IOP Conference Series:
Earth and
Environmental Science

PAPER • OPEN ACCESS

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To cite this article: Mostafa Elsebaei *et al* 2025 *IOP Conf. Ser.: Earth Environ. Sci.* **1530** 012025

A study to investigate the compressive strength and flow of alkali activated slag mortar using two curing regimes

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Abstract. This research investigates the potential for producing more environmentally friendly mortars by replacing cement with Ground Granulated Blast Furnace Slag (GGBS). The study examines the influence of key factors on the properties of GGBS-based mortar activated using sodium silicate (SS) and sodium hydroxide (NaOH). Specifically, it explores: (1) the effect of different SS types—base and neutral type; (2) the sodium oxide (Na_2O) content, derived from both activators, with concentrations of 12% and 15%; (3) the impact of curing methods, including ambient temperature curing and full water immersion (submerged); and (4) the role of the water-to-binder (w/b) ratio, assessed at 43% and 48%. The performance of GGBS mortars was evaluated in terms of compressive strength and flowability. The results showed no significant difference between the two SS types; however, the base SS was recommended due to its lower NaOH content to reach the same Na_2O content, which leads to reduced generated heat when preparing the solution. Additionally, a 12% Na_2O concentration yielded higher compressive strength and enhanced flowability. While increasing the w/b ratio improved flowability, it had a detrimental effect on compressive strength. Furthermore, submerged curing significantly reduced compressive strength compared to ambient curing.

Keywords: GGBS, Alkali Activation, Curing Regime, Na_2O Percentage, Compressive Strength.

1. Introduction

Studies in sustainable construction identify the cement industry as a major contributor to environmental harm due to its substantial emissions of CO_2 and other pollutants resulting from fossil fuel combustion. CO_2 emissions from cement production tripled between 1990 (0.576 billion tons) and 2014 (2.083 billion tons) [1], and are projected to reach 2.34 billion tons by 2050 if no mitigation strategy is implemented [2]. The cement industry currently accounts for approximately 8% of global CO_2 emissions which significantly contributing to climate change and global warming [3]. Beyond atmospheric pollution, cement production also adversely affects soil, water resources, and human health. The accumulation of heavy metals near cement plants degrades soil quality, while emissions of CO_2, SO_2, NO_X, and fine dust particles pose serious health risks [4]. Furthermore, cement manufacturing contributes to water contamination, increasing pH levels, and raising concentrations of phosphate, nitrate, as well as total dissolved and suspended solids [5].

Due to the environmental impact of the cement industry, research is increasingly focusing on alternative materials to conventional cement. Geopolymers and alkali-activated cements offer a sustainable solution with up to 80% lower embodied carbon reported [6]. Moreover, a number of studies highlight their advantages over cement, including rapid strength development, low permeability, high durability, and superior mechanical properties [7], [8]. Whilst natural materials can be used as aluminosilicate precursors, research focuses mainly on industrial by-products like ground-granulated blast-furnace slag (GGBS) or fly ash, that can be used as aluminosilicate precursor [7].

GGBS is one of the most common aluminosilicate precursors used in alkali-activated cements due to its low energy consumption which can reach approximately 30% with limited CO_2 emissions compared to cement industry energy consumption [9]. GGBS is a by-product of pig iron industry which consists of calcium-rich aluminosilicate impurities [10]. It has been widely studied and covered in literature and can have some enhanced properties compared to cement. According to Mohamed, O. [11] A. GGBS systems or cement systems with partial replacement with GGBS generally have better durability properties than cement systems for example GGBS exhibits higher resistance to sulfate attacks than cement system. In addition, the rapid and early strength development of GGBS system makes it a suitable alternative to some application in the construction industry like deep-water oil well cementing [11].

This paper aims to investigate the use of NaOH and SS-activated GGBS systems in mortars through testing which includes compressive strength and flow of different GGBS mortar mixes with different alkali solution concentrations and different curing regimes.

2. Material and Method

2.1. Materials

The GGBS used in this investigation, was supplied by ALBARIK (India). It is the same exact GGBS used in the research by Zidan et al.[12], [13]. The physical properties, as provided by the manufacturer, include a specific gravity of 2.8, and bulk density of 1.15 t/m^3, a specific surface area of 4088 cm^2/g and insoluble residues percentage of 1.4%. To determine its chemical composition, X-ray Diffraction (XRD) and X-ray Fluorescence (XRF) analyses were conducted. The XRF apparatus is Rigaku Supermini200 Spectrometer which is benchtop sequential wavelength dispersive X-ray fluorescence (WDXRF) spectrometer (Helium Type). As for the XRD apparatus, it is Panalytical Empyrean 3. The results of both tests are provided in the results sections in **Figure 1**, and **2**, and **Table 4**.

In this study, three types of activators were utilized: two types of waterglass (liquid sodium silicate) SS basic and neutral respectively, and sodium hydroxide (SH). The SH was a highly pure commercial powder with a purity of 96%. As for the waterglass SS, it was provided by local factory AlHamad. **Table 1** shows the properties of both types of SS (the neutral and the base).

Table 1: Liquid Sodium Silicate Data Sheet (obtained by the manufacturer)

Sodium Silicate (Waterglass)	SiO_2 %	Na_2O %	Ms	Sodium Silicate Solids %	Water %	Specific Gravity	Baume at 20 C°
Base Type	31.2	14.2	2.2	45.4	55.6	1.55	51.2
Neutral Type	36.5	11.5	3.2	48	52	1.45	45

The sand used in this study is a natural sand from Egypt desert sieved so that only the portion between sieve 0.3 mm and 1.18 mm is retained, according to the Egyptian code 203-2020 [14], [15]. This is to ensure the use of the same sand specified by the Egyptian code in all mixes.

2.2. Mix Design and Specimen Preparation

In this study, two sets of experiments were conducted to evaluate compressive strength and flow characteristics. The first set aimed to compare two different types of SS: the neutral type and the base type. The second set investigated the effect of w/b ratio on the compressive strength and flow and also studied the effect of two different curing regimes (ambient and submerged).

All mixes had a modulus of silicate Ms = 1.2 as best recommended in literature [12], [13], however, two different Na_2O percentages were examined (12% and 15%) in the first set of experiments. In the second set, the Na_2O selected for the investigation is 12%. **Table 2** and **Table 3** show respectively the mix design of the first and the second set of mixes.

Table 2: Mix design of the first set of tests

Mix #	Slag g	Sand g	Water g	NaOH	SS g	SS Type	w/b	a/b*	Ms	Na_2O	Curing
A1	100	275	11.5	8.8	57.71	Base	0.43	0.35	1.2	0.15	Ambient
A2	100	275	17.8	7.04	46.17	Base	0.43	0.28	1.2	0.12	Ambient
A3	100	275	17.4	12.04	49.32	Neutral	0.43	0.35	1.2	0.15	Ambient
A4	100	275	22.5	9.63	39.45	Neutral	0.43	0.28	1.2	0.12	Ambient

*a/b: activator to binder (activator refers here to the NaOH and solids ratio in the SS without water)

Table 3: Mix design of the second set of tests

#	Slag g	Sand g	Water g	NaOH	SS g	SS Type	w/b	a/b	Ms	Na_2O	Curing
B1	100	275	17.8	7.04	46.17	Base	0.43	0.28	1.2	0.12	Ambient
B2	100	275	17.8	7.04	46.17	Base	0.43	0.28	1.2	0.12	Submerged
B3	100	275	22.8	7.04	46.17	Base	0.48	0.28	1.2	0.12	Ambient
B4	100	275	22.8	7.04	46.17	Base	0.48	0.28	1.2	0.12	Submerged

2.3. Mortar tests

All mortar samples were tested for 7-days compressive strength and for a flow test according to ASTM C230 [16].

2.4. Mixing protocol

All materials were precisely weighed using a digital balance to ensure accuracy. The first step is to pre-prepare the alkaline activator NaOH solution a day at least prior to the mixing process. This alkaline activator NaOH solution was pre-prepared by dissolving sodium hydroxide (NaOH) in water under continuous stirring until complete dissolve of NaOH, then keeping it to be cooled for at least one day before being used. This is to avoid the heat generated from the chemical reaction. On the day of the mixing, the Ground Granulated Blast Furnace Slag (GGBS) and sand were combined and homogenized through stirring. Then the liquid sodium silicate (SS) is added to the alkaline activator

IOP Conf. Series: Earth and Environmental Science **1530** (2025) 012025 doi:10.1088/1755-1315/1530/1/012025

NaOH solution and stir well. The prepared solution (consisting of NaOH solution + SS) was then gradually added to the dry binder mixture (GGBS + sand) and stirred. The resulting fresh alkali activated cement mortar was mixed using a laboratory mortar mixer at a controlled speed for 2 minutes to achieve consistency. The mixture was subsequently cast into 70.6 mm cubic molds and compacted to eliminate air voids using standard metal rod. The specimens were covered with a plastic sheet to prevent moisture loss during the initial setting period of 24 hours. Thereafter, the samples were demolded and subjected to curing conditions as specified in the experimental mix design detailed in **Tables 2** and **3**.

2.5. Curing Regime

Two curing regimes are used in this study (ambient and submerged). The ambient curing regime refers to curing the sample (after demolding) in the room temperature in air till the testing day. On the other hand, the submerged curing regime refers to curing the sample in a water curing tank also with the same room temperature until the testing day.

3. Results and Discussion

3.1. GGBS XRD and XRF Results

XRD was used to determine the mineralogical and crystalline compound in the GGBS. The results of the XRD are shown in **Figure 1** and **2**. It is notable that although GGBS is amorphous, few traces of crystalline phase are found. As for the chemical composition, XRF results of this GGBS is presented in **Table 4**. The XRF results showed that the chemical composition of the GGBS used in this study was similar to GGBS used elsewhere in literature to make alkali activated cement [12], [13].

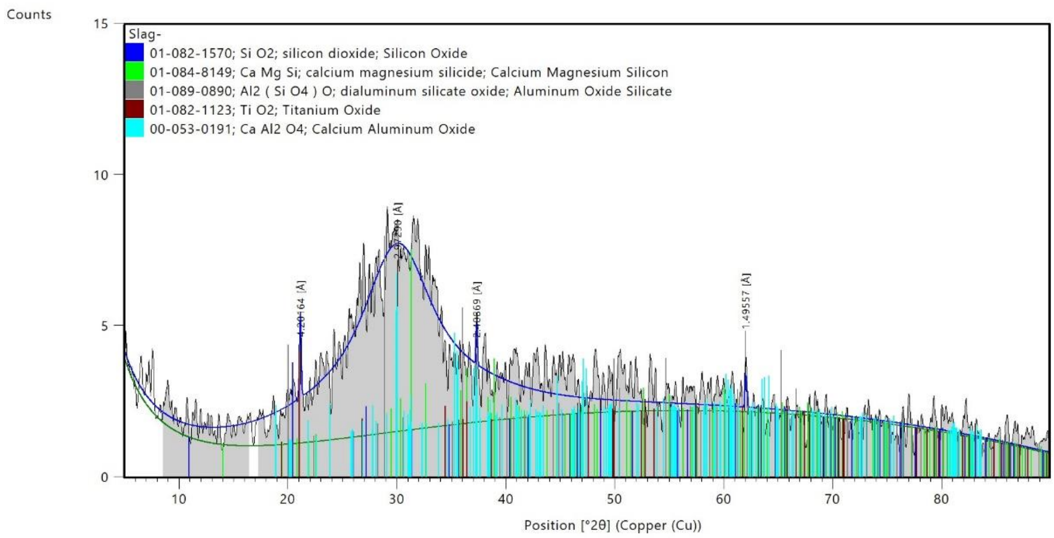

Figure 1. XRD result of GGBS used in this study.

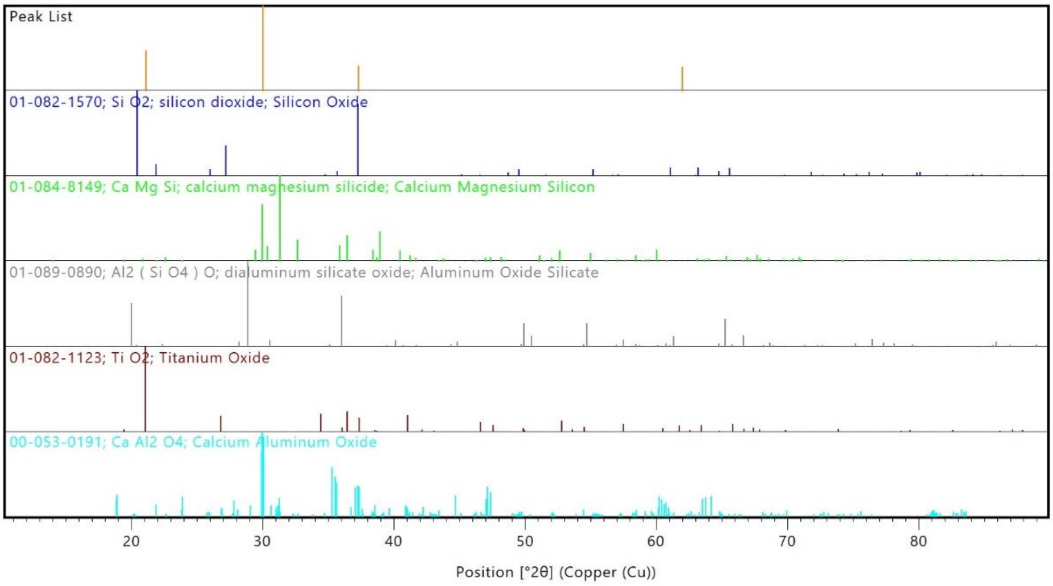

Figure 2. Specific traces selected in XRD result of GGBS used in this study.

Table 4. XRF Results of GGBS used in this study

Composition	SiO_2	CaO	Al_2O_3	MgO	Na_2O	SO_3	Cl	K_2O	TiO_2	MnO	Fe_2O_3	L.O.I
Percentage	30.3	40.4	14.7	6.06	0.65	1.84	0.11	0.88	0.87	0.39	1.32	2.03

3.2. First Set of Tests

The first set of mixes aimed at investigating the effect of the SS type (neutral and base). Four mixes in this set were tested, and their results of the compressive strength and flow are presented in **Table 5**. From the table, it can be noted that the compressive strength results of both types were close. The base SS mixes A1 and A2 achieved 45.5 and 55.1 MPa respectively, whereas neutral SS mixes reached 47.3 and 50.4 MPa respectively. Regardless of being base and neutral, the mixes with Na_2O percentage of 12% reached higher compressive strength and better flow, as compared to those with Na_2O percentage of 15%. So, it can be concluded that the type of SS does not have a significant effect on the compressive strength but can have an impact in flow.

It is decided to continue the second set of tests using the Base type of SS, as it contains higher amount of Na_2O so less sodium hydroxide is required to achieve the same Na_2O concentration in the mix. This reduces the heat generated when preparing the solution.

Table 5. Test Results of the First Set of Mixes

Mix #	w/b %	Ms	Na_2O %	a/b %	SS Type	Compressive Strength (MPa)					Flow mm
						1st MPa	2nd MPa	3rd MPa	Avrg MPa	SD	
A1	43%	1.2	15%	35%	*Base*	49.1	40.2	47.2	**45.5**	4.7	150
A2	43%	1.2	12%	28%	*Base*	59.5	53.4	52.3	**55.1**	3.9	165
A3	43%	1.2	15%	35%	*Neutral*	46.8	47.4	47.8	**47.3**	0.5	148
A4	43%	1.2	12%	28%	*Neutral*	54.3	47.3	49.7	**50.4**	3.6	160

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3.3. Second Set of Tests

The second set targets a comparison between GGBS mortars made using two different w/b ratios under two different curing regimes (ambient and submerged). Four mixes in this set were tested, and their results of the compressive strength and flow are presented in **Table 6**.

From the results of the flow test presented in **Table 6**, it can be noted that the flow is clearly affected by the w/b ratio: the higher the w/b, the higher the flow, as in regular cement mortar. Moreover, the higher w/b ratio caused also a drop in compressive strength, as samples B3 and B4 have lower compressive strength if compared to samples B1 and B2, as would be expected based on knowledge from regular cement mortar.

It is remarkable that there is a very large drop in compressive strength when samples are cured using the submerged curing regime. So, regardless of w/b ratio, the submerged curing regime causes a dramatic drop in compressive strength.

Table 6. Test Results of the Second Set of Mixes

Mix #	w/b	a/b	Ms	Na_2O	Curing	Compressive Strength (MPa)					Flow mm
						1st MPa	2nd MPa	3rd MPa	Avrg MPa	SD	
B1	43%	28%	1.2	12%	Ambient	59.5	53.4	52.3	**55.1**	3.9	165
B2	43%	28%	1.2	12%	Submerged	35.1	41.5	37.4	**38**	3.2	
B3	48%	28%	1.2	12%	Ambient	41.3	42.6	43.6	**42**	1.1	190
B4	48%	28%	1.2	12%	Submerged	39	33.8	29.4	**34**	4.9	

4. Conclusion

This paper studied the effect of q number of factors i.e., Na_2O content, sodium silicate type, curing regime, water to cement w/b ratio on the flowability and compressive strength of alkali activated GGBS mortars, using mixes of NaOH and Na_2SiO_3 activators. It can be concluded that:

- No significant impact on compressive strength and flow when using the base-type waterglass (SS) or the neutral-type.
- The submerged curing regime causes a significant drop in compressive strength regardless of the w/b used in the mix.
- The higher w/b ratio causes a drop in compressive strength but increase the flow.

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