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Corresponding address: 29 Polytechnicheskaya st., Saint Petersburg, 195251, Russia

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Contacts:
E-mail: mce@spbstu.ru
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Influence of NaOH-concentration and blast-furnace-slag on the properties of geopolymer mortars

T.V. Lam[1] , ***K.D. Vu***[2]

[1] Hanoi University of Mining and Geology, Bac Tu Liem, Ha Noi, Vietnam

[2] Moscow State University of Civil Engineering (National Research University), Moscow, Russia

lamvantang@gmail.com

Keywords: NaOH-concentration, granulated blast, workability, compressive strength, geopolymer mortars

Abstract. The paper focused of the production of geopolymer materials using solid wastes, including fly ash, bottom ash (BA), granulated blast furnace slag (GBFS) in thermal power plants, and granulated blast furnace slag. Using the BA and GBFS as source material for geopolymer mortar is cost-effective, it allows safe disposal of the postproduction industrial wastes and improves properties of mortar for green buildings approach and development. In the present investigation, BA and GBFS were used as alumino-silicate materials for making alkali-activated bottom ash mortar (GPM). The effects of NaOH content in the sodium hydroxide solution with the concentration of 10–16 M and the presence of granulated blast furnace slag content (0–60 %) on the workability and the compressive strength development of alkali-activated bottom ash mortar were studied. The absolute volume method combined with the experimental results was used to determine the compositions of GPM specimens. Furthermore, the compressive strength of the mortar samples was performed following ASTM C109 and Vietnamese Standard TCVN 6016:2011. The results revealed that both NaOH concentration and granulated blast furnace slag content greatly affected the workability of mixtures and compressive strength development of the tested samples. Moreover, the relationship between the 28-day compressive strength and a water-to-geopolymer solid ratio of GPM specimens is also determined in this work.

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1. Introduction

Ordinary Portland cement (OPC) clinker is made by heating a mixture of raw materials, including limestone and clay, to a calcining temperature exceeding 600 °C and then a fusion temperature of about 1450–1600 °C to sinter the materials into clinker, according to the following formula:

$$\begin{aligned}&12\mathrm{CaCO_3}+2\mathrm{SiO_2}+2\mathrm{Al_2O_3}+\mathrm{Fe_2O_3}\rightarrow 3\mathrm{CaO.SiO_2}\left(\mathrm{C_3S}\right)+2\mathrm{CaO.SiO_2}\left(\mathrm{C_2S}\right)+\\&+3\mathrm{CaO.Al_2O_3}\left(\mathrm{C_3A}\right)+4\mathrm{CaO.Al_2O_3.Fe_2O_3}\left(\mathrm{C_4AF}\right)+12\mathrm{CO_2}.\end{aligned}$$

Ordinary Portland/pozzolanic cement manufacturing is an energy-intensive process and releases significant quantities of toxic fumes and carbon dioxide into the atmosphere [1–3].

In recent years, many investigations have been focusing on the potential of utilizing natural materials, like fly ash, bottom ash, slag, granulated blast furnace slag. Such materials can be considered an alternative for PC to reduce the cement content in the concrete mixture and improve the development of modern cementitious materials in construction materials manufacturing. In 1978, Davidovits [4, 5] proposed that a new binder could be produced by a polymerization process involving a reaction between alkali-liquid solutions and compounds containing aluminum and silicon. These binders were termed "geopolymers." The geopolymer, including alumino-silicate material with alkaline liquids, is currently one of the most promising materials of environmentally-friendly binders for green concrete in the construction industry [6, 7].

Material types containing silicon (Si) and aluminum (Al) atoms in amorphous form, which come from natural mineral additions or by-product materials, and industrial wastes, could be used as source materials for alkali-activated bottom ash mortar (GPM) and geopolymer concrete. On the other hand, some pozzolanic materials are by-products such as metakaolin, fly ash, bottom ash (BA), granulated blast furnace slag (GBFS), and palm oil fuel ash, etc. [8–12]. For the manufacture of geopolymer products, the choice of raw materials depends mainly on their availability and cost, the type of application, and the specific demand of the producers [13–15].

In the synthesis of geopolymer materials, the granulated blast furnace slag and bottom ash provide excellent geopolymer mortar and concrete properties in both the fresh and hardened state. These made them suitable materials for structural applications in green buildings and replacing cement [16–18].

For the geopolymer concrete and mortar, the type of alkali liquid played an important role in the polymerization process as a concrete binder. The alkali-activator solutions (AAS) of NaOH and Na_2SiO_3 or KOH and K_2SiO_3 with different concentrations are the most common alkali-liquid solutions used in geopolymerisation [19–21]. The published studies [22–25] showed that the engineering properties of concrete/mortar increases when water glass (Na_2SiO_3) is added to the sodium hydroxide, compared with using only NaOH. Further, the addition of waterglass increases the ratios of Si/Al and Na/Al, resulting in increased formation of sodium aluminosilicate gel (Na_2O-Al_2O_3-SiO_2-H_2O) which indicates higher strength behavior tested samples.

The bottom ash and granulated blast furnace slag are major by-products of thermal and steel plants. These materials often cause disposal challenges and environmental pollution. Industrial waste materials, in particular BA obtained from the combustion process in thermal power plants (TPP), were used widely as a mineral additive for concrete/mortar due to their pozzolanic properties. At present, over a million tons of BA TPP are generated each year globally [26–28]. The class-F BA TPP, containing highly amorphous SiO_2 and Al_2O_3, was used as a raw material to produce geopolymer concrete and mortar.

Moreover, granulated blast furnace slag-GBFS is one of the by-products generated during the extraction of iron from iron ore that contains a high silica content in the form of non-crystalline or amorphous silica – SiO_2. To make such a by-product be used more sustainably, in-depth knowledge of the engineering and environmental properties of GBFS is required. This material is considered reactive with the alkali-activator solution to produce the aluminosilicate gel that binds the aggregate types and provides the mechanical properties of GPM [18, 29, 30].

In Vietnam in recent years, granulated blast furnace slag (GBFS), a solid waste, is a by-product of pig iron production in blast furnaces of Hoa Phat Group in Hai Duong Iron and Steel Complex.

Because both Vietnamese GBFS and BA TPP "Vung Ang" contain high levels of Si and Al, these alumino-silicate materials are effective for producing GPM and geopolymer concrete. Furthermore, the AAS plays an important role in the dissolving process of Si-Al from amorphous silica-alumina to form gel geopolymer precursors and alumino-silicate materials. In addition, NaOH concentration significantly affects the workability of mixtures and the compressive strength of the tested GPM specimens. Therefore, the main aim of the current research is to investigate the effect of the influence of NaOH concentration and granulated blast furnace slag content on workability and compressive strength development of BA alkali-activated mortar.

2. Materials and Methods

2.1. Material properties

The characteristics of the raw materials used in this study were determined in the laboratory according to the guidelines of the related standards, with the results as follows:

a) No coarse aggregates were used in geopolymer mortars preparation. The fine aggregates used for geopolymer mortar mixtures were Red River quartz sands (QS) (Vietnam), which conformed to the

Vietnamese Standard TCVN 7570:2006. The fineness modulus of QS was M_k = 3.0, and its specific gravity was 2.65 g/cm^3.

b) Alumino-silicate materials (ASM) used in the study included granulated blast furnace slag "Hòa Phat" (GBFS) and bottom ash (BA) from TPP "Vung Ang" class-F.

The experimental results of chemical compositions and physical properties of GBFS and BA TPP "Vung Ang", determined by X-ray fluorescence analysis of raw materials, are given in Table 1. The BA TPP "Vung Ang" was composed mainly of SiO_2 (54.62 %) and Al_2O_3 (25.17 %) and that the main constituent of GBFS was SiO_2 (36.3 %) and CaO (40.1 %).

Table 1. Physical properties and chemical compositions of BA TPP "Vung Ang" and GBFS "Hoa Phat".

Materials		**BA**	**GBFS**
Physical properties	Specific gravity (g/cm^3)	2.35	2.92
	The volume of natural porous state (kg/m^3)	765	1650
	Specific surface area (m^2/g)	0.755	0.960
	Mean particle size (mm)	17.6	10.5
	Water requirement (%)	100.7	124.1
Average chemical composition (%)	SiO_2	54.2	36.3
	Al_2O_3	23.3	12.6
	Fe_2O_3	9.8	3.4
	SO_3	2.5	5.7
	K_2O	1.4	0.4
	Na_2O	1.1	0.3
	MgO	0.6	–
	CaO	1.2	40.1
	P_2O_5	1.4	–
	Loss on ignition	4.5	1.2

Particle size distributions of BA and GBFS, determined by XRD analysis, are given in Fig. 1 and Fig. 2, respectively. Moreover, these results showed that the particles of GBFS were significantly smaller than the particles of BA.

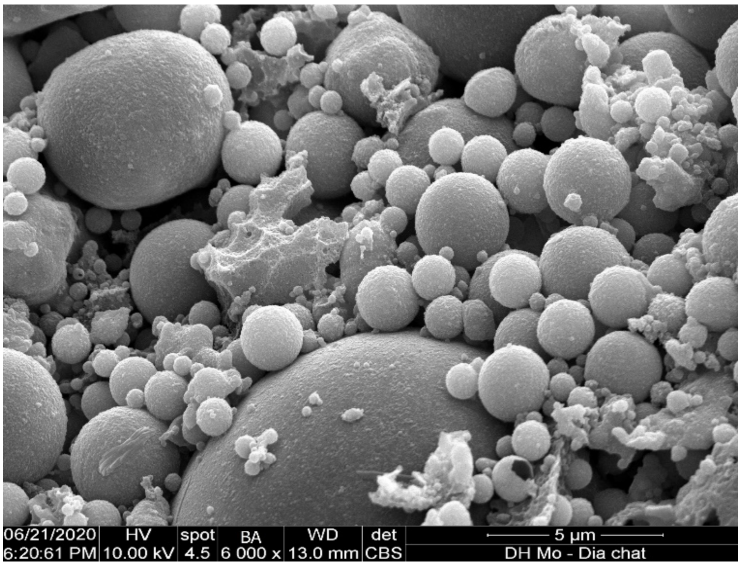

Figure 1. Particle size distribution of BA TPP "Vung Ang".

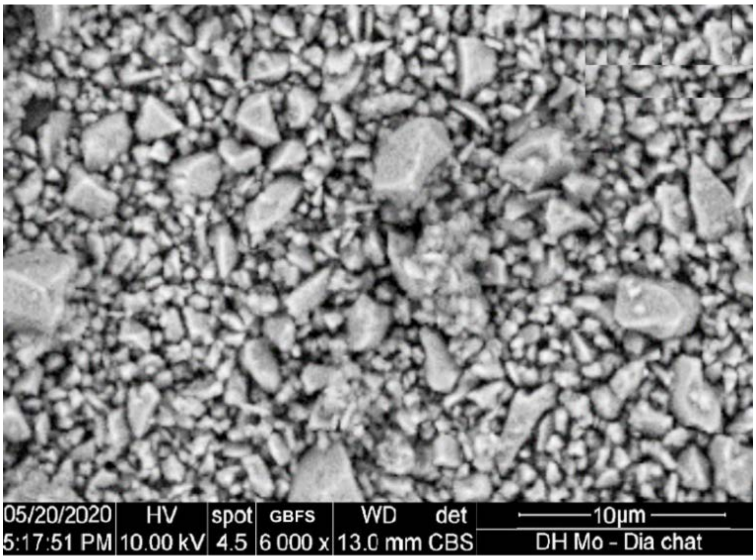

Figure 2. Particle size distribution of GBFS "Hoa Phat".

c). Activator: In the current experimental research, a combination of Na_2SiO_3 and NaOH solutions was used as the alkali-activator solution.

(i). The sodium hydroxide solids (NaOH) with 98–99 % purity was supplied by Viet-Nhat Co., Ltd. The sodium hydroxide solution was obtained by dissolving the NaOH flakes in the water to the required molarity. In this particular case, the molarity of sodium hydroxide (NaOH) solution was in the range of 10 M to 16 M. The specific gravity of the solution is 1.45 g/cm^3.

NaOH solution was prepared by simply dissolving the flakes in water. The mass of NaOH solids in a solution varied depending on the concentration of the solution expressed in terms of the molar – M. Note that the mass of NaOH solids was only a fraction of the mass of the NaOH solution where water was the major component [31, 32]. The composition of sodium hydroxide solution depending on its concentration is shown in Table 2.

Table 2. Composition of sodium hydroxide solution.

The concentration of the NaOH solution	Sodium hydroxide solution	
	NaOH solids (%)	Water (%)
10M	31.4	68.8
12M	36.1	63.9
14M	40.4	59.6
16M	44.4	55.6

(ii). Sodium silicate, also known as water-glass or liquid glass, is available in liquid (gel) form. In the present study, the Na_2SiO_3 liquid was supplied by Viet-Nhat Co., Ltd., with a SiO_2/Na_2O = 2.5, containing 29.5 % SiO_2, 11.8 % Na_2O, 58.7 % H_2O, and specific gravity of 1.55 g/cm^3. The chemical and physical properties of the silicates given by the manufacturer are shown in Table 3.

Table 3. Physical and chemical properties of Sodium Silicate.

1	Chemical Formula	Na_2OxSiO_{2}-xH_2O
2	Na_2O	11.8 %
3	SiO_2	29.5 %
4	H_2O	58.7 %
5	Appearance	Liquid (Gel)
6	Colour	Light Yellow Liquid
7	Boiling Point	102 °C for 40 % aqueous solution
8	Molecular Weight	184.04 g
9	Specific Gravity	1.55 g/cm^3

d) In the present study, the super-plasticizer admixture SR-5000F "SilkRoad" (SP) was procured from Hanoi-Korea Co., Ltd., with a specific gravity of 1.12 g/cm^3, which conformed to the Vietnamese

Standard TCVN 8826:2011. This admixture was used to increase the mortar mixtures' workability and reduce the water-cement ratios while increasing the strength of tested specimens.

e) Clean tap water (W) was used to prepare the sodium hydroxide solution and the curing of tested BA alkali-activated mortar specimens. All the tests met the requirements stated in Vietnamese Standard TCVN 4506:2012.

2.2. Experimental Methods

There have been very limited studies on the mixture design of geopolymer mortar and concrete raw materials to date. The influence of NaOH content and alumino-silicate raw materials on the geopolymer mortar properties was barely considered in the literature. First studies [29, 31, 32] proposing a composition of fly ash-based geopolymer concrete and bottom ash alkali-activated mortar were published in 2006 and 2008. This studied, however, did not discuss how to deal with the effects of a super-plasticizer content or the air content in the mixture. Recently, Ferdous et al. [33] have proposed a detailed mix design procedure for fly ash-based geopolymer concrete. In this study, the calculation method of the compositions of BA alkali-activated mortar mixture was applied following Ferdous et al. [33] and the absolute volume method, combined with the experimental results from the local raw materials in Vietnam.

- The workability of the BA alkali-activated mortar mixture is determined by the standard slump cone with dimensions of 80×70×40 mm, available in Vietnamese Standard TCVN 3121:2003.
- The compressive strength GPM tests were conducted to evaluate the BA alkali-activated mortar strength development for different periods. This experiment was performed in a standard mortar mould of 40×40×160 mm, at 3, 7, 14, 28, 56, and 90 days of curing time using 500T computer-controlled compression test. The "Controls Advantest 9" rig with a constant loading rate of 3000 N/s allowed maintaining the loading rate to a minimum. The compressive strength of the mortar samples was performed following ASTM C109 and Vietnamese Standard TCVN 6016:2011.

2.3. Mixture proportion

In the present research, the geopolymer mortars are prepared on the following basis:

(i) – Ratios of liquid-to-alumino-silicate materials $\left(\frac{L}{ASM}\right)$ ratio of 0.40 by mass, while sodium silicate solution-to-sodium hydroxide solution ratio of 2.5 [34, 35]. This ratio was fixed at 2.5 by mass in all the tested mixtures as the cost of sodium silicate solution is considerably cheaper than the sodium hydroxide solution.

(ii) – The sodium hydroxide solution was initially prepared by dissolving the NaOH flakes in water. The molarity of sodium hydroxide (NaOH) solution was considered in 10 M to 16 M [32]. These solutions were then mixed with the sodium silicate and were allowed to cool down to room temperature.

(iii) – In addition, GBFS was used to replace 0 %, 20 %, 40 %, and 60 % of BA TPP “Vung Ang” mass in the geopolymer mixtures [30]. Besides, the relative volume of entrapped air was 3.0 % in 1 m^3 of tested concrete [29, 31, 32].

(iv) – Furthermore, a quartz sand-to-alumino-silicate materials ratio of 1.30 was maintained for all bottom ash alkali-activated mortar mixtures [26, 27].

(v) – The super-plasticizer "SR-5000F SilkRoad" was equal to 1.0 % by mass of ASM (ASM = BA + + GBFS) [28].

All compositions of GPM mixture used in this investigation are calculated and presented in Table 4. Therefore, the water content, and water-to-geopolymer solid ratio $\left(\frac{W}{GS}\right)$ of mortar mixtures, are also shown in Table 4.

Table 4. Mixture proportions for the preparation of bottom ash alkali-activated mortar.

Sample code	$\frac{GBFS}{FA}$	NaOH molarities	Mix proportions of ingredients (kg/m^3)								W	$\frac{W}{GS}$
			BA	GBFS	QS	SP	Solutions		Solid content			
							NaOH	Na_2SiO_3	NaOH	Na_2SiO_3		
GPM-01	0/100	10	816	0	1061	8.2	93	233	29	96	201	0.213
GPM-02	0/100	12	816	0	1061	8.2	93	233	34	96	197	0.208
GPM-03	0/100	14	816	0	1061	8.2	93	233	38	96	193	0.203
GPM-04	0/100	16	816	0	1061	8.2	93	233	41	96	189	0.198
GPM-05	20/80	10	662	166	1076	8.3	95	237	30	98	204	0.213
GPM-06	20/80	12	662	166	1076	8.3	95	237	34	98	199	0.208
GPM-07	20/80	14	662	166	1076	8.3	95	237	38	98	195	0.203
GPM-08	20/80	16	662	166	1076	8.3	95	237	42	98	192	0.198
GPM-09	40/60	10	504	336	1092	8.4	96	240	30	99	207	0.213
GPM-10	40/60	12	504	336	1092	8.4	96	240	35	99	202	0.208
GPM-11	40/60	14	504	336	1092	8.4	96	240	39	99	198	0.203
GPM-12	40/60	16	504	336	1092	8.4	96	240	43	99	194	0.198
GPM-13	60/40	10	341	511	1108	8.5	97	243	31	101	210	0.213
GPM-14	60/40	12	341	511	1108	8.5	97	243	35	101	205	0.208
GPM-15	60/40	14	341	511	1108	8.5	97	243	39	101	201	0.203
GPM-16	60/40	16	341	511	1108	8.5	97	243	43	101	197	0.198

2.4. Curing specimens

In the present study, all the tested BA alkali-activated mortar series patterns were de-molded 24 h after casting. Next, the specimens were heat cured at 80 °C for up to 30 minutes in a laboratory oven and then left in ambient conditions (25 ± 2) °C until the required testing time.

3. Results and Discussion

3.1. Workability of alkali-activated bottom ash mortar mixtures

The slump of the cone rates the workability of alkali-activated bottom ash mortar mixtures with dimensions of 80×70×40 mm. Table 5 and Fig. 3 shows the value of a slump cone of BA alkali-activated mortar mixture with different both NaOH concentration and granulated blast furnace slag contents. The average value of the slump cone of these mixtures was measured after 0, 30, and 60 minutes after the completion of mixing.

The standard slump cone determines the workability of the geopolymer mortar mixture with dimensions of 80×70×40 mm recommended by Vietnamese Standard TCVN 3121:2003.

Table 5. The average value of slump cone of alkali-activated bottom ash mortar mixtures.

Sample code	$\frac{GBFS}{FA}$	NaOH concentration	$\frac{W}{GS}$	The slump of alkali-activated bottom ash mortar mixtures (cm)		
				Immediately after the completion of mixing	30 minutes after the completion of mixing	60 minutes after the completion of mixing
GPM-01	0/100	10	0.213	21.0	17.2	14.0
GPM-02	0/100	12	0.208	19.0	16.5	13.1
GPM-03	0/100	14	0.203	18.2	15.5	11.5
GPM-04	0/100	16	0.198	18.0	14.4	10.8
GPM-05	20/80	10	0.213	20.5	16.6	14.0
GPM-06	20/80	12	0.208	18.8	16.6	13.0
GPM-07	20/80	14	0.203	17.6	14.2	11.2
GPM-08	20/80	16	0.198	16.0	13.5	10.2
GPM-09	40/60	10	0.213	19.3	15.6	13.5
GPM-10	40/60	12	0.208	18.5	14.8	12.8
GPM-11	40/60	14	0.203	17.0	14.0	10.6
GPM-12	40/60	16	0.198	16.0	13.0	10.0
GPM-13	60/40	10	0.213	18.2	14.6	12.3
GPM-14	60/40	12	0.208	15.8	12.6	10.5
GPM-15	60/40	14	0.203	14.5	11.5	10.0
GPM-16	60/40	16	0.198	13.9	11.0	10.0

Furthermore, data in Table 5 was shown that the addition of GBFS with different levels only slightly decreased the workability of alkali-activated bottom ash mortar mixtures. At the same time, the molarity of the NaOH solution in the range of 10 M to 16 M greatly influences the workability of these mixtures.

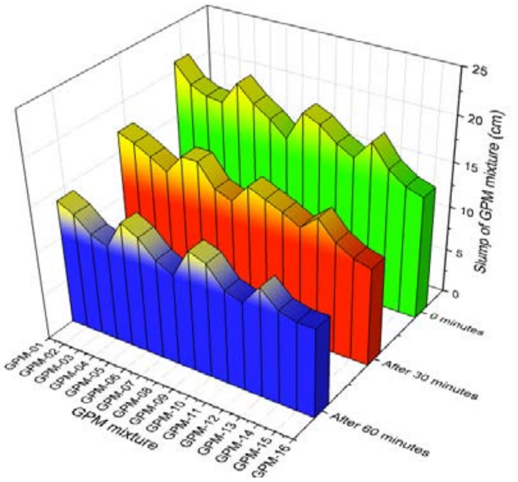

Figure 3. The average value of slump cone of GPM mixtures at times of 0, 30, and 60 minutes after the mixing.

Immediately after mixing raw materials, their slump was in the range of 13.9 cm to 21.0 cm. This could be explained by (1) – the specific surface area of GBFS was larger, (2) – the GBFS particles were significantly smaller than the BA TPP "Vung Ang" particles, which have tended to increase water requirement in the mixing for these mortar mixtures, and (3) – the fact that the water requirement of GBFS (124.1 %) and BA (100.7 %) was greater than that of OPC (about of 29 %). Such observation would be in agreement with the basic principles of OPC concrete mixtures. In this case, the superplasticizer SR 5000F reduces the water-to-geopolymer solid ratio, thereby increasing the density in the structure of the BA alkali-activated mortar mixture.

As shown from Fig. 3, the average value of slump cone of mortar mixtures, measured after 30, and 60 minutes after completion of mixing, decreased in the range of 15 % to 20 % and 30 % to 40 %, respectively. The presented results are similar to those found in previous studies [30, 36, 37].

3.2. Compressive strength of BA alkali-activated mortar samples

Table 6 shows the compressive strength development of tested geopolymer samples prepared with different NaOH concentrations and different levels of granulated blast furnace slag contents.

Table 6. The average value of compressive strength of BA alkali-activated mortar samples at different hydration times.

Sample code	$\frac{GBFS}{FA}$	NaOH concentration	$\frac{W}{GS}$	Compressive strength – f_{cs} at different curing ages (MPa)					
				3-day	7-day	14-day	28-day	56-day	90-day
GPM-01	0/100	10	0.213	18.5	24.2	45.9	50.1	58.5	63.5
GPM-02	0/100	12	0.208	19.6	25.6	48.0	53.0	62.2	65.4
GPM-03	0/100	14	0.203	21.1	27.1	51.1	55.7	65.4	69.7
GPM-04	0/100	16	0.198	19.7	26.2	48.8	52.4	62.5	65.1
GPM-05	20/80	10	0.213	22.0	28.0	53.3	58.8	70.1	73.8
GPM-06	20/80	12	0.208	22.2	29.1	54.7	60.0	71.5	75.1
GPM-07	20/80	14	0.203	24.1	29.8	57.1	62.0	74.0	77.1
GPM-08	20/80	16	0.198	23.0	29.0	55.8	60.9	73.1	76.2
GPM-09	40/60	10	0.213	22.5	29.2	56.1	60.8	72.5	75.1
GPM-10	40/60	12	0.208	24.4	30.5	58.3	62.4	75.1	77.8
GPM-11	40/60	14	0.203	25.0	31.4	59.1	63.9	76.2	80.0
GPM-12	40/60	16	0.198	23.1	29.5	57.0	61.6	73.5	76.8
GPM-13	60/40	10	0.213	19.5	25.1	48.0	52.8	61.5	64.9
GPM-14	60/40	12	0.208	21.8	28.0	51.8	56.8	67.6	72.2
GPM-15	60/40	14	0.203	23.1	29.5	55.6	60.6	71.9	74.9
GPM-16	60/40	16	0.198	21.0	27.8	52.0	57.1	68.7	70.5

Data in Table 6 shows that the compressive strength values at 3, 7, 14, 28, 56, and 90-days of curing time were in the range of 18.5 ÷ 25.0 MPa, 24.2 ÷ 31.4 MPa, 45.9 ÷ 59.1 MPa, 50.1 ÷ 63.9 MPa, 58.5 ÷ ÷ 76.2 MPa, and 63.5 ÷ 80.0 MPa, respectively. The experimental results also prove the compressive strength development of the mortar specimens depends not only on the concentration of sodium hydroxide solutions but also on GBFS content.

3.2.1. Effect of granulated blast furnace slag content on the compressive strength development of BA alkali-activated mortars at different hydration times

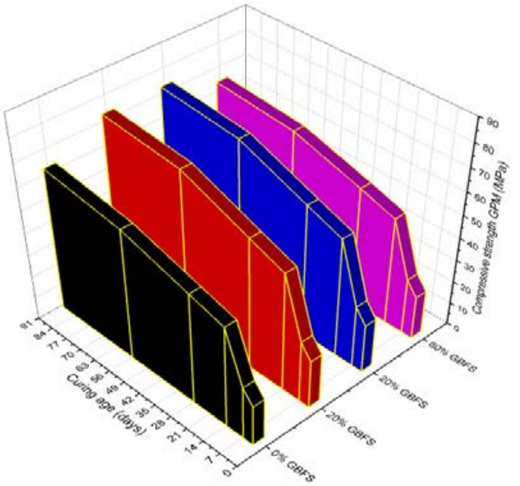

Figure 4. The development of geopolymer mortar compressive strength at NaOH molarities of 10 M.

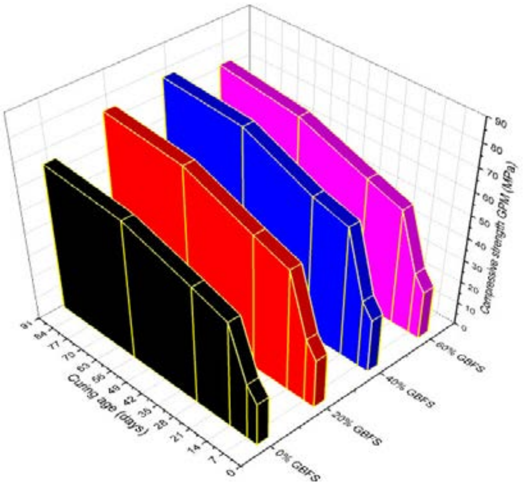

Figure 5. The development of geopolymer mortar compressive strength at NaOH molarities of 12 M.

The results also indicate that GPM compressive strengths have increased with curing periods (from 3 days to 90 days) and with the increase of Vietnamese granulated blast furnace slag content for all of the tested patterns. According to the study given by Kumar et al. and Venu et al. [18, 30], it has been reported that silica atoms increase with the increase in levels of GBFS content [23, 35, 38]. The strength of the alumino-silicate network in GPM structures should increase significantly with the increase in the amount of granulated blast furnace slag. Based on the outcomes of the present study, it is evident that the GPM compressive strength increased with the GBFS content from 0 % to 40 % and then started dropping back. The average value of the compressive strength at the 28-day curing time of BA alkali-activated mortar specimens that contained 0 %, 20 %, 40 %, and 60 % of GBFS felt in the range of 50.1÷55.7 MPa; 58.8÷62.0 MPa; 60.8÷63.9 MPa; and 52.8÷60.6 MPa, respectively.

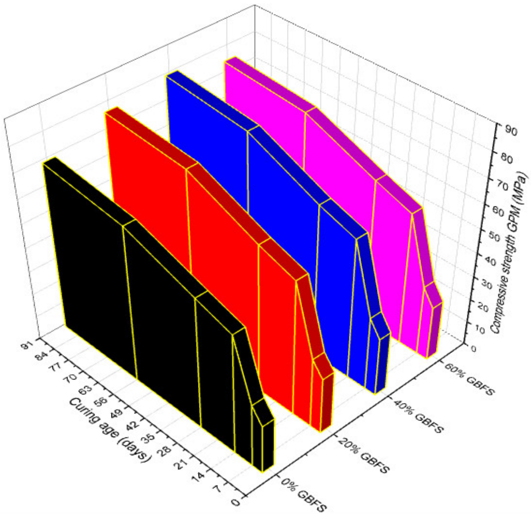

Figure 6. The development of geopolymer mortar compressive strength at NaOH molarities of 14 M.

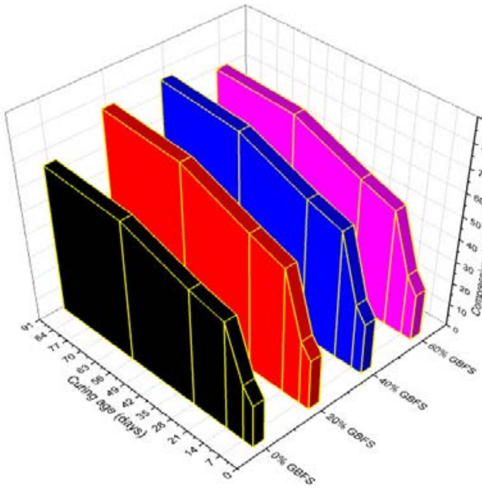

Figure 7. The development of geopolymer mortar compressive strength at NaOH molarities of 16 M.

Moreover, Fig. 4, Fig. 5, Fig. 6, and Fig. 7 showed that the addition of Vietnamese GBFS in the mortar mixes modifies properties of BA alkali-activated mortar significantly, especially with the GBFS contents of 20 % and 40 %. These are caused by – the increased levels of reactive silica (Si in SiO_2) from the Vietnamese GBFS resulted in a higher density of bonds, leading to the higher compressive strength of the GPM-samples – with higher levels of granulated blast furnace slag content of a high specific surface area is responsible for modifying and improving the compressive strength of tested specimens. Furthermore, in the alkali activation of GBFS mortar, the main reaction product is a hydrated calcium-silicate (C-S-H) gel with low CaO/SiO_2 [18, 30]. The C-S-H gel improves the strength characteristic of geopolymer, similar to the results presented in previous studies [10, 35, 38].

Contrary to these principles, while the current work found that the strength behavior increased as Vietnamese granulated blast furnace slag increased to 40 %, that strength levels started declining after the content of GBFS content was 60 % by mass bottom ash (Table 6 and Fig. 4, 5, 6, 7). The effect of other parameters could explain this in the geopolymerization process on the engineering properties of tested geopolymer mortar samples [10, 36, 39]. The factors possibly responsible for these phenomena include (1) relatively larger Vietnamese granulated blast furnace slag solid particles negatively affecting the rate and extent of the geopolymerization process. Especially when the granulated blast furnace slag comprises a higher content of the mortar mixture leading to weaker GPM samples [35, 40]; and (2) a higher concentration of soluble silica, but lower soluble alumina, which hinders the reorganization of Si and Al atoms in the material structures and weakens tested geopolymer mortar samples [32, 34, 35, 39]. According to the experimental results of the strength behavior, the current research found a level of about 40 % of granulated blast furnace slag, delivering the highest compressive strength value for the BA alkali-activated mortar.

The results in Table 6 have shown that the compressive strength of BA alkali-activated mortar gradually increases with GBFS contents.

Moreover, Fig. 4, Fig. 5, Fig. 6, and Fig. 7 prove the development of the compressive strength of BA alkali-activated mortars at the different levels of GBFS contents, at the NaOH molarities of 10 M, 12 M, 14 M, and 16 M, respectively.

3.2.2. Effect of NaOH concentration on the 28-day compressive strength of BA alkali-activated mortars at different hydration times

The present work investigated the 28-day compressive strength of BA alkali-activated mortars at different NaOH molarities of 10, 12, 14, and 16 M. It was found that the compressive strength was proportional to the concentration of NaOH solution and reached the maximum value of 63.9 MPa at 28 days, with NaOH concentration of 14 M (in Table 6) and GBFS content of 40 %, by BA mass.

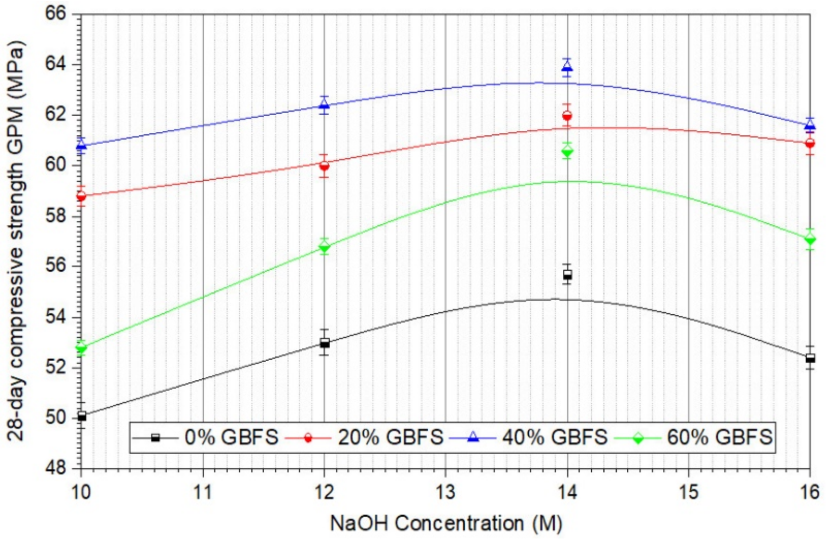

Figure 8. Effect of NaOH molarities on the 28-day compressive strength of BA alkali-activated mortars at 80 °C for 30 minutes.

In addition, Fig. 8 shows the influence of different NaOH contents on the 28-day compressive strength of BA alkali-activated mortars. Without GBSF addition and NaOH concentration of 10 M, this GPM sample contained only the bottom ash. The 28-day compressive strength was low, with only 50.1 MPa. This is due to the low pH value (only 10 M) of the liquid sodium silicate (Table 6) to form an effective excitation environment in this GPM sample, which is the main reason for its low compressive strength [19, 22, 41].

The alkalinity of the alkali-activator solution was significantly increased via the increase in NaOH concentration from 10 M to 14 M.

The pH value of NaOH solution has increased to the content of Na^+, which is very important to increase the polymerization degree and promote the formation of union alkali [2, 6, 40, 41]. Therefore, the 28-day compressive strength of these samples with NaOH concentrations of 12 M, 14 M was significantly higher when compared to that of the GPM sample with a NaOH concentration of 10 M.

In previous studies [23, 24, 34], it was proved that the increase in the concentration of sodium hydroxide solution leads to the following reaction processes: (1) the liberation of Si and Al ions species from aluminosilicate raw materials; (2) the formation of stronger ion pairs; and (3) the acceleration of polycondensation rates. These processes all contribute to the development of geopolymer strength.

3.2.3. Relationship between the water-to-geopolymer solids ratio and the 28-day compressive strength of BA alkali-activated mortars

Fig. 9 shows a relationship between the water-to-geopolymer solids ratio and the 28-day compressive strength of BA alkali-activated mortars.

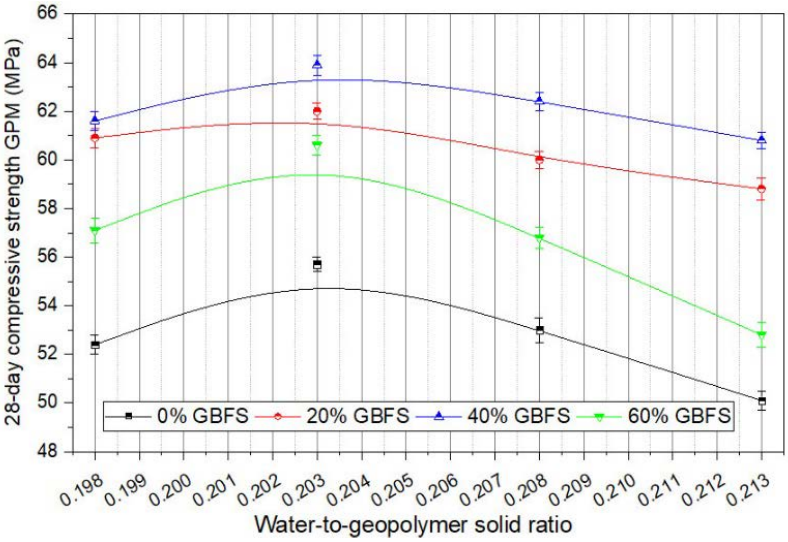

Figure 9. Correlation between the water-to-geopolymer solids ratio and the 28-day compressive strength of BA alkali-activated mortars.

Data from Fig. 9 shows the relationship between the water-to-geopolymer solids ratio and the 28-day compressive strength of BA alkali-activated mortars. Similar findings were reported by Ferdous et al. [33]. The data required to plot relationships for BA alkali-activated mortars were obtained from laboratory conditions where samples were heated up to 80 °C for 30 minutes in the oven. The association was used at the initial composition calculation of the different geopolymer mortar types when the liquid-to-alumino-silicate material ratio was fixed at 0.4 and NaOH molarities in the range of 10 M to 16 M.

4. Conclusions

Based on the experimental results, the following conclusions are drawn on tested alkali-activated bottom ash mortar containing different levels of both NaOH concentrations and granulated blast furnace slag contents used in this investigation:

- For the bottom ash-based geopolymer mortar, the liquid-to-alumino-silicate material ratio and the quartz sand-to-alumino-silicate materials ratio are fixed at 0.4 and 1.30, respectively. Both the sodium hydroxide solution concentration (10–16 M) and Vietnamese granulated blast furnace slag content (0–60 %) greatly affected the workability mixtures and strength behavior of geopolymer mortars. The slump fell in the range of 13.9 ÷ 21.0 cm, while the compressive strength values at the 28-days curing time reached 50.1 MPa to 63.9 MPa.
- The average value of the slump cone of BA alkali-activated mortars, measured after 30 and 60 minutes after completion of mixing, decreased to 15 %, 20 %, and 30 % to 40 %, respectively, compared with the mixture slump immediately after the completion of raw materials mixing.
- The average compressive strength value of all tested BA alkali-activated mortar specimens increased with curing times test, from 3 days to 90 days. The results supported using different hydration times to develop the compressive strength of tested mortar specimens, reflecting Portland Cement behavior principles.
- Concerning the BA alkali-activated mortar samples, the optimum NaOH solution concentration and granulated blast furnace slag content were consistently associated with a higher average value of characteristic strength. The compressive strength of tested specimens peaked at the optimum value and then decreased gradually as NaOH concentration and Vietnamese granulated blast furnace slag content increased. Based on the results, the geopolymer mortar samples prepared with NaOH molalities of 14 M and a GBFS content of 40 % by BA mass exhibited high strength behaviors. Moreover, they were comparable with or even much higher than the GPM specimens with different levels of NaOH concentration and GBFS content.
- The development of compressive strength in the GPM-specimens was triggered not only by the hydration time but also by the NaOH molarities (10–16 M) and GBFS content (0–60 %) by bottom ash mass.
- In the present study, the experimental results showed that the compressive strength of mortar specimens decreased with an increase in the ratio of the water-to-geopolymer solid. Such observation agrees with the basic principles of OPC concrete, which used a binder from ordinary

Portland cement and mineral additive, the strength of which decreases with an increase in the water-binder ratio.

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Information about authors:

***Tang Van Lam**, PhD*
ORCID: https://orcid.org/0000-0002-4857-835X
E-mail: lamvantang@gmail.com

***Kim Dien Vu**,*
ORCID: https://orcid.org/0000-0002-3367-9043
E-mail: kimdienxdtb@gmail.com

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