

# Durability and mechanical properties of cement concrete comprising pozzolanic materials with alkali-activated binder: A comprehensive review

Bassam A. Tayeh<sup>a</sup>, Hussein M. Hamada<sup>b,\*</sup>, Ibrahim Almeshal<sup>c,d</sup>, B.H. Abu Bakar<sup>d</sup>

<sup>a</sup> Faculty of Civil Engineering, Islamic University of Gaza, Gaza, Palestine

<sup>b</sup> Faculty of Civil Engineering, University Malaysia Pahang, Malaysia

<sup>c</sup> Civil Engineering Department, Faculty of Engineering, Islamic University of Gaza, P.O. Box 108, Gaza Strip, Palestine

<sup>d</sup> School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, 14300 Nibong Tebal, Malaysia

## ARTICLE INFO

### Keywords:

Alkali-activated binder  
Pozzolanic materials  
Cement concrete  
Supplementary cementitious materials  
Mechanical properties  
Durability

## ABSTRACT

The disintegration of concrete structures made of ordinary Portland cement (OPC) is a worrying topic of increasing significance. The trend for reusing waste products or industrial by-products to reduce the amount of OPC in concrete constructions has become an important task for industries and research institutions. Although OPC is an essential ingredient for concrete and is immensely popular, it greatly contributes to the release of a massive quantity of CO<sub>2</sub> into the atmosphere. To decrease the increasing CO<sub>2</sub> emission, scholars and researchers in the construction industry and academic institutions have exerted efforts to adopt alternative sustainable binders using pozzolanic materials, such as metakaolin, fly ash, slag, rice husk ash, and palm oil fuel ash, combined with alkali-activator (AA). Many researchers have stated that AA alumina-silicate (Al<sub>2</sub>SiO<sub>2</sub>) materials can produce convincing mechanical and durability properties, such as compressive strength, splitting tensile strength, and modulus of elasticity, in cement concrete at an early age with low CO<sub>2</sub> emission and energy consumption. Most researchers have reported that concrete containing pozzolanic materials and alkali-activated binder (AAB) has better durability than conventional concrete, while others call for further studies. According to previous studies, this research assesses the present studies on the mechanical and durability properties of cement concrete produced from the AAB related to the pozzolanic materials. Furthermore, few possible studies have been recommended in the future.

## 1. Introduction

It is known that concrete is the second most used material after water where it comprises more than 20% of ordinary Portland cement (OPC). The manufacturing of OPC is also accountable for approximately 8% of worldwide global carbon dioxide emissions [1–4]. Also, the rapid development in the construction industry worldwide encourages the scholars and academic to search alternative sustainable materials in the construction industry [5–7]. For the past few decades, supplementary cementitious materials (SCMs) derived from industry by-products or natural pozzolan materials have been used to partially substitute cement, including fly ash (FA),

\* Corresponding author.

E-mail addresses: [btayeh@iugaza.edu.ps](mailto:btayeh@iugaza.edu.ps) (B.A. Tayeh), [engh76@gmail.com](mailto:engh76@gmail.com) (H.M. Hamada), [ibraheem-almeshal@hotmail.com](mailto:ibraheem-almeshal@hotmail.com) (I. Almeshal), [cebad@usm.my](mailto:cebad@usm.my) (B.H.A. Bakar).

<https://doi.org/10.1016/j.cscm.2022.e01429>

Received 4 July 2022; Received in revised form 16 August 2022; Accepted 22 August 2022

Available online 24 August 2022

2214-5095/© 2022 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

ground granulated blast furnace slag (GGBS), silica fume (SF), metakaolin (MK), limestone, fine glass powder, etc [8–12]. Using SCMs not only reduces the production cost of concrete, but also has technical advantages. Use of SCMs can reduce the heat of hydration as well as enhance the durability of the concrete [13–16].

In fact, the durability of concrete containing cement is associated with the characteristics of its essential elements, that is, about 60% CaO, whereas its hydration produces approximately 25%  $\text{Ca}(\text{OH})_2$ .  $\text{Ca}(\text{OH})_2$  reacts with acidic environments, and thus, cement has lower resistance against all aggressive environmental factors [17,18]. By contrast, pozzolanic materials improve gels, and products with low quantity of calcium hydroxide enhance resistance to chemical attacks [19–21]. In addition, dumping of pozzolanic materials into landfills and open areas is considered one of the main environmental problems [22]. Finding greener and more sustainable construction materials with lower energy consumption and carbon footprint is now becoming essential [23–27].

Alkali Activated Binders (AABs) or Alkali Activated materials (AAMs) are one of the potential alternatives to conventional cement concrete to minimize carbon emissions released during OPC production. AAB is a globally emerging technology that involves the reaction of aluminosilicate existing in the precursor with the alkaline solution forming a hardened product. These precursors have much less embodied carbon than OPC, making them an attractive option for alkali-activation [28]. Most AABs are developed from industrial by-products such as slag and FA [29,30]. The synthesis of these binders is very sensitive to several factors. These include the source, constituents and fineness of the precursor materials, type and combination of alkaline activators, the quantity of free water, and type and duration of curing [30]. AABs could be designed to have superior properties compared to cement, namely the development of earlier and higher mechanical strengths, better resistance to acids and sulphates, and lower heat of cement hydration [31].

Extensive research and development on AAB began in the early 1980 s, with laboratory testing and investigations into the reactions' mechanisms [32]. The AAB is called by other terms such as “geopolymers” and “inorganic polymers” based on the physicochemical properties of the source materials and the type of alkali activator. Fig. 1 presents the distinction between these three last classifications(terms) [33]. However, only AAB will be used throughout this review to avoid this ambiguity. Furthermore, Glukhovskiy [34] classified the alkaline activators into six groups, where M is an alkali ion:

1. Alkalis, MOH.
2. Weak acid salts,  $\text{M}_2\text{CO}_3$ ,  $\text{M}_2\text{SO}_3$ ,  $\text{M}_3\text{PO}_4$ , MF.
3. Silicates,  $\text{M}_2\text{O} \cdot n\text{SiO}_3$ .
4. Aluminates,  $\text{M}_2\text{O} \cdot n\text{Al}_2\text{O}_3$ .
5. Aluminosilicates,  $\text{M}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot (2-6)\text{SiO}_2$ .
6. Strong acid salts,  $\text{M}_2\text{SO}_4$ .

Some pozzolanas, such as FA and slag, are commonly utilised in alkali-activated products to improve durability and mechanical characteristics of [35]. Khater [36] stated that alkali-activated slag (AAS) demonstrated important modifications in strength when exposed to high temperature (300–1000 °C) complemented by superior thermal constancy compared with cement concrete. Samples made of GGBS as cement replacement and 15% air cooling slag survived from thermal drop at 1000 °C. Another researcher [37] stated that the charge passed values were reduced when exposed to chloride ion permeable for AAS samples compared with control concrete samples. On the contrary, the rate of length change increases due to the increase in the ratio of liquid to binder and curing age of alkaline activator's composite blend of slag with FA [38]. Rashad [39] found the alkaline activator composite blend of slag and FA concrete and mortars. They observed that the increase in the slag content increases the drying shrinkage value of concrete.

Adam [40] stated that alkaline activators including FA improved the chloride penetration and sorptivity tests compared with the cement concrete. Bernal et al. [41] investigated the durability of alkaline activator containing MK and slag as blended materials. They

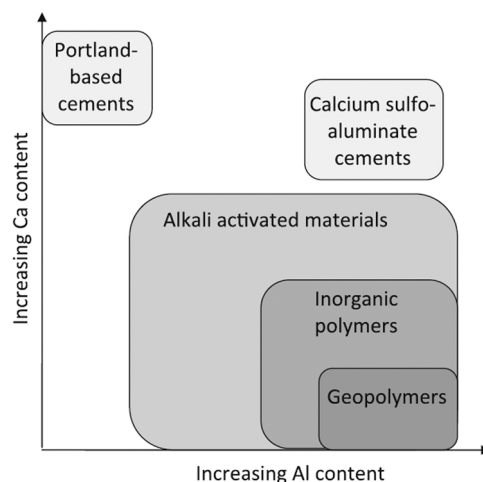


Fig. 1. Classification of different subsets of AAMs, with comparisons to OPC and calcium sulfoaluminate binder chemistry [33].

observed that the concrete samples showed lower chloride permeability and sorptivity due to the increase in the amount of MK and concentration of the alkaline-activated binders (AABs) [32,41]. The compressive strength and permeability values decreased. Sulphate expansion and drying shrinkage of MK replaced partially by POFA were investigated by Hawa et al. [42]. They noted that alkaline activator mortars comprising POFA reduced the drying shrinkage owing to the upsurge of curing period when exposed to high temperature. Instead, Kim et al. [43] stated that the use of RHA with  $\text{Na}_2\text{SiO}_3$  and NaOH can potentially replace cement concrete. They concluded that the durability properties of concrete in terms of acid and sulphate resistance in an aggressive environment contain HCl,  $\text{H}_2\text{SO}_4$ ,  $\text{MgSO}_4$  and  $\text{Na}_2\text{SO}_4$  solutions and significantly reduce the weight loss compared with the natural mortar samples. The present paper summarises the most related application of AAB in concrete and their durability performance for concrete comprising pozzolanic materials, such as FA, slag, POFA, RHA and MK. Table 1 shows the durability properties of AAB made of pozzolanic materials conducted by the previous studies.

The above-mentioned pozzolanic materials and AABs with OPC in construction projects have been steadily adopted by industries worldwide according to the existing standards [44]. Thus, the performance of these AABs concrete is a must now to fix the standard. Therefore, the current paper summarises the most relevant erudition regarding the durability and mechanical properties of concrete comprising AAB and pozzolans such as slag, FA, POFA, MK and RHA.

## 2. Alkali activated binders

### 2.1. Classification of AAB by the previous studies

As previously reported, massive quantities of industrial and agriculture wastes have been disposed without producing any importance. Recently, most by-product wastes generated from agricultural and industrial aspects have been considered to determine the probability of using them as supplements to AABs. Lastly, AABs are categorised according to the source of the raw materials and particularly according to the chemical composition that considerably affects the alkali reaction quality. Fig. 2 displays the main

**Table 1**  
Durability properties of AA mortar and concrete examined by previous studies.

References	Pozzolanic materials	Activator used	Concentration and molarity	Curing condition	Properties of concrete durability
Heikal et al. [45]	GBFS	$\text{Na}_2\text{SiO}_3$ and NaOH	0.5 mol/kg	Normal curing for 90 days.	Resistance of sulfate attacks
Al-Otaibi [46]	GBFS	$\text{Na}_2\text{SiO}_3$ and $\text{Ca}(\text{OH})_2$	4 %	Dry and water curing	Carbonation, chloride penetration resistance, and porosity.
Palacios and Puertas [47]	GBFS	$\text{Na}_2\text{SiO}_3$ and NaOH	4 %	28 days- normal curing	Carbonation test
Koenig et al. [48]	FA and slag	$\text{Na}_2\text{SiO}_3$ and NaOH	3.4 %	Heat curing for 48 h then water curing till test date	Resistance of acid attacks
Smirnova et al., [49]	Slag and lime	$\text{Na}_2\text{SiO}_3$ and NaOH	5 %	28-normal curing days	Frost resistance of alkali-activated slag concrete
Miranda et al. [50]	FA	$\text{Na}_2\text{SiO}_3$ and NaOH	8.2 %	Curing at high temperature (50 °C)	Corrosion resistance
Wallah [51]	FA	$\text{Na}_2\text{SiO}_3$ and NaOH	14.7 %	Dry and steam curing	Drying shrinkage test
Thokchom et al. [52]	FA	$\text{Na}_2\text{SiO}_3$ and NaOH	5 %	850 C&48 hr	Resistance of acid attacks
Allahverdi et al. [53]	GBFS	$\text{Na}_2\text{SiO}_3$ and NaOH	1 – 2 %	25 C for 42 days	Drying shrinkage test
Bernal et al. [54]	MK and GBFS	$\text{Na}_2\text{SiO}_3$ and NaOH	5 %	Ambient temperature for 24 hr, then normal curing for 28 days.	Sorptivity and carbonation tests
Wongpa et al. [55]	FA and RHA	$\text{Na}_2\text{SiO}_3$ and NaOH	14 Mol	Ambient condition for 90 days	Water permeability test
El-Sayed et al. [56]	GBFS	$\text{Na}_2\text{SiO}_3$ and NaOH	2 %	Normal curing up to 38 C	Resistance of sulfate attacks
Chaparro et al. [57]	GBFS	$\text{Na}_2\text{SiO}_3$ and NaOH	2.4 %	Normal curing	Corrosion resistance
Al Bakri et al. [58]	FA	$\text{Na}_2\text{SiO}_3$ and NaOH	8–16 Mol	Steam and dry curing	Resistance of acid attacks
Bernal et al. [59]	FA and GBFS	$\text{Na}_2\text{SiO}_3$ and NaOH	5 %	Normal and carbonation curing	Carbonation test
Beemamol et al. [60]	FA	NaOH	0.5 %	Moisture and sulfate curing	Shrinkage and chloride permeability
Shaikh [61]	FA	$\text{Na}_2\text{SiO}_3$ and NaOH	14 and 16 molar NaOH and $\text{Na}_2\text{SiO}_3$ to NaOH ratios of 2.5, 3.0 and 3.5	28-normal curing days	Corrosion resistance, sorptivity, and chloride penetration
Karim et al. [62]	RHA, POFA and GBFS	NaOH	1.0, 2.5 and 5.0 Mol	Water curing for 28 days	Thermal resistance, water absorption and porosity

classifications of the latest AABs.

## 2.2. Background of study

Exploration of durability properties of cement mortar and concrete using pozzolanic significantly affects the present research on concrete production. Even though many investigations were carried out in the formation of alkaline-activated binders, no comprehensive study has shown the mechanical and durability properties of this type of binder as an environmentally friendly material [64,65]. Nevertheless, numerous investigations are still required to show the durability properties of AAB. Table 1 shows some latest studies that were carried out to find out the durability properties of mortar and concrete using the pozzolanic materials in combination with alkaline-activated binders. Miranda et al. [50] showed that alkaline-activated mortar containing FA has better efficiency in terms of protection of the reinforcement considerably than cement mortar. They observed that alkaline activator containing FA has better resistance to chloride-ion penetration for effective and rapid reinforcement of bars than cement mortars.

Thokchom et al. [52] carried out many investigations to assess acid resistance of alkaline-activated mortar containing FA with  $\text{Na}_2\text{SiO}_3$  and NaOH solutions. They observed that the colour did not change, and the structural behavior was not influenced. Wallah [51] investigated the drying shrinkage of alkaline-activated concrete containing FA with  $\text{Na}_2\text{SiO}_3$  and NaOH solutions. They observed that the drying shrinkage was reduced for heat-cured alkaline-activated concrete compared with that corresponding to cement concrete. Bernal et al. [54] studied the effect of AAB on the carbonation value of mortars and activated MK and GBFS materials blended and exposed to  $\text{CO}_2$ . The results showed that the carbonation rate was faster, increasing sorptivity and decreasing the mechanical properties due to the increase in the amount of MK as a binder material.

In 2012, Kushal and Partha [66] examined porosity, sorptivity and water absorption of alkaline-activated mortar containing FA with  $\text{Na}_2\text{SiO}_3$  and NaOH solution. They observed a reduction in sorptivity and water absorption with improved compressive strength. Bakri et al. [58] investigated the alkaline-activated concrete containing FA with NaOH and  $\text{Na}_2\text{SiO}_3$ . They reported that the alkaline-activated concrete containing FA has better durability properties in aggressive environments compared with that of the cement concrete. Beemamol et al. [60] examined the compressive strength, shrinkage and permeability of alkaline-activated mortar comprising FA activated by NaOH. The results obtained showed a reduction in the shrinkage and permeability of concrete owing to the use of ceramic waste sand; this condition did influence the strength. Karim et al. [62] studied the potential use of pozzolanic POFA, RHA and slag as an alkaline-activated binder by inserting NaOH solution in various volumes (1.0, 2.5 and 5.0 M).

## 3. Properties of AABs

### 3.1. Chemical composition of alkali-activated binder

The composition of source materials greatly influences initially the fresh properties of AABs and subsequently, their hardened characteristics. The chemical composition of AAB is illustrated in Table 2. Silica oxide ( $\text{SiO}_2$ ) is the main component in different AABs, as reported by the previous studies. One of the difficulties in upscaling the AAB technology to the industrial level has been the huge variation in the chemical composition of precursors [30]. This variation in their composition requires different approach in the synthesis of AAB. For instance, the composition of natural pozzolan is entirely different from that of silicomanganese fume. Further, POFA lacks  $\text{Al}_2\text{O}_3$  and CaO that makes it different from low-Ca FA. The composition of rice husk ash is another example, which has no match with other precursor materials. Besides, ceramic waste and glass powder are rich in  $\text{SiO}_2$ , though, former has sizable amount of  $\text{Al}_2\text{O}_3$ , but latter lacks it [67,68].

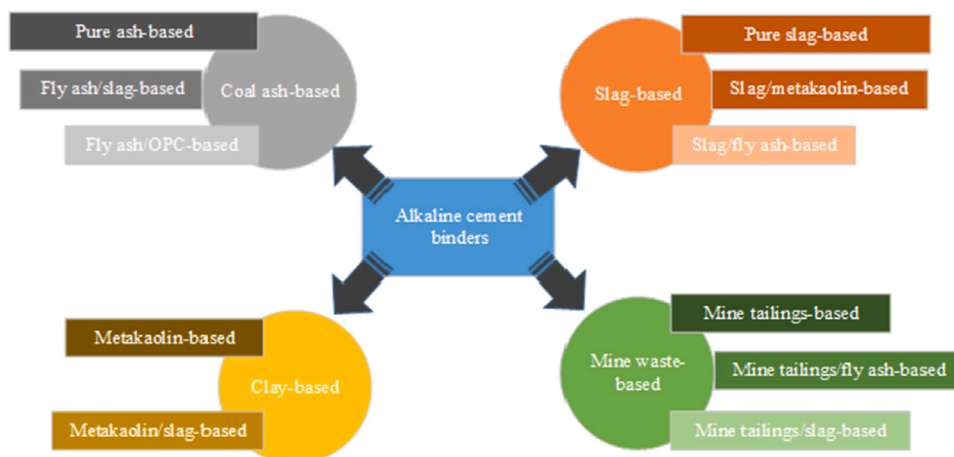


Fig. 2. Latest classifications of alkaline binders [63].

**Table 2**  
Chemical composition of AAB tested by the previous studies.

Ref.	Material type	SiO <sub>2</sub>	Fe <sub>2</sub> O <sub>3</sub>	Al <sub>2</sub> O <sub>3</sub>	MgO	CaO	Na <sub>2</sub> O	SO <sub>3</sub>	P <sub>2</sub> O <sub>5</sub>	K <sub>2</sub> O	TiO <sub>2</sub>	LOI
[69]	FA F	50.70	8.80	28.80	1.39	2.38	0.84	0.30	–	2.40	–	3.79
[70]	FA F	61.89	4.11	28.05	0.38	0.87	0.40	1.32	–	0.82	–	0.49
[71]	FA F	53.50	4.47	28.80	0.81	1.55	0.77	0.14	–	–	–	3.11
[72]	FA F	48.80	10.2	27.00	1.4	6.2	0.37	0.22	1.2	0.85	1.3	1.7
[73]	FA F	64.97	5.69	26.64	0.85	0.33	0.49	0.33	–	0.25	–	0.45
[74]	FA F	27.35	2.01	50.85	0.28	5.41	0.04	–	–	0.33	2.12	7.74
[75]	FA F	54.72	5.14	27.28	1.10	5.31	0.43	1.00	1.11	1.00	1.81	6.8
[76]	FA F	57.60	5.80	28.90	0.90	0.20	–	0.20	–	0.90	–	3.6
[77]	FA C	23.50	4.80	13.80	4.20	23.20	6.30	5.90	–	0.40	–	0.15
[78]	FA C	29.50	6.50	17.30	5.30	30.60	3.10	3.50	1.30	0.40	1.60	0.23
[79]	FA C	57.0	10.0	21.0	1.3	4.8	–	1.0	1.5	1.4	1.5	2.71
[79]	Slag	32.4	0.6	11.5	3.0	47.7	–	2.7	0.6	0.5	0.5	0.29
[80]	Slag	34.10	0.36	13.50	4.19	11.83	–	–	–	–	–	1.4
[81]	Slag	35.23	0.85	12.33	8.00	40.10	0.25	–	–	0.50	–	1.40
[82]	Slag	34.95	–	12.63	–	45.10	0.22	–	–	1.24	–	–
[83]	Slag	37.50	0.73	7.27	10.86	38.48	0.64	0.39	–	0.26	–	2.13
[84]	Slag	52.75	5.92	18.05	3.86	12.92	1.11	1.76	–	2.09	1.01	1.60
[85]	slag	35.80	1.97	13.21	9.76	35.68	0.48	0.21	–	0.57	–	2.32
[86]	Slag	33.05	0.53	16.36	6.41	45.0	0.13	1.21	–	0.42	–	3.05
[85]	RHA	89.47	0.53	0.83	0.37	0.68	0.22	0.12	–	0.17	–	7.61
[87]	RHA	89.34	0.40	0.45	0.49	0.76	–	0.90	2.58	4.98	–	–
[88]	RHA	93.46	0.52	0.58	0.515	1.03	0.08	0.60	1.60	1.82	–	7.76
[89]	RHA	89.17	0.41	–	1.22	0.61	1.22	–	–	1.12	0.03	0.15
[86]	RHA	87.75	0.19	0.38	0.69	1.04	0.05	0.56	1.31	2.83	0.02	3.04
[80]	POFA	47.37	6.19	3.53	4.19	11.83	–	–	–	–	0.24	1.84
[90]	POFA	44.40	2.10	1.20	9.13	10.30	0.55	5.80	–	12.40	–	–
[75]	POFA	64.17	6.33	3.73	4.87	5.80	0.18	0.72	5.18	8.25	0.19	6.30
[76]	POFA	63.40	4.20	5.5	3.70	4.30	–	0.9	–	6.30	–	6.00
[86]	POFA	47.22	2.65	2.24	5.86	6.48	1.22	9.19	5.37	11.86	0.17	5.42
[69]	SF	93.67	1.30	0.83	0.84	0.31	0.40	0.16	–	1.10	–	2.10
[81]	SF	94.90	1.7	0.49	0.70	0.56	–	–	–	–	–	1.61
[91]	SF	94.49	0.10	0.07	0.62	0.50	0.09	0.11	–	0.54	–	3.21
[92]	SF	93.67	1.30	0.83	0.84	0.31	0.40	0.16	–	1.10	–	2.10
[81]	MK	54.77	1.57	29.65	0.51	0.18	0.19	–	–	0.64	–	1.23
[82]	MK	55.54	–	44.16	–	0.08	0.05	–	–	0.90	–	–
[93]	MK	53.32	2.25	21.72	0.21	0.09	0.49	–	–	0.64	0.63	0.08
[88]	MK	51.70	0.64	40.60	0.96	0.71	0.31	0.10	3.00	2.00	0.20	1.19
[94]	MK	52.14	1.35	41.88	0.38	0.42	–	–	–	1.10	1.30	1.10
[95]	MK	51.30	0.42	44.42	0.01	0.05	0.33	0.13	–	0.14	1.69	1.30
[96]	BA	57.00	8.00	24.00	1.10	1.71	2.90	–	–	–	0.80	3.30
[96]	BA	54.00	4.00	25.00	2.00	5.00	–	3.00	1.00	1.00	2.00	2.00
[89]	WTS	58.99	6.63	24.64	1.14	0.69	4.08	–	–	1.54	0.88	–
[97]	FP	68.80	0.11	2.40	2.70	7.43	15.18	0.19	0.64	1.42	–	0.66
[98]	WCP	72.60	0.56	12.2	0.99	0.02	13.46	–	–	0.03	–	0.13
[86]	OPC	20.99	4.44	4.60	2.53	67.17	0.03	2.98	–	0.16	–	1.30

### 3.2. Physical properties of AABs

The physical properties of AAB has a major influence on the concrete properties. The physical properties are different depending on the origin of material. Table 3 shows the physical properties of AABs tested by the previous studies. The table shows that all these pozzolans are less dense than the OPC. The specific gravity of pozzolans in a variety of literature lies between 1.89 and 2.89, as compared to cement at 3.154. Processing, such as, grinding has a considerable effect on the specific gravity of pozzolans as examined by Karim et al. [86]. Furthermore, the particle size distribution and fineness of raw aluminosilicate materials have a substantial influence on hydration, strength development, and durability of AAB concrete. Finer particles increase the rate of hydration by providing better particle packing and by increasing nucleation sites, which ultimately leads to increase in strength. For these reasons, pozzolans are ground to obtain higher fineness for use. Similar to that observed for specific gravity, a significantly higher fineness in POFA (more than double in surface area) and RHA was observed after grinding the raw pozzolans [80,86,99].

## 4. Fresh properties of AAB

### 4.1. Setting time

The property of setting time in the case of AAB is a critical factor that affects selecting the materials to use in the construction field. This important property is introduced because of the effect on consumption time that includes mixture. The test of initial and final

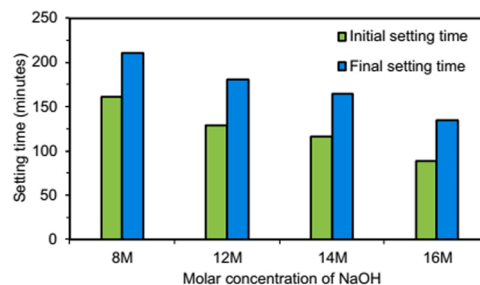
**Table 3**  
Physical properties of AAB examined by the previous studies.

Ref.	Material used	Blaine Fineness (m <sup>2</sup> /g)	Grain size (μm)	Passing through 45 mm (%)
[80]	Slag	3.27	–	–
[82]	Slag	–	10.8	89
[84]	Slag	–	15	–
[88]	Slag	0.405	–	–
[75]	FA	2.96	16.23	–
[100]	FA	–	3.43	83.25
[75]	POFA	12.92	22.78	–
[86]	POFA	0.458	16.08	–
[87]	RHA	67.33	16.76	–
[82]	MK	–	3.50	–
[86]	RHA	0.695	6.63	–
[86]	RHA (UG)	0.575	8.65	–
[86]	OPC	0.203	16	–
[74]	MK	–	0.011	–
[93]	MK	–	12.66	–
[92]	MK	–	2.55	–
[101]	BA	–	50.00	–
[96]	BA	–	39.60	90
[102]	NPOFA	1.96	0.982	–
[92]	SF	–	0.65	–
[73]	SF	–	0.004–0.016	–
[98]	WCP	12.2	35	–
[97]	CP	5.89	11.72	96.55
[97]	FP	10.03	4.65	97.84

setting time is affected by numerous factors, such as the sample preparation, arrangement of the pozzolanic materials, additive utilisation and curing conditions [103]. Nevertheless, in the AA-concrete (AAC) production, the ratio of alkaline activator to FA (AA/FA) and the ratio of sodium silicate (NaSiO<sub>3</sub>) to sodium hydroxide (NaOH) did not affect setting times [104]. Conversely, in another experiment when utilising NaOH as an activator instead of Na<sub>2</sub>SiO<sub>3</sub>, the setting time increased [105]. As illustrated in Fig. 3, the initial and final setting times were reduced significantly due to increase in the molarity of NaOH activator [106].

The setting time of AAB containing slag was reduced due to the increase in calcium content [107]. Li et al. reported an extended setting time due to the use of a large quantity of metakaolin and/or FA was combined in the FA-GGBS and metakaolin-GGBS alkaline binders [108,109]. Moreover, when slag was further added, the setting time will reduce significantly as reported by numerous studies [110–114]. Fig. 4 displays the effect of various percentage slags on the setting time when used to replace alkaline FA-based pastes [111]. Similar results have been mentioned by other studies, as presented in Fig. 4b [115].

In addition, the inclusion of high pozzolanic and calcium content, such as OPC and GGBS, into the binders deeply influence the setting times [95,116]. Wianglor et al. [95] observed a regular reducing tendency in setting time when replacing 5–30 % of metakaolin binder by the corresponding cement. Nevertheless, the presence of OPC increases the setting time considerably when compared with 100 % MK. This finding can be clarified owing to the plate-like morphology and high fineness of metakaolin [117,118]. Karim et al. [86] conducted many investigations on the POFA- and RHA-based binders with various slag contents and detected a substantial effect on setting time due to slag addition. Similar results were observed by POFA-based binders, which combined various amounts of slag that established similar influence on setting time [80,119]. The incorporation of 5 % ultrafine FA can effectively reduce the setting time due to its specific surface area, which is higher than that of other binder materials [120]. The setting times of binder containing FA were also influenced by the presence of nano-silica, which showed improved setting time with increasing nano-silica content, as shown in Fig. 5 [121]. Similar results were obtained by Zhang et al. [122], showing the influence of incorporating nano silica on setting time of AAB.



**Fig. 3.** Effect of NaOH concentration on setting times [106].

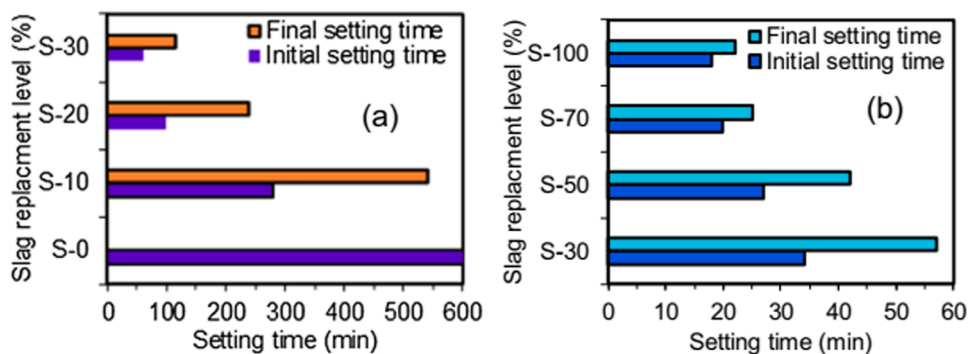


Fig. 4. Effect of slag on setting times of AAB [115].

#### 4.2. Workability of AAB

Workability is an important parameter that can be used to assess the ease and homogeneity of fresh matrix immediately after mixing. The workability property of AAB and alkali-activated concrete (AAC) is significant and can be obtained from slump test in fresh concrete [122,123], as well as from the mortar and paste that commonly determines the flow table method [116,124,125] or mini-slump test method [126]. The workability had a decreasing trend due to the addition of OPC or GGBS as high calcium powder to fly-ash based AAB [110,120,127]. Quartz sand with a particle size of up to 50  $\mu\text{m}$  improves the workability of slag-alkali materials, which causes the use of ultra-high filling with polypropylene microfiber to improve deformation properties [128,129].

Xie et al. [130] also investigated the influence of w/b of alkaline binders containing FA and GGBS on workability property. They observed that the slump values decreased because of GGBS utilisation instead of FA. The angular shape of GGBS decreases the slump values more than that of the FA particles with spherical shape [131,132]. A high-calcium FA-based binder has lower slump values than OPC binders due to the increase in the hydration products [78]. The activator nature has a significant influence on the slump value of AAB. For instance, sodium hydroxide and sodium silicate affect the whole workability. Increasing the superplasticiser is required to improve the workability due to the reduction in flow and slump values of AAB and AAC [133]. Similarly, the influence of  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratio on the slump value of AAB made of FA has been replaced by 10% OPC and GGBS [111,133]. The high viscous nature of  $\text{Na}_2\text{SiO}_3$  has a significant impact on the slump value [126]. In addition, related to mortars and FA-based alkaline paste, the slump value decreased due to the increase in percentage of GGBS content [115]. Parallel outcomes were observed with other studies [126,134].

### 5. Mechanical properties of AAB

The mechanical properties of alkaline activator mortar and concretes in the previous studies denote the acceptable performance of the final products. The mechanical properties that will be addressed in this study are in fresh and hardened cases. The fresh phase includes the setting time and workability. The hardened phase includes the compressive strength, flexural strength, splitting tensile strength, modulus of elasticity and fracture strength.

#### 5.1. Compressive strength

Compressive strength is one of the most static mechanical properties of AAB concrete. It is influenced by several factors such as the type and fineness of the raw cementitious materials, the type and dosage of the alkali activator, the solution to binder ratio, the curing regime, etc [135]. AAB concrete always shows relatively high early strength and quick strength development. The 1-day compressive strength can achieve 60 MPa and the 1-year compressive strength can exceed 100 MPa [136]. The high mechanical strength of AASC is

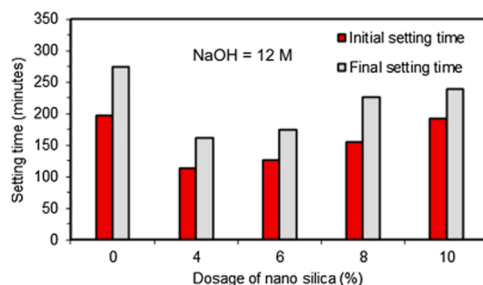


Fig. 5. Effect of nano  $\text{SiO}_2$  on setting time of AAB [121].



attributed to two factors: the fast rate of the hydration reactions at elevated pHs, which gives high early age strength; and a dense and homogenous interface transition zone (ITZ), with minimal strength differences between the ITZ and the binders [37].

AAB concrete is sensitive to curing conditions. Many studies stated that heat curing is important to increase the strength of AAB. Nasvi et al. [137] concluded that the heat curing improved strengths at early age, as well as Poisson's ratio and Young's modulus. Atiş et al. [138] observed that the duration and heat curing considerably increase the strength of low-calcium FA-based geopolymer concrete. Generally, decreasing the particle size of FA by grinding and milling produces a low porosity and denser microstructure given than the smaller particle size subsequently improves the compressive strength of AAB [139,140]. Nevertheless, Xie et al. [78] discovered a substantial increase in one day-compressive strength due to the addition of high calcium FA to the geopolymer concrete at room temperature curing.

High silica content in mine tailing based-concrete mixtures enhances the reaction rates in the thermal stability and compressive strength, owing to the minimised particle size of raw mine tailings [141]. Furthermore, Mejía et al. [142] detected similar results of compressive strengths for 28 days in FA-slag and ambient-cured FA-OPC mixtures with similar ratio to  $\text{SiO}_2/\text{Al}_2\text{O}_3$  of 6. This finding highlights the benefits of reducing heat curing in AAB. Pangdaeng et al. [124] studied the influence of curing circumstances for AAB containing cement and FA. The results obtained discovered that wet and vapour curing conditions improved the compressive strength at later age, whereas heat curing improves the compressive strength at early age. Fig. 6 shows the comparisons between the compressive strength of AAC at ambient curing. The figure illustrates that AAB made of FA shows abstemiously lower compressive strengths than AAB made of slag and FA.

Even though the addition of extra GGBFS in FA leads to growths in compressive strength, it reduces the paste rheology. Huseien et al. [116] indicated that addition of extra metakaolin instead of slag-based alkaline mortar increased the compressive strengths at 7 and 28 days. Nevertheless, the compressive strength produced at early age was lower due to the addition of metakaolin.

## 5.2. Tensile strength

Tensile strength is one of the essential properties used for several design aspects of structural components. For instance, when designing the shear and anchorage of reinforcing steel, the tensile strength of the concrete used plays a vital role [143]. The tensile strength of AAB has been conducted to evaluate the strength of AAB and AAC structures. Huseien et al. [116] detected the increase in the splitting tensile strength of AAB due to the replacement of slag-based AAB by metakaolin compared with cement mortar at different curing ages. In addition, the combination of 5% MK/95% GGBFS alkaline binders presented about 3 MPa tensile strength at one day and more than 5 MPa of tensile strength at 28 days, representing 10 times higher strengths obtained from cement. Influence of two alkaline solutions (NHNS and NH) and different curing temperatures (27 °C, 60 °C and 90 °C) on splitting tensile strengths at seven days of GGBFS/FA binder was investigated by Huseien et al. [127]. The decrease in splitting tensile strengths was due to high curing temperature, which produces a micro-crack in the concrete specimens. Nevertheless, the splitting tensile strengths of GGBFS/FA mortar recorded lower splitting tensile strength (3 MPa) than that of GGBFS/MK mortar (5 MPa), as stated by Huseien et al. [116].

## 5.3. Flexural strength

In general, the flexural strength of AAB was assessed by adopting a three-point bending test described by the previous studies [110, 127]. Fig. 7 displays the influence of adding GGBFS on the flexural strength of FA/GGBFS mortars.

The figure shows that inclusion of GGBS increased the flexural strength steadily for all curing ages. Nevertheless, the increase in seven-day flexural strengths is more noticeable than that in the 28-day flexural strength, that is, from 10% to 40%. The proportion of 5% MK/95%GGBFS produced higher flexural strength of mortar than of cement mortar. In addition, the compressive strengths were increased by 50%, that is, more than 8 MPa compared with cement mortar. Nevertheless, the flexural strength of FA/ GGBFS mortar decreased due to the increase in curing temperature of AAB specimens [144].

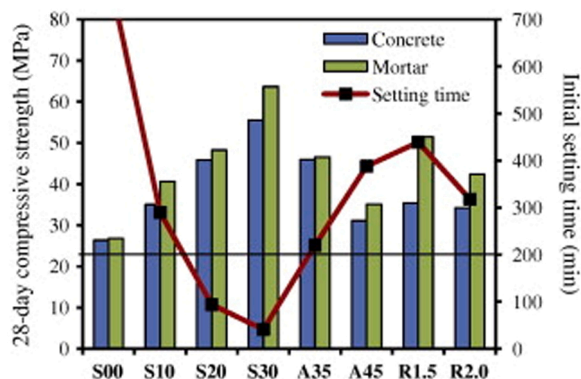


Fig. 6. Relationship between the compressive strength and setting time [111].



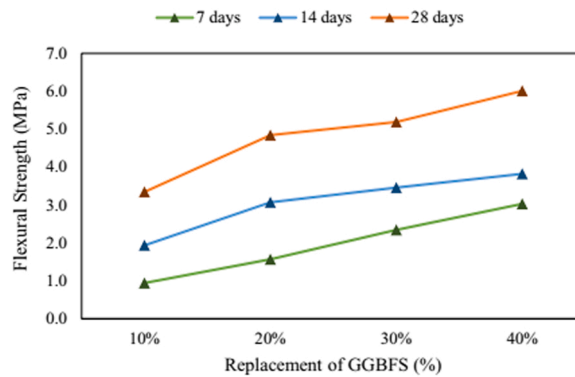


Fig. 7. Influence of GGBFS on flexural strength [110].

## 6. Durability properties of AAB

The durability properties of alkaline activator mortar and concrete conducted by the previous studies refer to a better concrete performance with a significant hydration heat, superior thermal resistance, a lower porosity, permeability and water absorption, superior corrosion resistance, outstanding resistance against sulphate and alkali-silica reactions and improved resistance of chloride attacks. Thomas et al. [144] stated that integration of pozzolanic materials can be considered useful materials to protect the concrete produced from degradation in the aggressive environment as well as to improve durability properties. The durability properties of AABs using pozzolanic waste materials (FA, slag, RHA, MK and POFA) have been discussed in detail in the following subsection.

### 6.1. Water permeability and water absorption

Bernal et al. [37] investigated the water absorption of cement and AAB samples with the same binder quantity at 28 and 90 curing days. They concluded that the water absorption and porosity of AAB had lower value than that of the cement concrete samples. The scientists recognised this finding given the accessibility of finer and closed pores in alkaline-activated samples when water cannot simply penetrate [145]. Qureshi and Ghosh [146] presented a reducing tendency in water absorption value for water cured samples comparing with oven-dried samples with alkaline activator amount ranging between 6.41% and 10.41%. The 10.41% of alkali content led to reduce the water absorption of 6.38% which indicates to better compact structure and homogenous of the concrete mix. Qureshi and Ghosh [147] displayed a better connection between apparent porosity and water absorption of AAS paste and  $\text{SiO}_2$  content, as shown in Fig. 8.

Chi et al. [38] investigated the water absorption of AAB containing slag and FA. In addition, the OPC mortar was used as a reference sample. They concluded that the use of AAB reduced the water absorption rate of AA mortar compared with the control cement mortar. The water absorption increased due to the use of FA as an AA in cement mortars. The chemistry of the binders was illustrated by Provis et al. [148], who stated that the water absorption of AA mortar made of FA is higher than the reference AA mortar.

### 6.2. Porosity

The distribution of pore size, hydration characteristics and microstructure of AAB is affected by the chemical and physical properties of GBFS and the alkaline activator nature [149]. According to the observation of the morphology and microstructure of the

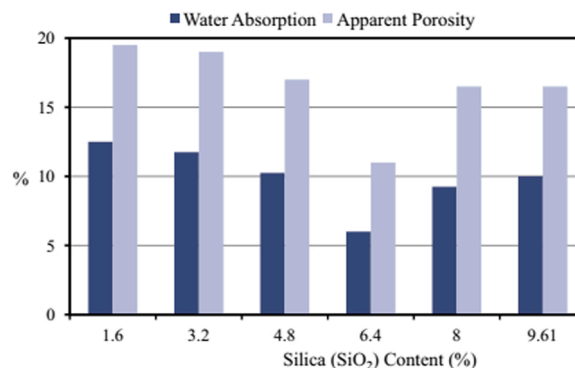


Fig. 8. Influence of silica content on apparent porosity and water absorption [147].

shaped stages, the researchers stated that the binder microstructure with  $\text{Na}_2\text{CO}_3$  and  $\text{NaOH}$  was porous and bulky, and no portlandite was found. Nevertheless, they stated that the binder microstructure containing  $\text{K}_2\text{SiO}_3$  as AB was tremendously denser than that of the control sample.

Al-Otaibi [46] similarly detected that the porosity value of AAB increased compared with the OPC binder. The author stated that the porosity value was 13–10% at 7 and 360 days for AAB. Conversely, the porosity values were 10.4% and 8% for the same time period. Qureshi and Ghosh [146] investigated the porosity of AAB when samples were treated in water tank and heated curing at different temperatures of 40 °C, 50 °C and 60 °C, as shown in Fig. 9.

### 6.3. Sulphate resistance

Sulphate attack is a chemical attack that affects the performance of concrete and mortar, leading to extreme extension and decrease in compressive strength [150]. Concrete and mortar with the combination of pozzolanic materials enhanced the impedance against sulphate attacks compared with cement concrete and mortar comprising  $\text{C}_3\text{A}$  [151]. In addition, Malviya and Goliya [152] stated that the concrete containing FA and activated by  $\text{Na}_2\text{SiO}_3$  and  $\text{NaOH}$ , decreased the weight and compressive strength more than that of the activated concrete samples. The cement concrete samples were immersed in  $\text{MgSO}_4$  solution resulted in the loss of weight of cement concrete samples by 0.36 % and 0.46 %, and compressive strength loss of more than the AAC samples. Heikal et al. [45] used GBFS with micro silica to examine the sulphate resistance of AAB. They concluded that the addition of micro silica to AAB reduced the chloride content of samples submerged in 5 %  $\text{MgCl}_2$  solution.

Bakharev [153] examined sulphate resistance of  $\text{KOH}$ ,  $\text{NaOH}$  and  $\text{Na}_2\text{SiO}_3$ -activated binder containing FA. The concrete samples were submerged in 5%  $\text{MgSO}_4$  and  $\text{Na}_2\text{SO}_4$  solutions and combined (5 %  $\text{MgSO}_4$  + 5 %  $\text{Na}_2\text{SO}_4$ ) solutions for 150 days. The results of sulphate attack in terms of changes in mass, loss in compressive strength, microstructural analysis and other visual observations were investigated. An important variation in compressive strength occurred. Shi et al. [154] and Bakharev [153] reported that concrete samples activated by AAB exhibited a superior resistance against sulphate attacks of slag cement and AA FA in  $\text{MgSO}_4$  solution. Furthermore, the concrete samples cured by heating and activated by  $\text{Na}_2\text{SiO}_3$  solution displayed a reduction in sulphate resistance when compared with ambient-cured samples. By contrast, Rangan [155] reported that a higher resistance to sulphate attacks was observed for low calcium FA-based activated concrete. The samples submerged for 365 days in the  $\text{Na}_2\text{SO}_4$  solution displayed no important variations in compressive strength values, surface deterioration and cracking. The change in shrinkage values was less than 0.015% of sample dimension.

### 6.4. Chloride ion penetration

The porous structure of concrete samples can permit chloride ions to pass through samples. These ions can be present in aggregates, water, additives and fresh concrete mixtures. The absorption of salts in reinforced concrete was observed with cathodic and anodic regions [156]. Consequently, owing to electrolytic effect, corrosion of the steel and concrete rupture can occur. Shi [157] stated that the passage of ions is completely associated with pore network of AAC, wherein electrical conductivity of the concrete samples is affected by the chemical composition and pore network of the pore solution. Fig. 10 shows a low value of charge passed for AAC samples compared with cement concrete. Shi [158] stated that the well-cured AAS concrete samples exhibited decreased permeability to ion chloride lower than that of cement concretes.

In blended MK with slag-based AAB, Bernal et al. [38] observed the charge passed according to the test of rapid chloride permeability for 28 and 90 curing days of the concrete samples. The high-concentrated activators in AAS increased the values of charge passed after 28 curing days; thus, it is extremely permeable to chlorides. The charge passed value was reduced by 40 % for the concrete containing 10 % MK in the binder, and the ratio of S/A ( $\text{SiO}_2/\text{Al}_2\text{O}_3$ ) was 3.6 after 28 curing days as compared with AAS concrete. In addition, the charge passed value decreased by 30 % compared with that of AAS samples due to the increase in 20 % MK content in the binder with higher S/A ratio. The authors [41] detected that for all concrete samples, the charge passed values slightly decreased after 90 curing days. According to the results obtained from the authors [41] in a short time up to 28 curing days, an increased quantity of MK in the binder possibly will not be important concerning the charge passed value in concrete samples.

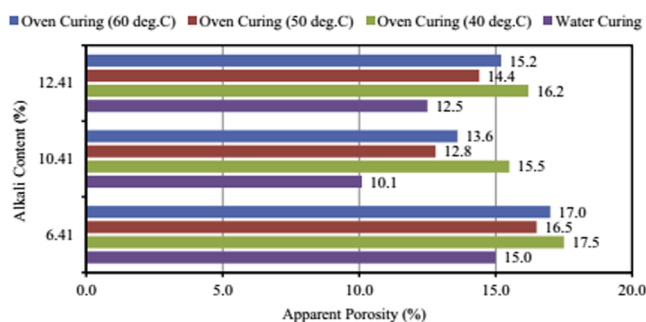


Fig. 9. Relationship between porosity and alkali content [146].



Fig. 10. Chloride permeability of activated slag concretes for 28 curing days [157].

### 6.5. Carbonation

Puertas et al. [159] arranged the AAS and cement mortars with constant ratio of 2:1 as aggregate/binder ratio activated by NaOH solution and 0.85 as ratio of ( $\text{Na}_2\text{O}/\text{SiO}_2$ ). The first group of samples did not add any additives whereas, the two other groups contained shrinkage reducing or vinyl copolymer admixtures. The outcomes obtained showed that the mechanical strength of cement mortar increased by 26 % after 120 days of exposure to carbonation compared with the value obtained in 28 days. However, the compressive strength did not increase during exposure to carbonation for 120–240 days. The carbonation rate of concrete can be investigated by the physical properties of the solid binder and the chemistry of the binder materials, in addition to the porosity and permeability of the binder [160,161]. Puertas et al. [159] also examined the carbonation depth of cement mortar and AAS for 120 days of carbonation by phenolphthalein indicator. The results show that the carbonation for AAS mortar samples up to 10 mm when used  $\text{Na}_2\text{SiO}_3$  as the sole activator was intense and much deeper than that observed in cement mortar samples [159], whereas the carbonation depth of only 3 mm was observed when NaOH was used as the sole activator.

Bernal et al. [59] stated that the attractive properties of binders produced from FA and AA slag have a significant role in the production of low-emission concrete. They stated that constant aluminosilicate gels that are highly polymerised remain in the AAS samples after enhanced carbonation. Compared with cement-based binders and AAS, AAB made of FA displays various structural and chemical properties, as described by Li et al. [64].

### 6.6. Corrosion resistance

Corrosion usually occurs in reinforced concrete bars and can be considered a significant durability issue. The excellent corrosion resistance of concrete is continually serious problem and has a significant effect, not less important than the mechanical properties of reinforced concrete. Various methods were utilised to protect the reinforced concrete bars against corrosion. Many researchers have investigated the corrosion resistance in activated concrete [50,162–166]. Miranda et al. [50] investigated the resistance against corrosion of AAB and detected a comparable corrosion resistance to FA mortar with 8 and 12.5 M of concentration NaOH solution. In addition, Bastidas et al. [162] stated the same results on the resistance against corrosion for AAB made of FA with a concentration of 12.5 M NaOH solutions. Oliva and Nikraz [163] investigated the resistance against corrosion of two AAC samples comprising NaOH solution with concentration of 14 M in hastened corrosive environment. The results show a higher resistance against corrosion value of both activated concrete mixtures was stated compared with cement concrete of the same compressive strength.

Currently, Patil and Allouche [165] reported that the higher resistance against corrosion value of AAC with NaOH solution was achieved. Overall, the compressive strength of concrete can be increased through improving the geopolymerisation by increasing the concentration of NaOH solution for a certain quantity of  $\text{Na}_2\text{SiO}_3$ . Fansuri et al. [166] reported that the quantities of  $\text{Na}_2\text{SiO}_3$  and concentrations of NaOH solution significantly affect the properties of AA concrete. Shaikh [61] stated that the reason for enhancing the activated concrete against corrosion is the increase in the amount of  $\text{Na}_2\text{SiO}_3$  solutions and NaOH molarity. Chaparro et al. [57] used inserted steel bars in the AAB samples and absorbed the samples in NaCl solution. In addition, cement concrete samples were immersed in the same solution for comparison. Aperador et al. [167] reported that the lower resistance against carbonation for AAB was due to the existence of NaOH solution. Bernal et al. [54] presented lower values of carbonation resistance of MK blends and activated slag. Conversely, Lloyd et al. [168] reported that the durability of reinforced concrete bars can be enhanced by AAB made of high calcium FA. In conclusion, different conceptions concerning resistance against corrosion were mentioned from several studies. Consequently, an extra investigation on the protection of steel bars against corrosion behavior for AAB samples is required.

### 6.7. Drying shrinkage

Drying shrinkage can occur due to the reactions between the water and mixture components in the whole volume. In AAB sample, hydrotalcite and C–S–H gels mostly affect the increase in drying shrinkage [38]. One of the shrinkage types is a chemical shrinkage, which occurs in materials and influence the durability properties. Rashad [39] stated that AA–FA mortar samples displayed a small reduction based on the drying shrinkage upsurge when the slag content increased in the mortar mixtures. Shen et al. [169] investigated the slag blended with FA and activated neat slag to determine the drying shrinkage for two months compared with the cement binder

shrinkage<sup>†</sup>. They concluded that the neat <sup>†</sup>AAS recorded the highest drying shrinkage value, FA assisted in the reduction of the drying shrinkage of pure AAS <sup>†</sup>paste, and cement recorded the lowest drying shrinkage value.

Chi et al. [38] investigated the drying shrinkage value of AAFS concrete and cement mortar for 7, 14 and 28 days. They concluded that increasing liquid to <sup>†</sup>binder ratio<sup>†</sup> and age of sample led to an increase in length change rate of all concrete samples, as illustrated in Fig. 11. Furthermore, AAFS mortar has a length change rate more than that of cement mortars for all curing ages. A length change rate was detected in AAS mortar higher than AAFS mortar. However, the AAFS mortar with a higher quantity of FA recorded a lower length change rate. Thus, the ratio of FA/slag considerably affected the drying shrinkage of the AAFS mortar, and the FA reduced the length change rate.

Other studies [170–172] stated that the AA–FA binders recorded a lower drying shrinkage rate than the cement binder, whereas others stated that the AAS binder recorded a higher drying shrinkage than the cement binder [173–176]. Nevertheless, the technical perspective of high drying shrinkage status of AAS is still mysterious. Few studies suggested that during the drying shrinkage process, a high capillary force occurred in the material components of fine pore structure, such as AAS [176,177].

## 6.8. Acid resistance

Topcu and Canbaz [178] stated that salts were created from the reaction between AAB and acid in acidic environment. Water with high salt content is mostly responsible for forming cracks in the binder materials, resulting in the dissolution of binders. They concluded that the micro-cracks were due to the development of small circular-shaped particles in addition to the dissolution of the binding phase in acidic environment. Bakharev et al. [179] reported that GBFS has positive influence in acid environment, whereas the microstructure of AAS concrete was adversely influenced by the same acidic environment. Chang et al. [180] detected an increase in drying shrinkage rate, decrease in strength and setting time of AAS pastes in acidic environment owing to acid influence. Kim et al. [43] conducted experimental investigations to improve AAB-based RHA activated by Na<sub>2</sub>SiO<sub>3</sub> and NaOH. AA mortars have a superior acid resistance owing to the existence of Ca(OH)<sub>2</sub>. Activated mortar presented an increase in weight by 2.5% after exposure for 28 days [181,182]. Koenig et al., [48] concluded that the concrete and mortar based on AAB have a significant impact on improving the resistance to organic acids compared with cement. The increase in CaO content in the AAB solution increased the resistance against organic acid.

Furthermore, Malviya and Goliya [152] stated that related to FA-based activated concrete, cement concrete samples (1.15 and 3.4)% lost more weight than the AAB samples soaked in 5% H<sub>2</sub>SO<sub>4</sub> solutions. The loss in the strength value of cement concrete samples was 4.51% and 2.74% more than those of activated concrete samples when immersed in 5% H<sub>3</sub>PO<sub>4</sub> solution. Comparable results were obtained by Thokchom et al. [183]. They stated that activated mortar samples prepared from combined alkaline activators and FA remained physically integral and did not demonstrate any considerable modification in colour in the H<sub>2</sub>SO<sub>4</sub> solution whereas it became yellow in HNO<sub>3</sub> solution.

## 7. Conclusions

According to the previous studies, the subsequent conclusions were created:

1. AAB have huge potential to replace the convention OPC, due to their eco-friendlier properties and enhanced properties. However, there are associated challenges in the use of AAB, which thus limit its usage.
2. The use of OPC can be considered harmful for the <sup>†</sup>environment due to the high amount of CO<sub>2</sub> released during its production. Therefore, <sup>†</sup>other cementitious materials were used to mitigate the negative effect of OPC.<sup>†</sup>
3. The silica oxide and Alumina oxide in the AAB materials, such as FA, RHA and slag, exhibited the highest values amongst other components in the chemical compositions of materials.
4. Most researchers have observed complex properties and some conflicts in their findings. However, they are on the same platform to establish a fixed standard for the durability resistance of mortar and concrete containing AAB with the mentioned pozzolans.
5. The use of high amount of slag reduced the initial and final setting time. However, using the nano silica with FA improved the setting time of AAB mix. The workability was reduced due to the use of GGBS or OPC as high <sup>†</sup>calcium powder to fly-ash-based AAB.
6. Duration and heat curing considerably increased the strength of low-calcium FA-based <sup>†</sup>GPC. Generally, decreasing the particle size of FA by grinding and <sup>†</sup>milling produced low porosity and dense microstructure owing to the small particle <sup>†</sup>size that subsequently improved the compressive strength of AAB.
7. The splitting tensile strength of AAB increased due to slag-based AAB replacement by <sup>†</sup>MK compared with cement mortar at different curing age. The decrease in splitting tensile strengths was due to high curing temperature, thereby <sup>†</sup>producing a micro-crack in the concrete specimens.
8. A comparison in durability and mechanical characteristics is required for specimens prepared at the laboratory and specimens taken from the field. Based on the current review article, few studies were found in the literature concerning the impact of nanomaterials on some durability properties such as carbonation resistance, sorptivity, chloride penetration resistance, thermal conductivity, and shrinkage.
9. Some investigations stated that enhancing the durability properties of AAB comprising FA, POFA, slag, RHA and MK is possible.

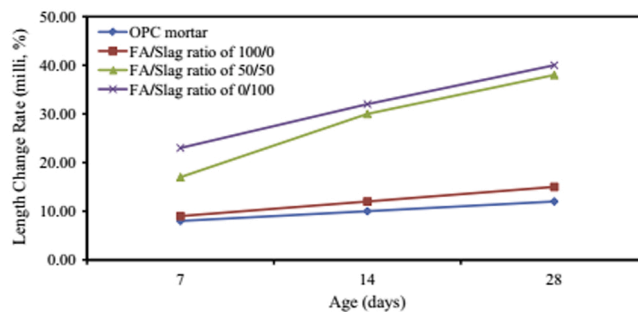


Fig. 11. Rate of changing length of AA-based FA and OPC and/or GBFS mortar [38].

- Other studies stated that the durability properties of concrete comprising AAB with different pozzolanic materials can be achieved at various concentrations of cement binders.
- Active recycle of these pozzolanic materials can provide numerous benefits, such as decrease in cement production, CO<sub>2</sub> emission and construction cost. Furthermore, the dumping issue related to the stated pozzolanic materials can be reduced by their actual depletion.

## 8. Recommendations

According to the investigations by the previous studies and to treat the gap in this field, the following recommendations are suggested for the upcoming studies:

- An extensive study should be carried out with various pozzolanic activators and alkali in concrete and mortar to determine the approach that would achieve a high-performance in terms of durability properties.
- Various environmental exposures and conditions should be conducted to discover the durability and mechanical properties of mortar and concrete comprising pozzolanic materials activated by alkali.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data Availability

Data will be made available on request.

## Acknowledgement

The authors would like to acknowledge the school of civil engineering, Universiti Sains Malaysia, Malaysia for funding the publication of this research paper. All authors has contributed equally to the conception and design of the study.

## References

- F. Matalkah, A. Ababneh, R. Aqel, Effects of nanomaterials on mechanical properties, durability characteristics and microstructural features of alkali-activated binders: a comprehensive review, *Constr. Build. Mater.* 336 (2022), 127545.
- M. Amin, A.M. Zeyad, B.A. Tayeh, I. Saad Agwa, Effects of nano cotton stalk and palm leaf ashes on ultrahigh-performance concrete properties incorporating recycled concrete aggregates, *Constr. Build. Mater.* 302 (2021), 124196.
- A. Adesina, A.R.G. de Azevedo, M. Amin, M. Hadzima-Nyarko, I.S. Agwa, A.M. Zeyad, B.A. Tayeh, Fresh and mechanical properties overview of alkali-activated materials made with glass powder as precursor, *Clean. Mater.* 3 (2022), 100036.
- A.A. El-Sayed, I.N. Fathy, B.A. Tayeh, I. Almehal, Using artificial neural networks for predicting mechanical and radiation shielding properties of different nano-concretes exposed to elevated temperature, *Constr. Build. Mater.* 324 (2022), 126663.
- M. Mosurović Ruzičić, M. Miletić, M. Dobrota, Does a national innovation system encourage sustainability? Lessons from the construction industry in Serbia, *Sustainability* 13 (7) (2021).
- Y. Geng, B. Doberstein, Developing the circular economy in China: challenges and opportunities for achieving 'leapfrog development', *Int. J. Sustain. Dev. World Ecol.* 15 (3) (2008) 231–239.
- A. Bahari, A. Sadeghi Nik, M. Roodbari, E. Mirshafiei, B. Amiri, Effect of silicon carbide nano dispersion on the mechanical and nano structural properties of cement, *Natl. Acad. Sci. Lett.* 38 (4) (2015) 361–364.
- A. Bahari, A. Sadeghi-Nik, E. Cerro-Prada, A. Sadeghi-Nik, M. Roodbari, Y. Zhuge, One-step random-walk process of nanoparticles in cement-based materials, *J. Cent. South Univ.* 28 (6) (2021) 1679–1691.
- M.H. Khalilpasha, A. Sadeghi-Nik, O. Lotfi-Omran, K. Kimiaiefard, M. Amirpour-Molla, Sustainable development using recyclable rubber in Self-Compacting Concrete. Third International Conference on Construction in Developing Countries (Advancing Civil, Architectural and Construction Engineering & Management), Bangkok, Thailand, July 4-6 (2012) 580-585.
- I.S. Agwa, A.M. Zeyad, B.A. Tayeh, M. Amin, Effect of different burning degrees of sugarcane leaf ash on the properties of ultrahigh-strength concrete, *J. Build. Eng.* 56 (2022), 104773.

- [11] I. Saad Agwa, A.M. Zeyad, B.A. Tayeh, A. Adesina, A.R.G. de Azevedo, M. Amin, M. Hadzima-Nyarko, A comprehensive review on the use of sugarcane bagasse ash as a supplementary cementitious material to produce eco-friendly concretes, *Mater. Today: Proc.* (2022).
- [12] M. Amin, B.A. Tayeh, M.A. Kandil, I.S. Agwa, M.F. Abdelmagied, Effect of rice straw ash and palm leaf ash on the properties of ultrahigh-performance concrete, *Case Stud. Constr. Mater.* 17 (2022), e01266.
- [13] A. Sadeghi-Nik, A. Bahari, A. Sadeghi-Nik, M.H. Khalilpasha, Nanotechnology Coating of Buildings with sol-gel method, *Am. J. Sci. Res.* 31 (2011) 69–72.
- [14] M. Amin, A.M. Zeyad, B.A. Tayeh, I. Saad Agwa, Effect of ferrosilicon and silica fume on mechanical, durability, and microstructure characteristics of ultra high-performance concrete, *Constr. Build. Mater.* 320 (2022), 126233.
- [15] S.A. Mostafa, N. Ahmed, I. Almeshal, B.A. Tayeh, M.S. Elgamal, Experimental study and theoretical prediction of mechanical properties of ultra-high-performance concrete incorporated with nanorice husk ash burning at different temperature treatments, *Environ. Sci. Pollut. Res.* (2022).
- [16] U.J. Udi, I. Almeshal, M.A. Megat Johari, M.Z.A. Mohd Zahid, M.H. Hassan, K.A. Musa, M. Albiajawi, B.H. Abu Bakar, Efficiency of high performance fiber reinforced cementitious composites as a retrofit material for fire-damaged concrete, *Mater. Today: Proc.* 61 (2022) 477–486.
- [17] P.K. Mehta, Properties of blended cements made from rice husk ash, *Acids J. Proc.* 74 (9) (1977).
- [18] Z. Bian, G. Jin, T. Ji, Effect of combined activator of  $\text{Ca(OH)}_2$  and  $\text{Na}_2\text{CO}_3$  on workability and compressive strength of alkali-activated ferronickel slag system, *Cem. Concr. Compos.* 123 (2021), 104179.
- [19] J. Newman, B.S. Choo, *Advanced Concrete Technology Set, Volume-1 Concrete Properties*, Butterworth-Heinemann, England, 2003.
- [20] M. Kasaniya, M.D.A. Thomas, E.G. Moffatt, Efficiency of natural pozzolans, ground glasses and coal bottom ashes in mitigating sulfate attack and alkali-silica reaction, *Cem. Concr. Res.* 149 (2021), 106551.
- [21] R. Alyousef, H. Mohammadhosseini, A.A. Ebid, H. Alabduljabbar, S.P. Ngian, A.M. Mohamed, Durability enhancement of sustainable concrete composites comprising waste metallized film food packaging fibers and palm oil fuel ash, *Sustainability* 14 (9) (2022).
- [22] Mohammad Ali Mousavi, Aref Sadeghi-Nik, Ali Bahari, Ashraf Ashour, Kamal H. Khayat, Cement paste modified by nano-montmorillonite and carbon nanotubes, *Acids Mater. J.* 119 (3) (2022).
- [23] M. Amin, I.Y. Hakeem, A.M. Zeyad, B.A. Tayeh, A.M. Maglad, I.S. Agwa, Influence of recycled aggregates and carbon nanofibres on properties of ultra-high-performance concrete under elevated temperatures, *Case Stud. Constr. Mater.* 16 (2022), e01063.
- [24] M. Amin, B.A. Tayeh, I.S. Agwa, Effect of using mineral admixtures and ceramic wastes as coarse aggregates on properties of ultrahigh-performance concrete, *J. Clean. Prod.* 273 (2020), 123073.
- [25] B. Amiri, A. Bahari, A.S. Nik, A.S. Nik, N.S. Movahedi, Use of AFM technique to study the nano-silica effects in concrete mixture, *Indian J. Sci. Technol.* 5 (2) (2012) 2055–2059.
- [26] M.A. Mousavi, A. Sadeghi-Nik, A. Bahari, A. Ashour, K.H. Khayat, Cement paste modified by nano-montmorillonite and carbon nanotubes, *ACI Mater. J.* 119 (2022) 173–185.
- [27] I.Y. Hakeem, M. Amin, B.A. Abdelsalam, B.A. Tayeh, F. Althoey, I.S. Agwa, Effects of nano-silica and micro-steel fiber on the engineering properties of ultra-high performance concrete, *Struct. Eng. Mech.* 82 (3) (2022) 295–312.
- [28] T.A. Aiken, L. Gu, J. Kwasny, G.F. Huseien, D. McPolin, W. Sha, Acid resistance of alkali-activated binders: a review of performance, mechanisms of deterioration and testing procedures, *Constr. Build. Mater.* 342 (2022), 128057.
- [29] V.S. Athira, A. Bahurudeen, M. Saljas, K. Jayachandran, Influence of different curing methods on mechanical and durability properties of alkali activated binders, *Constr. Build. Mater.* 299 (2021), 123963.
- [30] M. Ibrahim, M. Maslehuddin, An overview of factors influencing the properties of alkali-activated binders, *J. Clean. Prod.* 286 (2021), 124972.
- [31] Y. Kou, H. Jiang, L. Ren, E. Yilmaz, Y. Li, Rheological properties of cemented paste backfill with alkali-activated slag, *Minerals* 10 (3) (2020) 288.
- [32] B.A. Salami, M. Ibrahim, H.A. Algaifi, W. Alimi, A.O. Ewebejo, A review on the durability performance of alkali-activated binders subjected to chloride-bearing environment, *Constr. Build. Mater.* 317 (2022), 125947.
- [33] J.S.J. van Deventer, J.L. Provis, P. Duxson, D.G. Brice, Chemical research and climate change as drivers in the commercial adoption of alkali activated materials, *Waste Biomass Valoriz.* 1 (1) (2010) 145–155.
- [34] V.D. Glukhovskiy, *Slag-alkali Concretes Produced from Fine-grained Aggregate*, Vishcha Shkolay, Kiev, 1981.
- [35] P. Duxson, J.L. Provis, Designing precursors for geopolymer cements, *J. Am. Ceram. Soc.* 91 (12) (2008) 3864–3869.
- [36] H.M. Khater, Studying the effect of thermal and acid exposure on alkali-activated slag geopolymer, *Adv. Cem. Res.* 26 (1) (2014) 1–9.
- [37] S.A. Bernal, R. Mejía de Gutiérrez, A.L. Pedraza, J.L. Provis, E.D. Rodriguez, S. Delvasto, Effect of binder content on the performance of alkali-activated slag concretes, *Cem. Concr. Res.* 41 (1) (2011) 1–8.
- [38] M. Chi, Y. Liu, R. Huang, Mechanical and microstructural characterization of alkali-activated materials based on fly ash and slag, *Int. J. Eng. Technol.* 7 (1) (2015) 59.
- [39] A.M. Rashad, Properties of alkali-activated fly ash concrete blended with slag, *Iran. J. Mater. Sci. Eng.* 10 (1) (2013) 57–64.
- [40] A. Adam, **Strength and durability properties of alkali activated slag and fly ash-based geopolymer concrete**, (2009).
- [41] S.A. Bernal, R. Mejía de Gutiérrez, J.L. Provis, Engineering and durability properties of concretes based on alkali-activated granulated blast furnace slag/metakaolin blends, *Constr. Build. Mater.* 33 (2012) 99–108.
- [42] A. Hawa, D. Tonnayopas, W. Prachasaree, P. Taneerananon, Investigating the effects of oil palm ash in metakaolin based geopolymer, *Ceram. -Silik* 57 (4) (2013) 319–327.
- [43] Y.Y. Kim, B.-J. Lee, V. Saraswathy, S.-J. Kwon, Strength and durability performance of alkali-activated rice husk ash geopolymer mortar, *Sci. World J.* 2014 (2014).
- [44] M.M. Hossain, M.R. Karim, M.K. Hossain, M.N. Islam, M.F.M. Zain, Durability of mortar and concrete containing alkali-activated binder with pozzolans: a review, *Constr. Build. Mater.* 93 (2015) 95–109.
- [45] M. Heikal, M.E.A. Zaki, S.M. Ibrahim, Preparation, physico-mechanical characteristics and durability of eco-alkali-activated binder from blast-furnace slag, cement kiln-by-pass dust and microsilica ternary system, *Constr. Build. Mater.* 260 (2020), 119947.
- [46] S. Al-Otaibi, Durability of concrete incorporating GGBS activated by water-glass, *Constr. Build. Mater.* 22 (10) (2008) 2059–2067.
- [47] M. Palacios, F. Puertas, Effect of carbonation on alkali-activated slag paste, *J. Am. Ceram. Soc.* 89 (10) (2006) 3211–3221.
- [48] A. Koenig, A. Herrmann, S. Overmann, F. Dehn, Resistance of alkali-activated binders to organic acid attack: Assessment of evaluation criteria and damage mechanisms, *Constr. Build. Mater.* 151 (2017) 405–413.
- [49] O. Smirnova, L. Kazanskaya, J. Koplík, H. Tan, X. Gu, Concrete based on clinker-free cement: selecting the functional unit for environmental assessment, *Sustainability* 13 (1) (2021).
- [50] J.M. Miranda, A. Fernández-Jiménez, J.A. González, A. Palomo, Corrosion resistance in activated fly ash mortars, *Cem. Concr. Res.* 35 (6) (2005) 1210–1217.
- [51] S.E. Wallah, Drying shrinkage of heat-cured fly ash-based geopolymer concrete, *Mod. Appl. Sci.* 3 (12) (2009) 14–21.
- [52] S. Thokchom, P. Ghosh, S. Ghosh, Acid resistance of fly ash based geopolymer mortars, *Int. J. Recent Trends Eng.* 1 (6) (2009) 36.
- [53] A. Allahverdi, B. Shaverdi, K.E. Najafi, **Influence of sodium oxide on properties of fresh and hardened paste of alkali-activated blast-furnace slag**, (2010).
- [54] S.A. Bernal, R.M. de Gutierrez, J.L. Provis, V. Rose, Effect of silicate modulus and metakaolin incorporation on the carbonation of alkali silicate-activated slags, *Cem. Concr. Res.* 40 (6) (2010) 898–907.
- [55] J. Wongpa, K. Kiattikomol, C. Jaturapitakul, P. Chindaprasit, Compressive strength, modulus of elasticity, and water permeability of inorganic polymer concrete, *Mater. Des.* 31 (10) (2010) 4748–4754.
- [56] H.A. El-Sayed, E.-E.S.A. Abo, H.M. Khater, S.A. Hasanein, Resistance of alkali activated water-cooled slag geopolymer to sulphate attack, *Ceram. -Silikaty* 55 (2) (2011) 153–160.
- [57] W.A. Chaparro, J.H.B. Ruiz, R.D.J.T. Gómez, Corrosion of reinforcing bars embedded in alkali-activated slag concrete subjected to chloride attack, *Mater. Res.* 15 (2012) 57–62.



- [58] A.M.M. Al Bakri, H. Kamarudin, M. Bhusain, I.K. Nizar, A.R. Rafiza, Y. Zarina, The processing, characterization, and properties of fly ash based geopolymer concrete, *Rev. Adv. Mater. Sci.* 30 (1) (2012) 90–97.
- [59] S.A. Bernal, J.L. Provis, B. Walkley, R. San Nicolas, J.D. Gehman, D.G. Brice, A.R. Kilcullen, P. Duxson, J.S.J. van Deventer, Gel nanostructure in alkali-activated binders based on slag and fly ash, and effects of accelerated carbonation, *Cem. Concr. Res.* 53 (2013) 127–144.
- [60] U.S. Beemamol, A. Nizad, M. Nazeer, Investigations on cement mortar using ceramic tailing sand as fine aggregate, *Am. J. Eng. Res.* 3 (2013) 28–33.
- [61] F.U.A. Shaikh, Effects of alkali solutions on corrosion durability of geopolymer concrete, *Adv. Concr. Constr.* 2 (2) (2014) 109.
- [62] M.R. Karim, M.M. Hossain, M.N.N. Khan, M.F.M. Zain, M. Jamil, F.C. Lai, On the utilization of pozzolanic wastes as an alternative resource of cement, *Materials* 7 (12) (2014) 7809–7827.
- [63] M.H. Samarakoon, P.G. Ranjith, T.D. Rathnaweera, M.S.A. Perera, Recent advances in alkaline cement binders: A review, *J. Clean. Prod.* 227 (2019) 70–87.
- [64] C. Li, H. Sun, L. Li, A review: The comparison between alkali-activated slag (Si+Ca) and metakaolin (Si+Al) cements, *Cem. Concr. Res.* 40 (9) (2010) 1341–1349.
- [65] F. Pacheco-Torgal, J. Castro-Gomes, S. Jalali, Alkali-activated binders: a review: Part 1. Historical background, terminology, reaction mechanisms and hydration products, *Constr. Build. Mater.* 22 (7) (2008) 1305–1314.
- [66] K. Ghosh, P. Ghosh, Effect of  $\text{Na}_2\text{O}$  and  $\text{SiO}_2$  on apparent porosity and sorptivity of fly ash based geopolymer, *IOSR J. Eng.* 2 (2012) 96–101.
- [67] R. Xiao, Y. Ma, X. Jiang, M. Zhang, Y. Zhang, Y. Wang, B. Huang, Q. He, Strength, microstructure, efflorescence behavior and environmental impacts of waste glass geopolymers cured at ambient temperature, *J. Clean. Prod.* 252 (2020), 119610.
- [68] G.F. Huseien, A.R.M. Sam, K.W. Shah, J. Mirza, M.M. Tahir, Evaluation of alkali-activated mortars containing high volume waste ceramic powder and fly ash replacing GBFS, *Constr. Build. Mater.* 210 (2019) 78–92.
- [69] F.N. Okoye, J. Durgaprasad, N.B. Singh, Effect of silica fume on the mechanical properties of fly ash based-geopolymer concrete, *Ceram. Int.* 42 (2) (2016) 3000–3006.
- [70] P. Pavithra, M. Srinivasula Reddy, P. Dinakar, B. Hanumantha Rao, B.K. Satpathy, A.N. Mohanty, A mix design procedure for geopolymer concrete with fly ash, *J. Clean. Prod.* 133 (2016) 117–125.
- [71] L. Assi, S. Ghahari, E. Deaver, D. Leaphart, P. Ziehl, Improvement of the early and final compressive strength of fly ash-based geopolymer concrete at ambient conditions, *Constr. Build. Mater.* 123 (2016) 806–813.
- [72] D.L.Y. Kong, J.G. Sanjayan, Effect of elevated temperatures on geopolymer paste, mortar and concrete, *Cem. Concr. Res.* 40 (2) (2010) 334–339.
- [73] D. Adak, M. Sarkar, S. Mandal, Structural performance of nano-silica modified fly-ash based geopolymer concrete, *Constr. Build. Mater.* 135 (2017) 430–439.
- [74] P. Duan, C. Yan, W. Luo, W. Zhou, Effects of adding nano-TiO<sub>2</sub> on compressive strength, drying shrinkage, carbonation and microstructure of fluidized bed fly ash based geopolymer paste, *Constr. Build. Mater.* 106 (2016) 115–125.
- [75] N. Ranjbar, M. Mehrabi, U.J. Alengaram, H.S.C. Metselaar, M.Z. Jumaat, Compressive strength and microstructural analysis of fly ash/palm oil fuel ash based geopolymer mortar under elevated temperatures, *Constr. Build. Mater.* 65 (2014) 114–121.
- [76] M.Y.J. Liu, U.J. Alengaram, M. Santhanam, M.Z. Jumaat, K.H. Mo, Microstructural investigations of palm oil fuel ash and fly ash based binders in lightweight aggregate foamed geopolymer concrete, *Constr. Build. Mater.* 120 (2016) 112–122.
- [77] G. Xu, X. Shi, Exploratory investigation into a chemically activated fly ash binder for mortars, *J. Mater. Civ. Eng.* 29 (11) (2017), 06017018.
- [78] N. Xie, X. Shi, Y. Dang, A. Pace, Upcycling of waste materials: green binder prepared with pure coal fly ash, *J. Mater. Civ. Eng.* 10 (2016).
- [79] H.N. Yoon, S.M. Park, H.K. Lee, Effect of MgO on chloride penetration resistance of alkali-activated binder, *Constr. Build. Mater.* 178 (2018) 584–592.
- [80] M.A. Salihi, N. Farzadnia, A.A. Abang Ali, R. Demirboga, Development of high strength alkali activated binder using palm oil fuel ash and GGBS at ambient temperature, *Constr. Build. Mater.* 93 (2015) 289–300.
- [81] E. Najafi Kani, A. Allahverdi, J.L. Provis, Calorimetric study of geopolymer binders based on natural pozzolan, *J. Therm. Anal. Calorim.* 127 (3) (2017) 2181–2190.
- [82] P.H.R. Borges, N. Banthia, H.A. Alcamand, W.L. Vasconcelos, E.H.M. Nunes, Performance of blended metakaolin/blastfurnace slag alkali-activated mortars, *Cem. Concr. Compos.* 71 (2016) 42–52.
- [83] N. Marjanović, M. Komljenović, Z. Bašćević, V. Nikolić, R. Petrović, Physical–mechanical and microstructural properties of alkali-activated fly ash–blast furnace slag blends, *Ceram. Int.* 41 (1) (2015) 1421–1435.
- [84] D.M.A. Huiskes, A. Keulen, Q.L. Yu, H.J.H. Brouwers, Design and performance evaluation of ultra-lightweight geopolymer concrete, *Mater. Des.* 89 (2016) 516–526.
- [85] A. Mehta, R. Siddique, Sustainable geopolymer concrete using ground granulated blast furnace slag and rice husk ash: Strength and permeability properties, *J. Clean. Prod.* 205 (2018) 49–57.
- [86] M.R. Karim, M.F.M. Zain, M. Jamil, F.C. Lai, Fabrication of a non-cement binder using slag, palm oil fuel ash and rice husk ash with sodium hydroxide, *Constr. Build. Mater.* 49 (2013) 894–902.
- [87] A. Kusbiatoro, M.F. Nuruddin, N. Shafiq, S.A. Qazi, The effect of microwave incinerated rice husk ash on the compressive and bond strength of fly ash based geopolymer concrete, *Constr. Build. Mater.* 36 (2012) 695–703.
- [88] A. Sharmin, U.J. Alengaram, M.Z. Jumaat, M.O. Yusuf, S.M.A. Kabir, I.I. Bashar, Influence of source materials and the role of oxide composition on the performance of ternary blended sustainable geopolymer mortar, *Constr. Build. Mater.* 144 (2017) 608–623.
- [89] E. Nimwinya, W. Arjhaan, S. Horpibulsuk, T. Phoo-ngernkham, A. Poowancum, A sustainable calcined water treatment sludge and rice husk ash geopolymer, *J. Clean. Prod.* 119 (2016) 128–134.
- [90] N. Nadzir, I. Ismail, S. Hamdan, Binding gel characterization of alkali-activated binders based on palm oil fuel ash (POFA) and fly ash, *J. Sustain. Cem. -Based Mater.* 7 (1) (2018) 1–14.
- [91] H. Alanazi, J. Hu, Y.-R. Kim, Effect of slag, silica fume, and metakaolin on properties and performance of alkali-activated fly ash cured at ambient temperature, *Constr. Build. Mater.* 197 (2019) 747–756.
- [92] S. Jena, R. Panigrahi, P. Sahu, Effect of silica fume on the properties of fly ash geopolymer concrete, *Sustainable, Constr. Build. Mater.* (2019) 145–153.
- [93] B. Yan, P. Duan, D. Ren, Mechanical strength, surface abrasion resistance and microstructure of fly ash-metakaolin-sepiolite geopolymer composites, *Ceram. Int.* 43 (1) (2017) 1052–1060.
- [94] T. Kovářik, D. Rieger, J. Kadlec, T. Krěnek, L. Kullová, M. Pola, P. Bělský, P. Franče, J. Říha, Thermomechanical properties of particle-reinforced geopolymer composite with various aggregate gradation of fine ceramic filler, *Constr. Build. Mater.* 143 (2017) 599–606.
- [95] K. Wianglor, S. Sinthupinyo, M. Piyaworapaiboon, A. Chaipanich, Effect of alkali-activated metakaolin cement on compressive strength of mortars, *Appl. Clay Sci.* 141 (2017) 272–279.
- [96] R.A. Antunes Boca Santa, C. Soares, H.G. Riella, Geopolymers obtained from bottom ash as source of aluminosilicate cured at room temperature, *Constr. Build. Mater.* 157 (2017) 459–466.
- [97] T. Tho-In, V. Sata, K. Boonserm, P. Chindaprasirt, Compressive strength and microstructure analysis of geopolymer paste using waste glass powder and fly ash, *J. Clean. Prod.* 172 (2018) 2892–2898.
- [98] G.F. Huseien, A.R.M. Sam, K.W. Shah, M.A. Asaad, M.M. Tahir, J. Mirza, Properties of ceramic tile waste based alkali-activated mortars incorporating GBFS and fly ash, *Constr. Build. Mater.* 214 (2019) 355–368.
- [99] M.M.A. Elahi, M.M. Hossain, M.R. Karim, M.F.M. Zain, C. Shearer, A review on alkali-activated binders: materials composition and fresh properties of concrete, *Constr. Build. Mater.* 260 (2020), 119788.
- [100] S. Zeng, J. Wang, Characterization of mechanical and electric properties of geopolymers synthesized using four locally available fly ashes, *Constr. Build. Mater.* 121 (2016) 386–399.
- [101] T. Xie, T. Ozbakkaloglu, Behavior of low-calcium fly and bottom ash-based geopolymer concrete cured at ambient temperature, *Ceram. Int.* 41 (4) (2015) 5945–5958.

- [102] H.M. Hamada, F.M. Yahaya, K. Muthusamy, G.A. Jekhio, A.M. Humada, Fresh and hardened properties of palm oil clinker lightweight aggregate concrete incorporating Nano-palm oil fuel ash, *Constr. Build. Mater.* 214 (2019) 344–354.
- [103] J. Rouyer, A. Poulesquen, Evidence of a fractal percolating network during geopolymerization, *J. Am. Ceram. Soc.* 98 (5) (2015) 1580–1587.
- [104] S. Jumrat, B. Chatveera, P. Rattanadecho, Dielectric properties and temperature profile of fly ash-based geopolymer mortar, *Int. Commun. Heat Mass Transf.* 38 (2) (2011) 242–248.
- [105] S. Musaddiq Laskar, S. Talukdar, Development of ultrafine slag-based geopolymer mortar for use as repairing mortar, *J. Mater. Civ. Eng.* 29 (5) (2017), 04016292.
- [106] S. Saloma, H. Hanafiah, A. Saggaff, A. Mawarni, Geopolymer mortar with fly ash, *EDP Sci.* (2016) 1–6.
- [107] C. Shi, B. Qu, J.L. Provis, Recent progress in low-carbon binders, *Cem. Concr. Res.* 122 (2019) 227–250.
- [108] N. Li, C. Shi, Z. Zhang, A study on the setting characteristics of alkali-activated slag cement, 2017, p. 65.
- [109] N. Li, Z. Zhang, C. Shi, J. Zhang, Some Progresses in the Challenges for Geopolymer, IOP Publishing, 2018, 022003.
- [110] M.H. Al-Majidi, A. Lampropoulos, A. Cundy, S. Meikle, Development of geopolymer mortar under ambient temperature for in situ applications, *Constr. Build. Mater.* 120 (2016) 198–211.
- [111] P. Nath, P.K. Sarker, Effect of GGBFS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition, *Constr. Build. Mater.* 66 (2014) 163–171.
- [112] P.S. Deb, P. Nath, P.K. Sarker, The effects of ground granulated blast-furnace slag blending with fly ash and activator content on the workability and strength properties of geopolymer concrete cured at ambient temperature, *Mater. Des.* 62 (1980–2015) (2014) 32–39.
- [113] G. Fang, W.K. Ho, W. Tu, M. Zhang, Workability and mechanical properties of alkali-activated fly ash-slag concrete cured at ambient temperature, *Constr. Build. Mater.* 172 (2018) 476–487.
- [114] S. Kumar, R. Kumar, S.P. Mehrotra, Influence of granulated blast furnace slag on the reaction, structure and properties of fly ash based geopolymer, *J. Mater. Sci.* 45 (3) (2010) 607–615.
- [115] M. Nedeljković, Z. Li, G. Ye, Setting, strength, and autogenous shrinkage of alkali-activated fly ash and slag pastes: effect of slag content, *Materials* 11 (11) (2018) 2121.
- [116] G.F. Huseien, J. Mirza, M. Ismail, S.K. Ghoshal, M.A.M. Ariffin, Effect of metakaolin replaced granulated blast furnace slag on fresh and early strength properties of geopolymer mortar, *Ain Shams Eng. J.* 9 (4) (2018) 1557–1566.
- [117] E. Badogiannis, G. Kakali, G. Dimopoulou, E. Chaniotakis, S. Tsilivilis, Metakaolin as a main cement constituent. Exploitation of poor Greek kaolins, *Cem. Concr. Compos.* 27 (2) (2005) 197–203.
- [118] G. Görhan, R. Aslaner, O. Şinik, The effect of curing on the properties of metakaolin and fly ash-based geopolymer paste, *Compos. Part B: Eng.* 97 (2016) 329–335.
- [119] P. Chindaprasirt, P. De Silva, K. Sagoe-Crentsil, S. Hanjitsuwan, Effect of SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> on the setting and hardening of high calcium fly ash-based geopolymer systems, *J. Mater. Sci.* 47 (12) (2012) 4876–4883.
- [120] P.S. Deb, P.K. Sarker, Effects of ultrafine fly ash on setting, strength, and porosity of geopolymers cured at room temperature, *J. Mater. Civ. Eng.* 29 (2) (2017), 06016021.
- [121] D. Adak, M. Sarkar, S. Mandal, Effect of nano-silica on strength and durability of fly ash based geopolymer mortar, *Constr. Build. Mater.* 70 (2014) 453–459.
- [122] H.Y. Zhang, V. Kodur, B. Wu, L. Cao, F. Wang, Thermal behavior and mechanical properties of geopolymer mortar after exposure to elevated temperatures, *Constr. Build. Mater.* 109 (2016) 17–24.
- [123] P. Nath, P.K. Sarker, Use of OPC to improve setting and early strength properties of low calcium fly ash geopolymer concrete cured at room temperature, *Cem. Concr. Compos.* 55 (2015) 205–214.
- [124] S. Pangdaeng, T. Phoo-ngernkham, V. Sata, P. Chindaprasirt, Influence of curing conditions on properties of high calcium fly ash geopolymer containing Portland cement as additive, *Mater. Des.* 53 (2014) 269–274.
- [125] J.-X. Lu, C.S. Poon, Use of waste glass in alkali activated cement mortar, *Constr. Build. Mater.* 160 (2018) 399–407.
- [126] B. Nematollahi, J. Sanjayan, Effect of different superplasticizers and activator combinations on workability and strength of fly ash based geopolymer, *Mater. Des.* 57 (2014) 667–672.
- [127] G.F. Huseien, J. Mirza, M. Ismail, M.W. Hussin, Influence of different curing temperatures and alkali activators on properties of GBFS geopolymer mortars containing fly ash and palm-oil fuel ash, *Constr. Build. Mater.* 125 (2016) 1229–1240.
- [128] O.M. Smirnova, I. Menendez Pidal, A.V. Alekseev, D.N. Petrov, M.G. Popov, Strain hardening of polypropylene microfiber reinforced composite based on alkali-activated slag matrix, *Materials* 15 (4) (2022) 1607.
- [129] L.F. Kazanskaya, O.M. Smirnova, Technological Approaches to Increase the Quality of Lightweight Concrete based on Hybrid Binders, IOP Publishing, 2019, 012038.
- [130] J. Xie, J. Wang, R. Rao, C. Wang, C. Fang, Effects of combined usage of GGBS and fly ash on workability and mechanical properties of alkali activated geopolymer concrete with recycled aggregate, *Compos. Part B: Eng.* 164 (2019) 179–190.
- [131] C.-C. Hung, J.-J. Chang, The influence of mixture variables for the alkali-activated slag concrete on the properties of concrete, *J. Mar. Sci. Technol.* 21 (3) (2013) 1.
- [132] S.M. Laskar, S. Talukdar, Preparation and tests for workability, compressive and bond strength of ultra-fine slag based geopolymer as concrete repairing agent, *Constr. Build. Mater.* 154 (2017) 176–190.
- [133] P. Chindaprasirt, T. Chareerat, V. Sirivivatnanon, Workability and strength of coarse high calcium fly ash geopolymer, *Cem. Concr. Compos.* 29 (3) (2007) 224–229.
- [134] R. Siddique, M.I. Khan, *Supplementary Cementing Materials*, Springer Science & Business Media, 2011.
- [135] Y. Ding, J.-G. Dai, C.-J. Shi, Mechanical properties of alkali-activated concrete: a state-of-the-art review, *Constr. Build. Mater.* 127 (2016) 68–79.
- [136] X.C. Pu, C.C. Gan, S.D. Wang, C.H. Yang, Summary reports of research on alkali-activated slag cement and concrete, *Chongqing Institute of Architecture and Engineering Chongqing*, 1, 6, 1988.
- [137] M.M.C. Nasvi, R.P. Gamage, S. Jay, Geopolymer as well cement and the variation of its mechanical behavior with curing temperature, *Greenh. Gases: Sci. Technol.* 2 (1) (2012) 46–58.
- [138] C.D. Atiş, E.B. Görür, O. Karahan, C. Bilim, S. İlkenntapar, E. Luga, Very high strength (120MPa) class F fly ash geopolymer mortar activated at different NaOH amount, heat curing temperature and heat curing duration, *Constr. Build. Mater.* 96 (2015) 673–678.
- [139] K. Somna, C. Jaturapitakkul, P. Kajitvichyanukul, P. Chindaprasirt, NaOH-activated ground fly ash geopolymer cured at ambient temperature, *Fuel* 90 (6) (2011) 2118–2124.
- [140] J. Temuujin, R.P. Williams, A. van Riessen, Effect of mechanical activation of fly ash on the properties of geopolymer cured at ambient temperature, *J. Mater. Process. Technol.* 209 (12) (2009) 5276–5280.
- [141] X. Jiao, Y. Zhang, T. Chen, Thermal stability of a silica-rich vanadium tailing based geopolymer, *Constr. Build. Mater.* 38 (2013) 43–47.
- [142] J.M. Mejía, E. Rodríguez, R. Mejía de Gutiérrez, N. Gallego, Preparation and characterization of a hybrid alkaline binder based on a fly ash with no commercial value, *J. Clean. Prod.* 104 (2015) 346–352.
- [143] S.Kumar Das, A. Adediran, C. Rodrigue Kaze, S. Mohammed Mustakim, N. Leclou, Production, characteristics, and utilization of rice husk ash in alkali activated materials: an overview of fresh and hardened state properties, *Constr. Build. Mater.* 345 (2022), 128341.
- [144] M. Thomas, R.D. Hooton, C. Rogers, B. Fournier, 50 years old and still going strong, *Concr. Int.* 34 (1) (2012).
- [145] S.A. Bernal, J.L. Provis, V. Rose, R. Mejía de Gutiérrez, Evolution of binder structure in sodium silicate-activated slag-metakaolin blends, *Cem. Concr. Compos.* 33 (1) (2011) 46–54.
- [146] M.N. Qureshi, S. Ghosh, Alkali-activated blast furnace slag as a green construction material, *J. Mech. Civ. Eng.* 2 (1) (2013) 24–28.

- [147] L.V. Zhang, A.R. Suleiman, M. Mehdizadeh Allaf, A. Marani, M. Tuyan, M.L. Nehdi, Crack self-healing in alkali-activated slag composites incorporating immobilized bacteria, *Constr. Build. Mater.* 326 (2022), 126842.
- [148] J.L. Provis, R.J. Myers, C.E. White, V. Rose, J.S.J. van Deventer, X-ray microtomography shows pore structure and tortuosity in alkali-activated binders, *Cem. Concr. Res.* 42 (6) (2012) 855–864.
- [149] R. Tanzer, Dependency of the physical properties of alkali-activated granulated blast furnace slag on the nature of the alkaline activator, pp. 353–358.
- [150] H.N. Atahan, D. Dikme, Use of mineral admixtures for enhanced resistance against sulfate attack, *Constr. Build. Mater.* 25 (8) (2011) 3450–3457.
- [151] D. Bondar, Alkali activation of Iranian natural pozzolans for producing geopolymer cement and concrete, (2009).
- [152] M. Malviya, H.S. Goliya, Durability of fly ash based geopolymer concrete using alkaline solutions (NaOH and Na<sub>2</sub>SiO<sub>3</sub>), *Int. J. Emerg. Trends Eng. Dev.* 6 (4) (2014) 18–33.
- [153] T. Bakharev, Durability of geopolymer materials in sodium and magnesium sulfate solutions, *Cem. Concr. Res.* 35 (6) (2005) 1233–1246.
- [154] C. Shi, D. Roy, P. Krivenko, *Alkali-activated Cements and Concretes*, CRC Press, 2003.
- [155] B.V. Rangan, Fly ash-based geopolymer concrete, (2008).
- [156] G. Roa-Rodriguez, W. Aperador, A. Delgado, Resistance to chlorides of the alkali-activated slag concrete, *Int. J. Electrochem. Sci.* 9 (1) (2014) 282–291.
- [157] C. Shi, Another Look at the Rapid Chloride Permeability Test (ASTM C1202 or ASSHTO T277), FHWA Resource Center, Baltimore, 2003.
- [158] C. Shi, Effect of mixing proportions of concrete on its electrical conductivity and the rapid chloride permeability test (ASTM C1202 or ASSHTO T277) results, *Cem. Concr. Res.* 34 (3) (2004) 537–545.
- [159] F. Puertas, M. Palacios, T. Vázquez, Carbonation process of alkali-activated slag mortars, *J. Mater. Sci.* 41 (10) (2006) 3071–3082.
- [160] R. Wassermann, A. Katz, A. Bentur, Minimum cement content requirements: a must or a myth? *Mater. Struct.* 42 (7) (2009) 973–982.
- [161] A. Steffens, D. Dinkler, H. Ahrens, Modeling carbonation for corrosion risk prediction of concrete structures, *Cem. Concr. Res.* 32 (6) (2002) 935–941.
- [162] D.M. Bastidas, A. Fernández-Jiménez, A. Palomo, J.A. González, A study on the passive state stability of steel embedded in activated fly ash mortars, *Corros. Sci.* 50 (4) (2008) 1058–1065.
- [163] M. Olivia, H. Nikraz, Corrosion performance of embedded steel in fly ash geopolymer concrete by impressed voltage method, (2011).
- [164] D.V. Reddy, J.B. Edouard, K. Sobhan, S.S. Rajpathak, Durability of reinforced fly ash-based geopolymer concrete in the marine environment, 2011.
- [165] K. Kupwade-Patil, E.N. Allouche, Examination of chloride-induced corrosion in reinforced geopolymer concretes, *J. Mater. Civ. Eng.* 25 (10) (2013) 1465–1476.
- [166] H. Fansuri, D. Prasetyoko, Z. Zhang, D. Zhang, The effect of sodium silicate and sodium hydroxide on the strength of aggregates made from coal fly ash using the geopolymerisation method, *Asia-Pacific J. Chem. Eng.* 7 (1) (2012) 73–79.
- [167] W. Aperador, R. Mejía de Gutiérrez, D.M. Bastidas, Steel corrosion behaviour in carbonated alkali-activated slag concrete, *Corros. Sci.* 51 (9) (2009) 2027–2033.
- [168] R.R. Lloyd, J.L. Provis, J.S.J. van Deventer, Pore solution composition and alkali diffusion in inorganic polymer cement, *Cem. Concr. Res.* 40 (9) (2010) 1386–1392.
- [169] W. Shen, Y. Wang, T. Zhang, M. Zhou, J. Li, X. Cui, Magnesia modification of alkali-activated slag fly ash cement, *J. Wuhan Univ. Technol. -Mater. Sci. Ed.* 26 (1) (2011) 121–125.
- [170] B. Rangan, S. Wallah, D. Sumajouw, D. Hardjito, Heat-cured, low-calcium, fly ash-based geopolymer concrete, *Indian Concr. J.* 80 (2006) 47–52.
- [171] S. Wallah, B.V. Rangan, Low-calcium fly ash-based geopolymer concrete: long-term properties, (2006).
- [172] A.P. Ana, M. Fernandez-Jimenez, L.-H. Cecilio, Engineering properties of alkali-activated fly ash concrete, *Acids Mater. J.* 103 (2) (2006).
- [173] C.P. Cartwright, Shrinkage characteristics of alkali-activated slag cements, (2014).
- [174] C.P. Cartwright, F. Rajabipour, A. Radlińska, Measuring the chemical shrinkage of alkali-activated slag cements using the buoyancy method, *Mech. Phys. Creep Shrinkage Durab. Concr.* (2013) 308–315.
- [175] M.-C. Chi, J.-J. Chang, R. Huang, Strength and drying shrinkage of alkali-activated slag paste and mortar, *Adv. Civ. Eng.* 2012 (2012).
- [176] A.A. Melo Neto, M.A. Cincotto, W. Repette, Drying and autogenous shrinkage of pastes and mortars with activated slag cement, *Cem. Concr. Res.* 38 (4) (2008) 565–574.
- [177] F. Collins, J.G. Sanjayan, Effect of pore size distribution on drying shrinking of alkali-activated slag concrete, *Cem. Concr. Res.* 30 (9) (2000) 1401–1406.
- [178] I.B. Topcu, M. Canbaz, Microstructural analysis of alkali-activated slag mortars under acid attack, 2015.
- [179] T. Bakharev, J.G. Sanjayan, Y.B. Cheng, Resistance of alkali-activated slag concrete to acid attack, *Cem. Concr. Res.* 33 (10) (2003) 1607–1611.
- [180] J.J. Chang, W. Yeih, C.C. Hung, Effects of gypsum and phosphoric acid on the properties of sodium silicate-based alkali-activated slag pastes, *Cem. Concr. Compos.* 27 (1) (2005) 85–91.
- [181] A.M. Rashad, S.R. Zeedan, The effect of activator concentration on the residual strength of alkali-activated fly ash pastes subjected to thermal load, *Constr. Build. Mater.* 25 (7) (2011) 3098–3107.
- [182] O.A. Abdulkareem, M.M. Al Bakri, Abdullah H. Kamarudin, I. Khairul Nizar, Alteration in the microstructure of fly ash geopolymers upon exposure to elevated temperatures *Trans. Tech. Publ.*, 2013, pp. 201–205.
- [183] S. Thokchom, P. Ghosh, S. Ghosh, Effect of water absorption, porosity and sorptivity on durability of geopolymer mortars, *ARPN J. Eng. Appl. Sci.* 4 (7) (2009) 28–32.