12%, whereas it was about 14.2% for a combination of 60% GGBS and 40% FA. A noticeable increase in water absorption was observed with a decrease in FA percentage. This elevated water absorption could adversely impact the structural performance and durability of the geopolymer. The water absorption rate was influenced by the voids present in the geopolymer. Consequently, employing a high percentage of FA with an increased amount of Al_2SO_4, resulted in a densely packed microstructure. The voids in the geopolymer were reduced, leading to decreased water absorption and porosity.

Similar to porosity, increasing the amount of GGBS in the mix decreases the porosity of the geopolymer. GGBS has a favourable pore filling effect as a result of the production of C-S-H gel after hydration, leading to a decrease in water absorption and porosity. The inclusion of GGBS reduces porosity, highlighting the pore-filling effect of the C-S-H products generated by adding GGBS. The decrease in water absorption and porosity is attributed to the increased formation of C-S-H hydration products in the mixture due to the addition of GGBS [21]. Apart from GGBS, FA also have the pore filling effect, which consequently reduced the porosity of the POFA geopolymer concrete. This can be proven by the study of where the porosity of FA reduced aligned with the increasing of the FA in the mix [74]. Therefore, both FA

and GGBS have characteristics that reduce the porosity of POFA geopolymer concrete, thereby enhancing the microstructure.

3.6 Durability properties

The capacity of concrete to withstand deterioration and disintegration is referred to as durability [75]. Permeability is a key factor affecting durability, as it can accelerate capillary absorption and improve the resistance of concrete to harmful substances.. Reduction in the permeability can avoid the ingress of acids into geopolymer matrix [76] and subsequently improve the resistance of geopolymer concrete towards acid attacks [77].

Due to appropriate polycondensation, spherical shape, and particle size, integration of FA would decrease the permeability of geopolymer and increase the consolidation of geopolymer concrete [78]. In addition, adding GGBS can improve the C-S-H gel in the geopolymer concrete, which will minimize the porosity of the mortars and create a denser structure by filling up the pores. By integrating calcium into the geopolymer network system, the CaO in GGBS can improve the dissolution of aluminosilcate from POFA and counter-balance cation in the geopolymer pore structure. This is demonstrated by research of Isa et al. [22], which found that the POFA geopolymer mortar's permeability decreased as the amount of GGBS increased.

Drying shrinkage is another crucial characteristic as it will significantly impact the durability of geopolymer concrete [79]. It occurs as the water evaporates form the exposed surface, leading to moisture differentials along the geopolymer concrete. This variation in moisture content induces strain, resulting in tensile stresses that, in turn, lead to the appearance of cracks on the surface [80]. According to the study of Tay [80], when 10% of POFA is substituted in OPC concrete, the drying shrinkage is comparable to that of the control OPC concrete. POFA contributes to pore refinement, transforming large pores into smaller ones, which reduces water loss and consequently decreases drying shrinkage.

The study of Huseien et al. [82], provides evidence that the addition of FA to POFA geopolymer concrete can reduce drying shrinkage; however, the addition of GGBS will cause the draying shrinkage to increase. This is because GGBS has a higher CaO concentration, which slows down the rate of hydration reaction. High concentrations of FA and POFA in the mix can result in excellent inter-link capillary-types of networks in the geopolymer mix [83], so the ratio of FA to GGBS in the POFA geopolymer mortar is also essential to improve the durability.

3.7 Thermal Properties

A study determined that the thermal conductivity of geopolymer bricks composed of 40% POFA and 60% FA could reach 0.6 W/mK [14]. The researchers concluded that the inclusion of FA in POFA geopolymer bricks has the potential to mitigate the temperature changes within walls, thereby contributing to a reduction in the electricity costs associated with building operations.

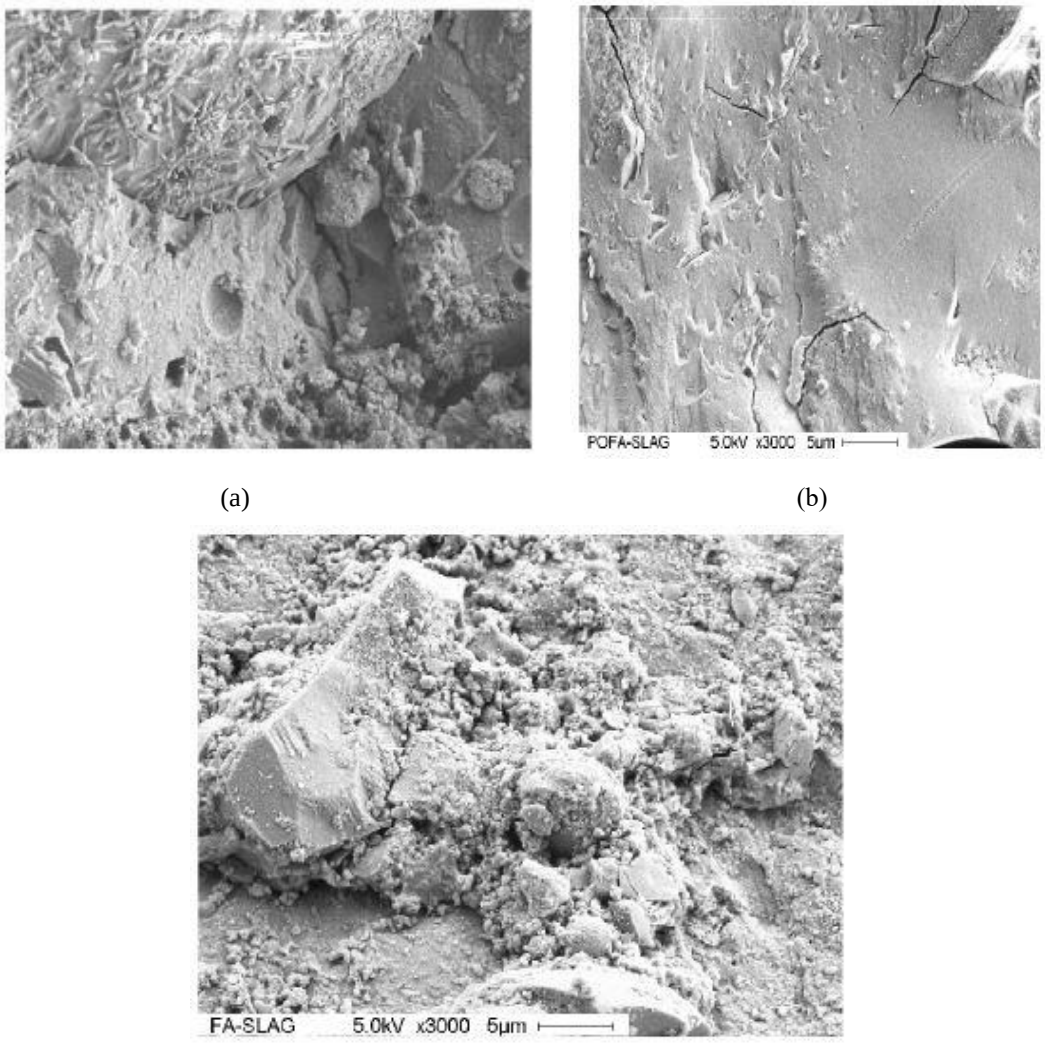
Amran et al. [36] found that FA-based geopolymer concrete demonstrates excellent thermal and fire resistance. When subjected to temperatures as high as 1000 ℃, it showed only slight surface cracking and a minimal mass loss of approximately 4.8%. [84]. The heat transferred more rapidly in the FA geopolymer concrete, which led to a small temperature differential in the geopolymer concrete. FA-based geopolymer concrete offers a superior thermal insulation range of 0.15 W/mK to 0.48 W/mK than OPC concrete [85]. These factors collectively contribute to the overall thermal performance of geopolymer concrete, as demonstrated by the research findings of [22].

Khoukhi et al. [86] established a correlation between material density and thermal conductivity, demonstrating that as the density decreases, the thermal conductivity decreases because of the increased porosity in geopolymer concrete. Ali et al. [87] emphasized that thermal conductivity is influenced by the density of geopolymer concrete, in which a lower density will result in small thermal conductivity due to the lower porosity and reduced the heat transfer through the material. In addition to density, several factors influence the thermal properties of geopolymer concrete, such as thermal expansion, alkali activator ratio,

liquid-to-binder ratio, and the types of binder materials employed.

3.8 Microstructure of POFA, FA and GGBS Geopolymer Concrete

In **Fig. 12** (a), (b) and (c), the combination of POFA with FA, POFA with GGBS and FA with GGBS revealed a more consolidated and densely structured composition. The denser and more compacted arrangement in the structure would then positively impact and elevate the compressive strength. When POFA was mixed with FA, the small pores might contain unreacted particles, as illustrated in **Fig. 12** (a). This finding suggests that incorporating FA into POFA, which contains SiO_2 and CaO, facilitated the production of C-S-H and N-A-S-H gels, has the potential to increase the microstructure of POFA and FA-based mortar, thereby enhancing geopolymerisation and improving the compressive strength [88].



(a) (b)

(c)

Fig. 12. **(a)** POFA + FA, **(b)** POFA + GGBS, and **(c)** FA + GGBS [88]

Fig. 12 (a), **(b)** and **(c)** illustrate the SEM images of geopolymer mortar high volume of GGBS with POFA and FA. As shown in **Fig. 13** (a), where there is 70% GGBS with 30% FA, the microstructure shows dense structure with the increasing content of GGBS, which might be due to the increasing C-S-H gel in the matrix. The presence of GGBS promotes the transformation of C-S-H gel into C-A-S-H gel, as aluminum substitutes for silicon [89]. This substitution resulted in a dense and compacted microstructure

[90]. Importantly, the substitution of Al in the C-S-H gel was attributed to an improvement in the compressive strength of the geopolymer concrete [51]. **Fig 13** (b) shows the microstructure of 70% GGBS with POFA. The partially reacted and unreacted particles increase, which indicates a less dense and high porous surface. Therefore, the inclusion of FA can enhance the microstructure with less porous and high dense structure as compared to POFA.

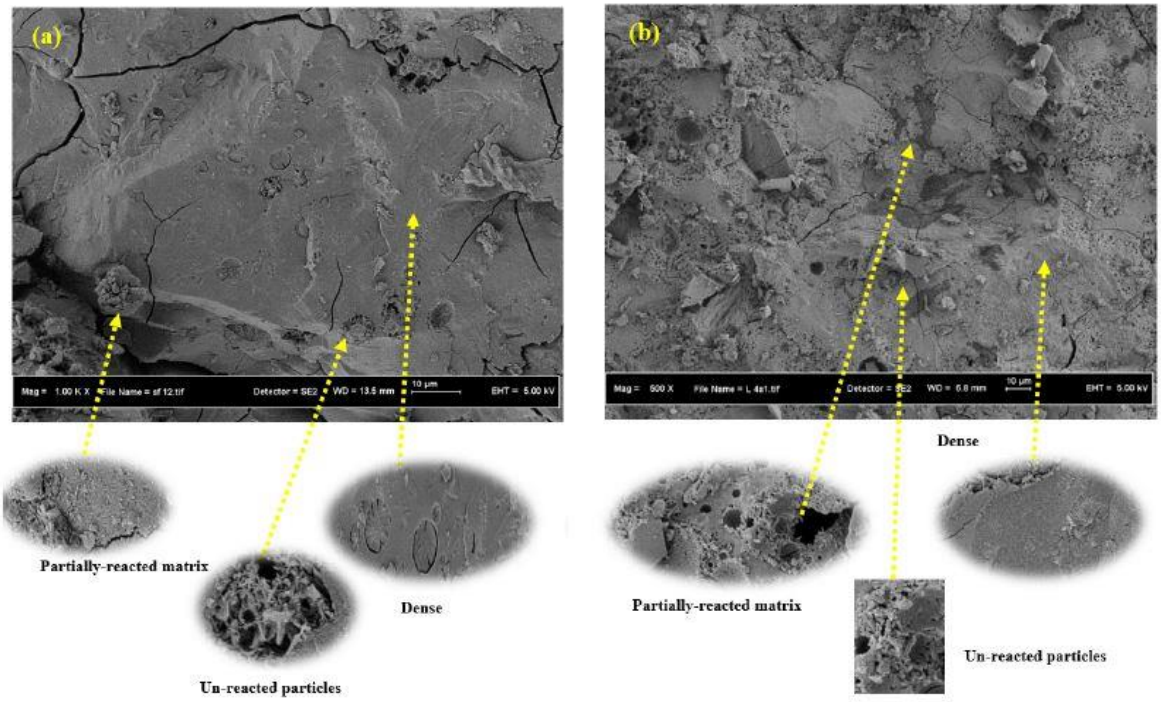


Fig. 13. **(a)** 70% GGBS + 30% POFA, and **(b)** 70% GGBS + 30% FA [91]

4 Prospect and future research

The early strength development in POFA geopolymers is significantly constrained, necessitating elevated temperatures during the curing phase to accelerate the geopolymerisation process and promote early strength advancement. Therefore, the inclusion of GGBS with a high CaO content could potentially eliminate the necessity for heat curing in POFA geopolymer mortar.

Numerous research endeavors have been undertaken to comprehensively analyze the intricate physical properties, microstructural characteristics, and various performance aspects of geopolymer concrete formulated with POFA, FA, and GGBS. Whilst studies have contributed substantially to the knowledge of the mechanical and structural elements of the geopolymer concrete, the investigation into the thermal properties has been notably limited. Given that POFA, FA, and GGBS are residue from industrial processes, the resulting geopolymer concrete may exhibit commendable thermal performance. The inherent properties of these by-products, when integrated into the geopolymer mix, may lead to enhanced resistance to temperature variations, thereby making the geopolymer concrete potentially beneficial for applications where thermal stability is essential.

The use of geopolymer concrete in the construction industry can reduce embodied carbon by up to 80%, depending on the types of precursors and activators employed. POFA geopolymer concrete with FA and GGBS can possess high mechanical strength due to the high degree of polycondensation. In addition, it has high durability, high fire resistance, chemical corrosion resistance, and good thermal performance. It may thus be used in the construction industry sector.

The activation of geopolymer mixes necessitates the use of alkali activators. A majority of earlier

studies utilized industrial chemical alkaline activators for geopolymer concrete, such as Na2SiO3 and NaOH. However, conventional industrial-grade alkali activators often incur high costs. This financial aspect necessitates a deep exploration into alternative alkali activators that can effectively initiate the geopolymerisation process whilst offering a cost-effective solution. Alternative alkaline activators, such as using waste materials to replace the industrial chemicals, should be investigated to enhance the cost efficiency and environmental friendliness of geopolymer concrete. The identification and development of such alternatives would not only contribute to the economic viability of geopolymer concrete but also open avenues for sustainable practices within the construction industry. This avenue of research aligns with the broad objective of optimizing the environmental impact of geopolymer concrete production and utilization.

5 Conclusions

A comprehensive review of the chemical, mechanical and durability properties of POFA geopolymer concrete integrated with FA and GGBS could be acquired from this study. POFA may display equivalent strength to OPC conventional concrete, however at large volume of POFA in the matrix, it will exhibit poor workability and low strength owing to high water demand and lesser pozzolanic reactivity. Which consequently restricts the deployment of large volume POFA geopolymer concrete. The incorporation of Al_2O_3 and Fe_2O3 in FA enhances chloride binding capacity, leading to a denser microstructure with high strength in geopolymer concrete. The inclusion of GGBS and FA increases the production of C-S-H and C-A-S-H gels, decreasing porosity, and leading to a compact and refined microstructure; therefore, lowering the water absorption rate. The addition of FA and GGBS in POFA may increase the early strength development. The denser microstructure will therefore be useful in strengthening the mechanical qualities and durability of the POFA geopolymer concrete. Additionally, inclusion of GGBS to POFA may shorten the initial and final setting periods of the POFA geopolymer, due to the presence of CaO in GGBS. Additionally, the workability of the POFA geopolymer will be increased. Mortar combining GGBS and FA displays higher flexural strength owing to the presence of CaO, which increases the dissolving rate of aluminosilicate minerals, resulting in a very dense microstructure. FA-based geopolymer concrete demonstrates outstanding thermal and fire resistance, exceeding OPC concrete. The incorporation of FA in POFA geopolymers has the ability to minimize temperature variations inside walls; and boost thermal insulation qualities, leading to decrease in electricity costs associated with building operations.

In summary, the incorporation of FA and GGBS demonstrates the potential to improve the mechanical, rheological, and thermal properties of POFA geopolymer mortar. It is suggested that further investigation is needed to explore the optimal composition of POFA, FA, and GGBS in the mix design. As a recommendation, in consideration of the high costs associated with commonly used industrial alkali activators such as NaOH and Na_2SiO_3, a potential avenue for research is to explore and incorporate alternative alkaline activators derived from waste products, to enhance the cost efficiency of geopolymer production.

Acknowledgement

The authors gratefully acknowledge the Ministry of Higher Education, Malaysia for providing financial support to this research through the Fundamental Research Grant Scheme Grant Ref. No. FRGS/1/2022/TK01/USM/02/2.

CRediT authorship contribution statement

Ying Yi Tan: Conceptualization, Formal analysis, Writing – original draft. **Hanizam Awang**: Conceptualization, Supervision, Writing – review & editing. **Noor Haida Mohd Kaus**: Supervision, Writing – review & editing.

Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

References

[1] Andrew RM. Global CO2 emissions from cement production. *Earth System Science Data* 2019; 10(1): 195-217. https://doi.org/10.5194/essd-10-195-2018

[2] Kajaste R, Hurme M. Cement industry greenhouse gas emissions - management options and abatement cost. *Journal of Cleaner Production* 2016; 112(5): 4041-4052. https://doi.org/10.1016/j.jclepro.2015.07.055

[3] Shobeiri V, Bennett B, Xie T, Visintin P. A comprehensive assessment of the global warming potential of geopolymer concrete. *Journal of Cleaner Production* 2021; 297: 126669. https://doi.org/10.1016/j.jclepro.2021.126669

[4] Wong LS. Durability Performance of Geopolymer Concrete: A Review. *Polymers* 2022; 14(5): 868. https://doi.org/10.3390/polym14050868

[5] Değirmenci F.N. Utilization of Natural and Waste Pozzolans as an Alternative Resource of Geopolymer Mortar. *International Journal of Civil Engineering* 2018; 16: 179-188. https://doi.org/10.1007/s40999-016-0115-1

[6] Sikder A and Saha P. Effect of different types of Waste as Binder on Durability Properties of Geopolymer Concrete: A Review. *IOP Conference Series: Earth and Environmental Science* 2021; 796: 012018. https://doi.org/10.1088/1755-1315/796/1/012018

[7] Nascimento LC, Junior GB, Xavier GdC, Monteiro SN, Vieira CMF, Azevedo ARGd, Alexandre J. Use of wood bottom ash in cementitious materials: a review. *Journal of Materials Research and Technology* 2023; 23: 4226-4243. https://doi.org/10.1016/j.jmrt.2023.02.071

[8] Tangchirapat W, Jaturapitakkul C, Chindaprasirt P. Use of palm oil fuel ash as a supplementary cementitious material for producing high-strength concrete. *Construction and Building Materials* 2009; 23(7): 2641-2646. https://doi.org/10.1016/j.conbuildmat.2009.01.008

[9] Chindaprasirt P, Homwuttiwong S, Jaturapitakkul C. Strength and water permeability of concrete containing palm oil fuel ash and rice husk–bark ash. *Construction and Building Materials* 2007; 21(7): 1492-1499. https://doi.org/10.1016/j.conbuildmat.2006.06.015

[10] Amri A, Fathurrahman G, Najib AA, Awaltanova E, Aman, Chairul. Composites of palm oil fuel ash (POFA) based geopolymer and graphene oxide: structural and compressive strength. *IOP Conference Series: Materials Science and Engineering* 2018; 420: 012063. https://doi.org/10.1088/1757-899X/420/1/012063

[11] Iskra-Kozak W, Konkol J. The impact of Nano-Al_2O_3 on the Physical and Strength Properties as well as on the Morphology of Cement Composite Crack Surfaces in the Early and Later maturation Age. *Materials* 2021; 14(16): 4441. https://doi.org/10.3390/ma14164441

[12] Yip C, Lukey G, Deventer Jv. The coexistence of geopolymeric gel and calcium silicate hydrate at the early stage of alkaline activation. *Cement and Concrete Research* 2005; 35(9): 1688-1697. https://doi.org/10.1016/j.cemconres.2004.10.042

[13] Tan J, Jamellodin ZB. A Review of Geopolymer Bricks and Concrete Containing fly ash and Palm oil Fuel ash. *Recent Trends in Civil Engineering and Built Environment* 2022; 3: 1752-1764. https://doi.org/10.3390/ma14164441

[14] Suraneni P, Burris L, Shearer CR, H. Doug H. ASTM C618 Fly Ash Specification: Comparison with Other Specifications, Shortcomings, and Solutions. *ACI Materials Journal* 2021; 118(1): 157-167. https://doi.org/10.14359/51725994

[15] Ahmad J, Kontoleon KJ, Majdi A, Naqash MT, Deifalla AF, Kahla NB, Isleem HF, Qaidi SM. A Comprehensive Review on the Ground Granulated Blast Furnace Slag (GGBS) in Concrete Production. *Sustainability* 2022; 14(14): 8783. https://doi.org10.3390/su14148783

[16] Olivia M, Tambunan LM, Saputra E. Properties of Palm Oil Fuel Ash (POFA) Geopolymer Mortar Cured at Ambient Temperature. *MATEX Web of Conferences* 2017; 97: 01006. https://doi.org/10.1051/matecconf/201797 01006

[17] Hamsan NF, Hamid NAA. A Comparative Study on Utilization of Palm Oil Fel Ash (POFA) as Partial Cement Replacement in Concrete. *Recent Trends in Civil Engineering and Built Environment* 2021; 2(1): 773-782. https://doi.org/10.30880/rtcebe.2021.02.01.085

[18] Hamada H, Abed F, Humada AM. Effect of silica fume on the properties of sustainable cement concrete. *Journal of Materials Research and Technology* 2023; 24: 8887-8908. https://doi.org/10.1016/j.jmrt.2023.05.147

[19] Ismail, MA, Budiea, AMA, Hussin, MW, Muthusamy KB. Effect of POFA fineness on durability of high strength concrete. *The Indian Concrete Journal* 2010; 84(11): 21-27. http://www.icjonline.com/

[20] Mulizar, Fazliah, Iskandar, Aiyub, Fauzi A. Effect of POFA as replacement material on fly ash based geopolymer

mortar. *IOP Conf. Series: Materials Science and Engineering* 2020; 854: 012012. https://doi.org/10.1088/1757-899X/854/1/012012

[21] Isa MN, Awang H. Characteristics of palm oil fuel ash geopolymer mortar activated with wood ash lye cured at ambient temperature. *Journal of Building Engineering* 2023; 66: 105851. https://doi.org/10.1016/j.jo be.2023.105851

[22] Depthan S, Phiangphimai C, Wachum A, Hanjitsuwan S, Phoo-ngernkham T, Chindaprasirt P. Strength development and thermal conductivity of POFA lightweight geopolymer concrete incorporating FA and PC. *Engineering and Applied Science Research* 2021; 48(6): 718-723. https://doi.org/10.14456/easr.2021.73

[23] Fariz A, Putra K, Hasyim S, Nurjannah SA. The properties of palm oil fuel ash-fly ash based geopolymer mortar. *AIP Conference Proceedings* 2021; 2347(1): 020228. https://doi.org/10.1063/5.0051723

[24] Sooraj V, Sethapathi M. Strength Properties of Palm Oil Fuel Ash (POFA) Concrete. *Journal of University of Shanghai for Science and Technology* 2022; 24(6): 265-271.

[25] Huseien GF, Hussein Z, Kubba Z, Nikolaevich BM, Mizra J. Improved Bond Strength Performance of Geopolymer Mortars: Role of High Volume Ground Blast Furnace Slag, Fly Ash and Palm Oil Fuel Ash Incorporation. *Minerals* 2023; 13(8): 1096. https://doi.org/10.3390/min13081096

[26] Ghopampour A, Ho VD, Ozbakkaloglu T. Ambient-cured geopolymer mortars prepared with waste-based sands: mechanical and durability-related properties and microstructure. *Composites Part B: Engineering* 2019; 160(1): 519-534. https://doi.org/10.1016/j.compositesb.2018.12.057

[27] Guo X, Yang J. Intrinsic properties and micro-crack characteristics of ultra-high toughness fly as /steel slag based geopolymer. *Construction and Building Materials* 2020; 230: 116965. https://doi.org/10.1016/j.conbuildmat.2019.116965

[28] Hu Y, Tang Z, Li W, Li Y, Tam VW. Physical-mechanical properties of fly ash/BBGFS geopolymer composites with recycled aggregates. *Construction and Building Materials* 2019; 226(2): 139-151. https://doi.org/10.1016/j.conbuildmat.2019.07.211

[29] Khan I, Xu T, Castel A, Gilbert R.I, Babaee M. Risk of early age cracking in geopolymer concrete due to restrained shrinkage. *Construction and Building Materials* 2019; 229: 116840. https://doi.org/10.1016/j.conbuildmat.2019.116840

[30] Yu J, Chen Y, Chen G, Wang L. Experimental study of the feasibility of using anhydrous sodium metasilicate as a geopolymer activator for soil stabilization. *Engineering Geopolymer* 2020; 264: 105316. https://doi.org/10.1016/j.enggeo.2019.105316

[31] Alrefaei Y, Wang Y, Dai J. The effectiveness of different superplasticizers in ambient cured one-part alkali activated pastes. *Cement and Concrete Composites* 2019; 97: 166-174. https://doi.org/10.1016/j.cemconcomp.2018.12.027

[32] Bouaissi A, Li LY, Abdullah MMAB. Mechanical properties and microstructure analysis of FA-GGBS-HMNS based geopolymer concrete. *Construction and Building Materials* 2019; 210: 198-209. https://doi.org10.1016/j.conbuildmat.2019.03.202

[33] Alonso MN, Gasco C, Morales MM, Suarze-Navarro JA, Zamorano M, Puertas F. Olive biomass ash as an alternative activator in geopolymer formation: A study of strength, radiology and leaching behaviour. *Cement and concrete composites* 2019; 104: 103384. https://doi.org/10.1016/j.cemconcomp.2019.103384

[34] Kwek SY, Awang H, Cheah CB. Influence of Liquid-to-solid and Alkaline Activator (Sodium Silicate to Sodium Hydroxide) Ratios on Fresh and Hardened Properties of Alkali-Activated Palm Oil Fuel Ash Geopolymer. *Materials* 2021; 14: 4253. https://doi.org/10.3390/ma14154253

[35] Amran M, Debbarma S, Ozbakkaloglu T. Fly ash-based eco-friendly geopolymer concrete: A critical review of the long-term durability properties. *Construction and Building Materials* 2021; 270: 121857. https://doi.org/10.1016/j.conbuildmat.2020.121857

[36] Zailani W, Abdullah M, Arshad M, Burduhos-Nergis D,Tahir M. Effect of Iron Oxide (Fe2O3) on the Properties of Fly Ash Based Geopolymer. *IOP Conference Series: Materials Science and Engineering* 2020; 877: 01207. https://doi.org/10.1088/1757-899X/877/1/012017

[37] Kaze RC, Moungam LMBà, Cannio M, Rosa R, Kamseu E, Melo UC, Leonelli C. Microstructure and engineering properties of Fe_2O_3(FeO)-Al_2O_3-SiO_2 based geopolymer composites. *Journal of Cleaner Production* 2018; 199: 849-859. https://doi.org/10.1016/j.jclepro.2018.07.171

[38] Qaidi S, Najm HM, Abed SM, Ahmed HU, Dughaisi H, Lawati JA, Sabri MM, Alkhatib F, Milad A. Fly Ash-Based Geopolymer Composites: A Review of the Compressive Strength and Microstructure Analysis. *Materials* 2022; 15(20): 7098. https://doi.org/10.3390/ma15207098

[39] Wan Z, Shui Z, Lin Z. Analysis of geometric characteristics of GGBS particles and their influences on cement

properties. *Cement and Concrete Research* 2004; 34(1): 133-137. https://doi.org/10.1016/S0008-8846(03)00252-7

[40] Aydin S, Baradan B. Effect of Activator Type and Content on Properties of Alkali-Activated Slag Mortars. *Composites Part B: Engineering* 2014; 57: 166-172. https://doi.org/10.1016/j.compositesb.2013.10.001

[41] Saludung A, Ogawa Y, Kawai K. Microstructure and mechanical properties of FA/GGBS-based geopolymer. *MATEC Web of Conferences* 2018; 195: 01013. https://doi.org/10.1051/matecconf/201819501013

[42] Liu B, Zhuang K, Li D, Fang Y, Pan G. Understanding the early reaction and structural evolution of alkali activated slag optimized using K-A-S-H nanoparticles with varying K_2O/SiO_2 ratios. *Composites Part B: Engineering* 2020; 200: 108311. https://doi.org/10.1016/j.compositesb.2020.108311

[43] Ravikumar D, Peethamparan S, Neithalath N. Structure and strength of NaOH activated concretes containing fly ash or GGBFS as the sole binder. *Cement and Concrete Composites* 2010; 32(6): 399-410. https://doi.org/10.1016/j.cemconcomp.2010.03.007

[44] Jamil NH, Abdullah MAB, Che Pa F, Mohamad H, Ibrahim WMAW, Chaiprapa J. Influences of SiO_2, Al_2O_3, CaO and MgO in phase transformation of sintered kaolin-ground granulated blast furnace slag geopolymer. *Journal of Materials Research and Technology* 2020; 9(6): 14922-14932. https://doi.org/10.1016/j.jmrt.2020.10.045

[45] Mahmood A, Noman MT, Pechočiaková M, Amor N, Petrů M, Abdelkader M, Militký J, Sozcu S, Hassan SZU. Geopolymers and Fiber-Reinforced Concrete. *Composites in Civil Engineering* 2021; 13(13): 2099. https://doi.org/10.3390/polym13132099

[46] Khale D, Chaudhary R. Mechanism of geopolymerization and factors influencing its development: a review. *Journal of Materials Science* 2007; 42: 729-746. https://doi.org/10.1007/s10853-006-0401-4

[47] Thakur G, Singh Y, Singh R, Prakash C, Saxena KK, Pramanik A, Basak A, Subramaniam S. Development of GGBS-Based Geopolymer Concrete Incorporated with Polypropylene Fibers as Sustainable Materials. *Sustainability* 2022; 14(17): 10639. https://doi.org/10.3390/su141710639

[48] Perez-Cortes P, Escalante-Garcia IJ. Alkali activated metakaolin with high limestone contents – Statistical. *Cement and Concrete Composites* 2020; 106: 103450. https://doi.org/10.1016/j.cemconcomp.2019.103450

[49] Mugahed A, Gunasekaran M, Roman F, Nikolai V, Yuriy V, Hakim A. Palm Oil Fuel Ash-Based Eco-Efficient Concrete: A Critical Review of the Short-Term Properties. *Materials* 2021; 14(2): 332. https://doi.org/10.3390/ma14020332

[50] Alsubari B, Shafigh P, Jumaat MZ. Utilization of high-volume treated palm oil fuel ash to produce sustainable self-compacting concrete. *Journal of Cleaner Production* 2016; 137: 982-996. https://doi.org/10.1016/j.jclepro.2016.07.133

[51] Salih MA, Farzadnia N, Ali AAA, Demirboga R. Development of high strength alkali activated binder using palm oil fuel ash and GGBS at ambient temperature. *Construction and Building Materials* 2015; 93: 289-300. https://doi.org/10.1016/j.conbuildmat.2015.05.119

[52] Xu H, Gong W, Sytltebo L, Izzo K, Lutze W, Pegg IL. Effect of blast furnace slag grades on fly ash based geopolymer waste forms. *Fuel* 2014; 133: 322-340. https://doi.org/10.1016/j.fuel.2014.05.018

[53] Monita O, Lora MT, Edy S. Properties of Palm Oil Fuel Ash (POFA) Geopolymer Mortar Cured at Ambient Temperature. *MATEC Web of Conferences* 2017; 97: 01006. https://doi.org/10.1051/matecconf/20179701006

[54] Wijaya AL, Ekaputri JJ, Triwulan. Factors influencing strength and setting time of fly ash based-geopolymer paste. *MATEC Web of Conferences* 2017; 138: 01010. https://doi.org/10.1051/matecconf/201713801010

[55] Verma M, Dev N. Effect of Liquid to Binder Ratio and Curing Temperature on the Engineering Properties of the Geopolymer Concrete. *Silicon* 2021; 14: 1743-1757. https://doi.org/10.1007/s12633-021-00985

[56] Patankar SV, Jamkar SS, Ghugal YM. Effect of Water-to-Geopolymer Binder Ratio on the Production of Fly ash Based Geopolymer Concrete. *International Journal of Advanced Technology in Civil Engineering* 2013; 2(1): 79-83. https://doi.org/10.13140/2.1.4792.1284

[57] Duxson P, Provis JL, Lukey GC, Mallicoat SW, Kriven WM, van Deventer JSJ. Understanding the relationship between geopolymer composition, microstructure and mechanical properties. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 2005; 269(1-3): 47–58. https://doi.org/10.1016/j.colsurfa.2005.06.060

[58] Ranjbar N, Mehrali M, Behnia A, Alengara UJ, Jumaat MZ. Compressive strength and microstructural analysis of fly ash/palm oil fuel ash based geopolymer mortar. *Materials and design* 2014; 59: 532-539. http://dx.doi.org/10.1016/j.matdes.2014.03.037

[59] Sasikumar S, Natarajan M, Balasundaram N, Karthik V. Study on Behaviour of Geopolymer Bricks Under Different Curing Temperature and Alkaline Solution Concentrations. *International Journal of Applied*

Engineering Research 2020; 15(7): 690-694.
[60] Lavanya B, Preet DK, Suganesh S, Indrajith R, Chokkalingam RB. Properties of geopolymer bricks made with fly ash and GGBS. *IOP Conf. Series: Materials Science and Engineering* 2020; 872: 012141. https://doi.org/10.1088/1757-899 X/872/1/012141
[61] Shilar FA, Ganachari SV, Patil VB, Almakayeel N, Khan TY. Development and optimization of an eco-friendly geopolymer brick production process for sustainable masonry construction. *Case Studies in Construction Materials* 2023: 18: e02133. https://doi.org/10.1016/j.cscm.2023.e02133
[62] Islam A, Alengaram UJ, Jumaat MZ, Bashar II. The development of compressive strength of ground granulated blast furnace slag-palm oil fuel ash-fly ash based geopolymer mortar. *Materials and Design* 2015; 56: 833-841. https://doi.org/10.1016/j.matdes.2013.11.080
[63] Bellum RR, Nerella R, Madduru SRC, Indukuri CSR. Mix Design and Mechanical Properties of Fly Ash and GGBFS-Synthesized Alkali-Activated Concrete (AAC). *Infrastructures* 2019; 4(2): 20. https://doi.org/10.3390/infrastructures4020020
[64] Ionescu BA, Chira M, Vermeșan H, Hegyi A, Lăzărescu A, Thalmaier G, Neamțu BV, Gabor T, Sur IM. Influence of Fe_2O_3, MgO and Molarity of NaOH Solution on the Mechanical Properties of Fly Ash-Based Geopolymer. *Materials* 2022; 15(19): 6965. https://doi.org/10.3390/ma15196965
[65] Ahmad J, Martinez-Garcia R, Szelag M, de-Prado-Gil J, Marzouki R, Alqurashi M, Hussein EE. Effects of Steel Fibres (SF) and Ground Granulated Blast Furnace Slag on Recycled Aggregate Concrete. *Materials* 2021; 14: 7497. https://doi.org/10.3390/ma14247497
[66] Kumar K, Ashok, Partheeban P. Experimental Investigation on Flexural Strength of Geopolymer Concrete Paver Block. *International Journal of Applied Engineering Research* 2017; 12(16): 5791-5794.
[67] Hamada HM, Thomas BS, Tayeh B, Yahaya FM, Muthusamy K, Yang J. Use of oil palm shell as an aggregate in cement concrete: A review. *Construction and Building Material*s 2020; 265: 120357. https://doi.org/10.1016/j.conbuildmat.2020.120357
[68] Sata V, Jaturapitakkul C, Kraiwood, Kiattikomol. Influence of pozzolan from various by-product materials on mechanical properties of high-strength concrete. *Construction and Building materials* 2007; 21(7): 1589-1598. https://doi.org/10.1016/j.conbuildmat.2005.09.011
[69] Kumar AG, Ramasamy S, Venkatachalam BKK, Nachimuthu B. Experimental investigation on the viability of palm oil fuel ash as a sustainable additive in high performance concrete. *Matéria* 2024; 29(2): e20240149. https://doi.org/10.1590/1517-7076-RMAT-2024-0149
[70] Saravanan S, Elavenil S. Strength properties of geopolymer concrete using msand by assessing their mechanical characteristics. *Journal of Engineering and Applied Sciences* 2018; 13: 4028-4041. https://www.arpnjournals.org/jeas/research_papers/rp_2018/jeas_0718_7165.pdf
[71] Mathes W, Vollpracht A, Villagrán Y, Kamali-Bernard S, Hooton D, Gruyaert E, Soutsos M, De Belie, Ground Granulated Blast-Furnace Slag, in: De Belie N, Soutsos Mm Gruyaert E (Eds.), Properties of Fresh and Hardened Concrete Containing Supplementary Cementitious Materials, Springer International Publishing, Switzerland, 2018; 1-54. https://doi.org/10.1007/978-3-319-70606-1
[72] Ibrahim WMW, Kamarudin H, Abdullah, Bakri AMMAB, Abdul KA. Geopolymer lightweight bricks manufactured from fly ash and foaming agent. *AIP Conference Proceedings* 2017; 0835: 020048. https://doi.org/10.1063/1.4981870
[73] Singh P, Shah ND, Majumdar PK. Influence of flyash on Fineness, Porosity and Permeability of Flyash blended Cement paste. *International Research Journal of Engineering and Technology* 2018; 5(1): 1056-1058.
[74] Amran M, Al-Fakih A, Chu SH, Fediuk R, Haruna S, Azevedo A, Vatin N. Long-term durability properties of geopolymer concrete: An in-depth review. *Case Studies in Construction materials* 2021; 15: e00661.https://doi.org/10.1016/j.cscm.2021.e00661
[75] Koushkbaghi M, Alipour P, Tahmouresi B, Mohseni E, Saradar A, Sarker PK. Influence of different monomer ratios and recycled concrete aggregate on mechanical properties and durability of geopolymer concretes, *Construction and Building Materials* 2019; 205: 519-528. https://doi.org/10.1016/j.conbuildmat.2019.01.174
[76] Deb PS, Sarker PK, Barbhuiya S. Sorptivity and acid resistance of ambient-cured geopolymer mortars containing nano-silica. *Cement and Concrete Composites* 2016; 72: 235-245. https://doi.org/10.1016/j.cemconcomp.2016.06.017
[77] Pacheco-Torgal F, Castro-Gomes J, Jalali S. Alkali-activated binders: A review. Part 2. About materials and binders manufacture. *Construction and Building materials* 2008; 22(7): 1315-1322. https://doi.org/10.1016/j.conbuildmat.2007.03.019
[78] Parveen S, Rana S, Fangueiro R. Macro- and nanodimensional plant fiber reinforcements for cementitious

composites, in Junior HS, Fiorelli J, dos Santos SSF (Eds.), Sustainable and Nonconventional Construction Materials Using Inorganic Bonded Fiber Composites, Woodhead Publishing, Cambridge, 2017; 343-382. https://doi.org/10.1016/b978-0-08-102001-2.00020-6

[79] Choudhury AKR. Antishrink finishing, in: Choudhury AKR (Eds.), Principles of Textile Finishing, Woodhead Publishing, Cambridge, 2017; 41-59. https://doi.org/10.1016/b978-0-08-100646-7.00003-5

[80] Tay J. Ash from Oil-Palm Waste as a Concrete Material. *Journal of Materials in Civil Engineering* 1990; 2(2): 94-105. https://doi.org/10.1061/(ASCE)0899-1561(1990)2:2(94)

[81] Huseien GF, Asaad MA, Abadel AA, Ghoshal SK, Hamzah HK, Benjeddou O, Mirza J. Drying Shrinkage, Sulphuric Acid and Sulphate Resistance of High-Volume Palm Oil Fuel Ash-Included Alkali-Activated Mortars. *Sustainability* 2022; 14(1): 498. https://doi.org/10.3390/su14010498

[82] Saha AK. Effect of class F fly ash on the durability properties of concrete. *Sustainable environment research* 2018; 28(1): 25-31. https://doi.org/10.1016/j.serj.2017.09.001

[83] Sarker PK, Kelly S, Yao Z. Effect of fire exposure on cracking, spalling and residual strength of fly ash geopolymer concrete. *Materials & Design* 2014; 63: 584-592. https://doi.org/10.1016/j.matdes.2014.06.059

[84] Nuaklong P, Jonvivatsakul P, Pothisiri T, Sata V, Chindaprasirt P. Influence of rice husk ash on mechanical properties and fire resistance of recycled aggregate high-calcium fly ash geopolymer concrete. *Journal of Cleaner Production* 2020; 252: 119797. https://doi.org/10.1016/j.jclepro.2019.119797

[85] Khouki M, That M. Effect of temperature and density variations on thermal conductivity of polystyrene insulation materials in Oman Climate. *Journal of Engineering Physics and Thermophysics* 2015; 88: 994-998. https://doi.org/10.1007/s10891-015-1275-6

[86] Ali MF, Natrajan V. A Review of Geopolymer Composite Thermal Properties A Review of Geopolymer Composite Thermal Properties. *IOP Conference Series Earth and Environmental Science* 2021; 822 (1): 012051. https://doi.org/10.1088/1755-1315/822/1/012051

[87] Elbasir OM, Johari MAM, Ahmad ZA, Mashaan NS, Milad A. The Comprehensive Strength and Microstructure of Alkali-Activated Mortars Utilizing By-Product-Based Binary-Blended Precursors. *Applied Mechanics* 2023; 4(3): 885-898. https://doi.org/10.3390/applmech4030046

[88] Provis JL, Palomo A, Shi C. Advances in understanding alkali-activated materials. *Cement and Concrete Research* 2015; 78: 110-125. https://doi.org/10.1016/j.cemconres.2015.04.013

[89] Nath P, Sarker PK. Effect of GGBFS on setting, workability, and early strength properties of fly ash geopolymer concrete cured in ambient condition. *Construction and Building Materials* 2014; 66: 163-171, https://doi.org/10.1016/j.conbuildmat.2014.05.080

[90] Huseien GF, Hussein ZJ, Kubba Z, Nikolaevich BM, Mirza J. Improved Bond Strength Performance of Geopolymer Mortars: Role of High Volume Ground Blast Furnace Slag, Fly Ash, and Palm Oil Fuel Ash Incorporation. *Minerals* 2023; 13: 1096. https://doi.org/10.3390/min13081096

[91] Xiao JZ, Liu HR, Ding T, Ma GW. 3D printed concrete components and structures: an overview. *Sustainable Structures* 2021; 1(2): 000006. https://doi.org/10.54113/j.sust.2021.000006.

[92] Su JW, Li HT, Xiong ZH, Lorenzo R. Structural design and construction of an office building with laminated bamboo lumber. *Sustainable Structures* 2021; 1(2): 000010. https://doi.org/10.54113/j.sust.2021.000010.

[93] Vahedian A, Shrestha R, Crews K. Experimental and analytical investigation on CFRP strengthened glulam laminated timber beams: Full-scale experiments. *Composites Part B: Engineering* 2019; 164: 377-389. https://doi.org/10.1016/j.compositesb:2018.12.007

[94] Sulaiman O, Hashim R, Wahab R, Ismail ZA, Samsi HW, Mohamed A. Evaluation of shear strength of oil treated laminated bamboo. *Bioresource Technology* 2006; 97(18): 2466-2459. https://doi.org/10.1016/j.bior tech.2005.10.026.