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Strength Development of Alkali-Activated Mortar with GGBS and Fly Ash Binder

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Abstract – This paper presents the impact of curing in different environments, air and water, on the strength development of mortar with alkali-activated binder consisting of ground granulated blast furnace slag (GGBS) and fly ash. A combination of commercial sodium silicate solution (waterglass) and sodium hydroxide were used to activate the binder. The strength development was assessed including the effect of variation in NaOH activator concentration from 10 mol/L to 16 mol/L. The effect of binder composition was evaluated considering two combinations, a GGBS:fly ash ratio of 1:1 and GGBS:fly ash ratio of 3:1. Samples were tested in compression after 7, 28, and 90 days of curing. Compression tests showed that samples cured in water gain strength continuously from 7 to 90 days, irrespective of NaOH concentration and for both binder combinations. However, samples with NaOH concentration from 10 mol/L to 14 mol/L that were cured in air gained strength at the age of 28 days compared to 7 days but decreased in strength at the age of 90 days. This indicates water curing ensures continuity of the geopolymerization reaction and the development of C-A-S-H and N-A-S-H that contribute the strength development. However, air-cured samples lost strength at the age of 90 days, possibly due to the time-dependent loss of moisture leaving unreacted activator deposits. However, at NaOH concentration of 16 mol/L, air-cured samples continued to gain strength until the age of 90 days, likely due to the higher alkalinity of the solution that increases the concentration of ions and binds water more tightly. In addition, higher activator concentration accelerates the reaction and develops more products which binds water chemically and physically.

***Keywords*:** Geopolymer concrete; compressive strength; alkaline activator concentration; slag; fly ash; water curing; air curing.

1. Introduction

Wardhono et al. [1] studied the compressive strength development of 50 mm cubic mortar samples that were cured by submerging them in water at ambient temperature and tested at 3, 7, 14, and 28 days. Binders comprising either GGBS alone or a combination of Class F fly ash and GGBS were activated using a mixture of 15 M NaOH solution and sodium silicate solution. The activator solution was proportioned to achieve a 15% Na_2O content and a SiO_2/Na_2O modulus of 1.25. Mixes were created with various binder ratios of GGBS and fly ash. With the exception of the 100% GGBS mix, all mixes showed an increase in compressive strength from 3 to 28 days of curing. After 28-days of moist curing at ambient temperature, the mortar samples with 50% GGBS and 50% fly ash exhibited the highest compressive strength. The 100% GGBS mix developed the highest compressive strength at the age of 3 days, but by the age of 7-days, the mix with 50%GGBS + 50% fly ash developed higher compressive strength.

Many studies identified the main reaction product of alkali-activated GGBS-fly ash concrete to be chain-structured C-A-S-H type gel [2]. In addition to C-A-S-H, the presence of fly ash promotes formation of sodium aluminosilicate (N-A-S-H) which is more porous and less compact than C-A-S-H [3]. Uppalapati et al. [4] reported that in the early hours after mixing GGBS-fly ashy binder combination, only C-A-S-H is present due to the fast hydration of GGBS with little or no N-A-S-H. This is because dissolution of fly ash takes longer time than hydration of GGBS. Nonetheless, Lee et al. [5] reported identifying C–N–A–S–H as reaction product in early-hours after mixing GGBS-fly ash mortar samples. Studies consistently reported that increasing GGBS content in GGBS-fly ash binders results in denser matrix of reaction products.

In unsaturated concrete, the rate of water ingress is controlled to great extent by absorption due to capillary rise. The industrial by-products GGBS and fly ash are sustainable alternatives to OPC, that offer high potential of producing durable concrete for infrastructure projects. Curing method, temperature, and relative humidity affect strength development in concrete that uses OPC as binder. Concrete in which up to 90% of OPC was replaced by selected combinations of GGBS, fly ash, and silica fume developed higher 28-day compressive strength when cured in air at 45 ^{0}C temperature and 70% RH, than similar OPC-based concrete cured under water in ambient laboratory conditions [6].

Collins and Sanjayan [7] reported that 100 mm x 200 alkali-activated slag concrete cylinders that were bath cured and sealed (w/b ratio of 0.5) developed similar compressive strength over time. On the other hand, after 365 days, samples left exposed in the laboratory at 23^{0}C and 50% relative humidity (RH) developed 41.4% and 53.5% lower compressive strength than sealed and bath cured cylinders. Similarly, cylinders experienced a 17.2% loss in compressive strength when exposed compared to sealed or bath cured cylinders. The investigators attributed the loss of compressive strength to microcracking that started to appear on exposed samples during the first 3 days after casting. Mercury Intrusion Porosity (MIP) testing of the cylinders showed higher total porosity and coarser pore size distribution in exposed samples compared to bath and sealed cylinders. For exposed samples, porosity increased with distance to the exterior surface of the samples. The investigators considered that the reason for the higher porosity and coarser pore size distribution of exposed samples was detected with MIP testing of this microcracking itself. This study used 1% hydrated lime ($Ca(OH)_2$ solution) to activate the slag.

This article evaluates the effect of curing mortar with alkali-activated binder in air versus immersion in sulfuric acid on compressive strength development from 7 to 90 days of curing. The effect of activator concentration on the development of compressive strength in the two curing environments is also evaluated.

2. Materials and Methods

This section describes the materials used and experimental procedure to prepare the mixes and determine the compressive strength at the ages of 7, 28, and 90 days.

2.1. Material Properties

The alkali-activated binder used in this study is a combination of GGBS and fly ash, as shown in Fig. 1(a) and (b), with its properties listed in Table 1. The binder components were supplied by RMB Ready Mix (Abu Dhabi, United Arab Emirates). The percentages of calcium oxide (CaO), the combined silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and iron oxide (Fe_2O_3), and sulfur trioxide (SO_3) are consistent with ASTM C618 [8] Class F fly ash specifications. The sodium hydroxide flakes and sodium silicate solution used to activate the binder were supplied by Dubichem, Dubai, United Arab Emirates.

Table 1: Properties of ground granulated blast furnace slag and fly ash.

	CaO	**SiO_2**	**Al_2O_3**	**SO_3**	**Fe_2O_3**	**TiO_2**	**K_2O**	**MnO**	**SrO**	**ZrO_2**	**CuO**	**Cr_2O_3**	**Y_2O_3**
GGBS (%)	59.44	25.68	8.12	2.75	1.499	1.048	0.609	0.562	0.125	0.065	0.031	0.026	0.016
Fly Ash (%)	4.294	58.158	24.351	0.068	8.517	2.565	1.534	0.094	0.062	0.085	0.037	0.047	0.015


(a) (b)

Fig. 1: Binders used in the study including (a) fly ash, (b) ground granulated blast furnace slag.

2.2 Experimental Procedure and Mix Design

The activator solution was prepared by mixing anhydrous NaOH flakes with clean water to achieve the target molarity of 10M, 12M, 14M, or 16M, as investigated in this study. The solution was then left to cool to room temperature for approximately two hours. A commercial sodium silicate solution (SiO_2 = 28.8 wt%, Na_2O = 9.8 wt%, and H_2O = 61.4 wt%) was subsequently added to the NaOH solution in an appropriate quantity to achieve a sodium silicate/sodium hydroxide (Na_2SiO_3/NaOH) ratio of 1.5. After the activator solution had cooled to room temperature, a polycarboxylic ether superplasticizer was added at a dosage of 2.5%, which enhanced workability while limiting bleeding. The superplasticizer was produced and marketed by BASF Corporation (Ludwigshafen, Germany) under the commercial name MasterGlenium SKY 504. This dosage was selected after several trials that considered the relative contents of GGBS and fly ash in the total binder. Furthermore, the 2.5% dosage relative to the total binder content is consistent with the findings of Jang et al. [9], who identified it as optimal for strength development beyond 7 days of curing, while higher dosages adversely affected long-term strength development. Finally, the activator solution was incorporated into a pre-blended mixture of sand and precursor GGBS/fly ash at predetermined ratios, and the mixture was stirred for 5 minutes. Several studies have shown that adding the activator in solution form to the precursor material improves both workability and compressive strength compared to the approach of first adding anhydrous activator to the precursor and then mixing with water [10].

Two groups of mortar samples were prepared based on binder combinations, with each group containing four mixes. Group 1 was prepared using 75% GGBS and 25% fly ash (G75F25), while Group 2 consisted of 50% GGBS and 50% fly ash (G50F50). Studies have shown that a GGBS-to-fly ash ratio of 3:1 results in lower water absorption rates and a finer pore structure [11]. Within each group, four mixes were prepared using NaOH activator solutions with molarities of 10M, 12M, 14M, and 16M. The solution-to-binder ratio was 0.55 for all eight mixes shown in Table xx. The total binder content (GGBS + fly ash) per mix was 436 grams. The sand used in the mortar mixes was graded and sourced in accordance with ASTM C778 [12], and the sand-to-binder ratio was maintained at 2.75, consistent with ASTM C109 [13]. Consequently, the total sand content per mix was 1199.2 grams.

After continuously mixing the binder and activator solution for five minutes, the mortar samples were cast into molds. The molds were vibrated to improve compactness and consolidation. The cubic samples (50 mm) remained in the molds for 24 hours before being demolded and weighed using a scale with a precision of 0.01 kg. Two sets of all mixes were created, one set was left in air under ambient laboratory conditions and another set was submerged in 10% sulfuric acid until the test day. Originally, the purpose of immersing samples in sulfuric acid was to determine the resistance to acid and results were reported elsewhere (O. A. Mohamed, 2022, O. A. Mohamed et al., 2022). After 7 days, 28 days, and 90 days of curing, the samples were surface-dried and weighed. Sufficient specimens were cast so that the compressive strength results are the average of three samples. The compressive strength of the 50 mm cubic samples was determined in accordance with ASTM C109 [13].

Table 2**:** Mortar mixes tested in the program, based on binder type, molarity of NaOH, and ratio of Sodium Silicate/Sodium Hydroxide.

	Mix No.	GGBs (%)	GGBS (grams)	Fly Ash (grams)	NaOH concentration (mol/L)	Total activator content (grams)	Sodium Silicate (grams)	Sodium hydroxide Solution(grams)	Sodium Hydroxide-Flakes (grams)	Water (grams)
Group 1	1	75	327	109	10	239.8	143.88	95.92	38.368	57.552
	2	75	327	109	12	239.8	143.88	95.92	46.0416	49.8784
	3	75	327	109	14	239.8	143.88	95.92	53.7152	42.2048
	4	75	327	109	16	239.8	143.88	95.92	61.3888	34.5312
Group 2	5	50	218	218	10	239.8	143.88	95.92	38.368	57.552
	6	50	218	218	12	239.8	143.88	95.92	46.0416	49.8784
	7	50	218	218	14	239.8	143.88	95.92	53.7152	42.2048
	8	50	218	218	16	239.8	143.88	95.92	61.3888	34.5312

3. Results and Discussion

Fig. 2(a)–(d), indicate that mortar samples with 50% GGBS and 50% fly ash binders (G50F50), which were immersed in sulfuric acid, continued to gain strength as curing progressed from 7 to 90 days, regardless of the activator concentration. Although acid exposure may have affected compressive strength, the enclosed curing environment provided by water facilitated continued polymerization reactions that outpaced the effects of the acid, resulting in higher strength with age. In contrast, when cured in air under laboratory conditions, samples with NaOH concentrations ranging from 10 mol/L to 14 mol/L exhibited a decrease in strength at 90 days compared to 28 days, as shown in Fig. 2(a)–(c). This is likely due to moisture loss, which led to the deposition of solid precipitates within the samples rather than the formation of geopolymerization products. Notably, this 90-day decrease in strength did not occur in air-cured samples with a NaOH concentration of 16 mol/L, as shown in Fig. 2(d). This high concentration created a highly alkaline environment that promoted the formation of geopolymerization products at a rate greater than the moisture loss due to evaporation. The development of geopolymerization products, such as C-A-S-H, results in a denser microstructure that further impedes moisture loss. Nonetheless, the increase in strength from 38.55 MPa at 28 days to 41.04 MPa at 90 days for mortar with a NaOH concentration of 16 mol/L was small (see Fig. 2(d)).

Preventing moisture loss during strength development is crucial, as samples immersed in water containing sulfuric acid consistently achieved significantly higher compressive strength than those cured in air, regardless of NaOH concentration. By minimizing water evaporation, the impact of a higher NaOH concentration on increasing solution alkalinity and promoting geopolymerization becomes evident. This is demonstrated by the mortar with a NaOH concentration of 16 mol/L, which achieved the highest compressive strength of 74.77 MPa in samples with a GGBS:fly ash ratio of 1:1 (G50F50), outperforming all other concentrations.

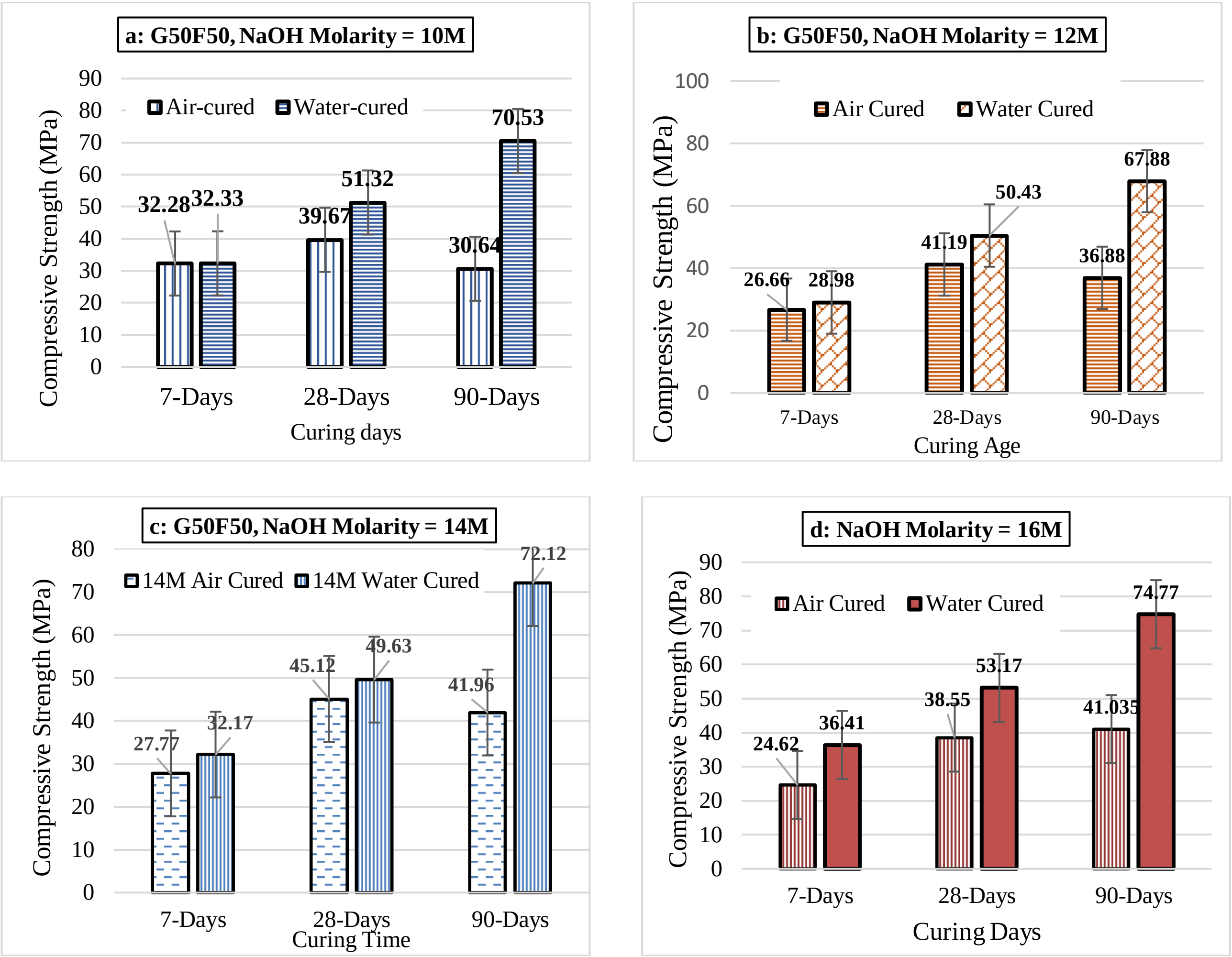

Fig. 2: Strength development is samples with GGBS:fly ash ratio of 1:1 (G50F50) cured in air or immersed in water containing sulfuric acid.

The effect of air-curing and moisture loss is also evident in mortar containing 75% GGBS and 25% fly ash (a GGBS:fly ash ratio of 3:1), as shown in Fig. 3(a)–(d). All mortar samples developed lower compressive strength at 90 days compared to 28 days, irrespective of the NaOH concentration. Therefore, increasing the GGBS content from 50% to 75% did not alter the trend of strength loss in air-cured mortar. Similarly, mortar immersed in water containing sulfuric acid continued to develop higher strength as the curing age increased from 7 to 90 days. Mortar immersed in water consistently developed higher strength than their air-cured counterparts, irrespective of NaOH concentration. Comparing Figs. 3 and 2, it can be stated that water-cured G75F25 mortar developed higher strength than the G50F50 counterparts for NaOH concentrations ranging from 10 to 14 mol/L. This is attributed to the higher GGBS content in G75F25, which reacts faster in the presence of water to produce more C-A-S-H gel, thereby enhancing compressive strength. On the other hand, the G50F50 mix contains equal amounts of GGBS and fly ash; therefore, the influence of water on hydration—and consequently on strength—is lower than in G75F25 due to the relatively higher content of the slower-reacting fly ash. The favourable effect of water curing is also reported in the literature [16].

The mortar with a GGBS:fly ash ratio of 3:1 (see Fig. 3(a)) developed the highest compressive strength when the NaOH concentration was 10 mol/L. A higher NaOH concentration (16 mol/L) is associated with excessive sodium ions that may leach or cause gel swelling and microcracking. Furthermore, higher NaOH concentrations may lead to carbonation in the presence of CO_2 or cause shrinkage and related microcracking. Fig. 3(a)–(d) show that for a GGBS:fly ash ratio of 3:1 (G75F25), a NaOH concentration of 10 mol/L is optimal, as the compressive strength of water-cured mortar at all ages (7, 28, and 90 days) decreased with further increases in NaOH concentration.

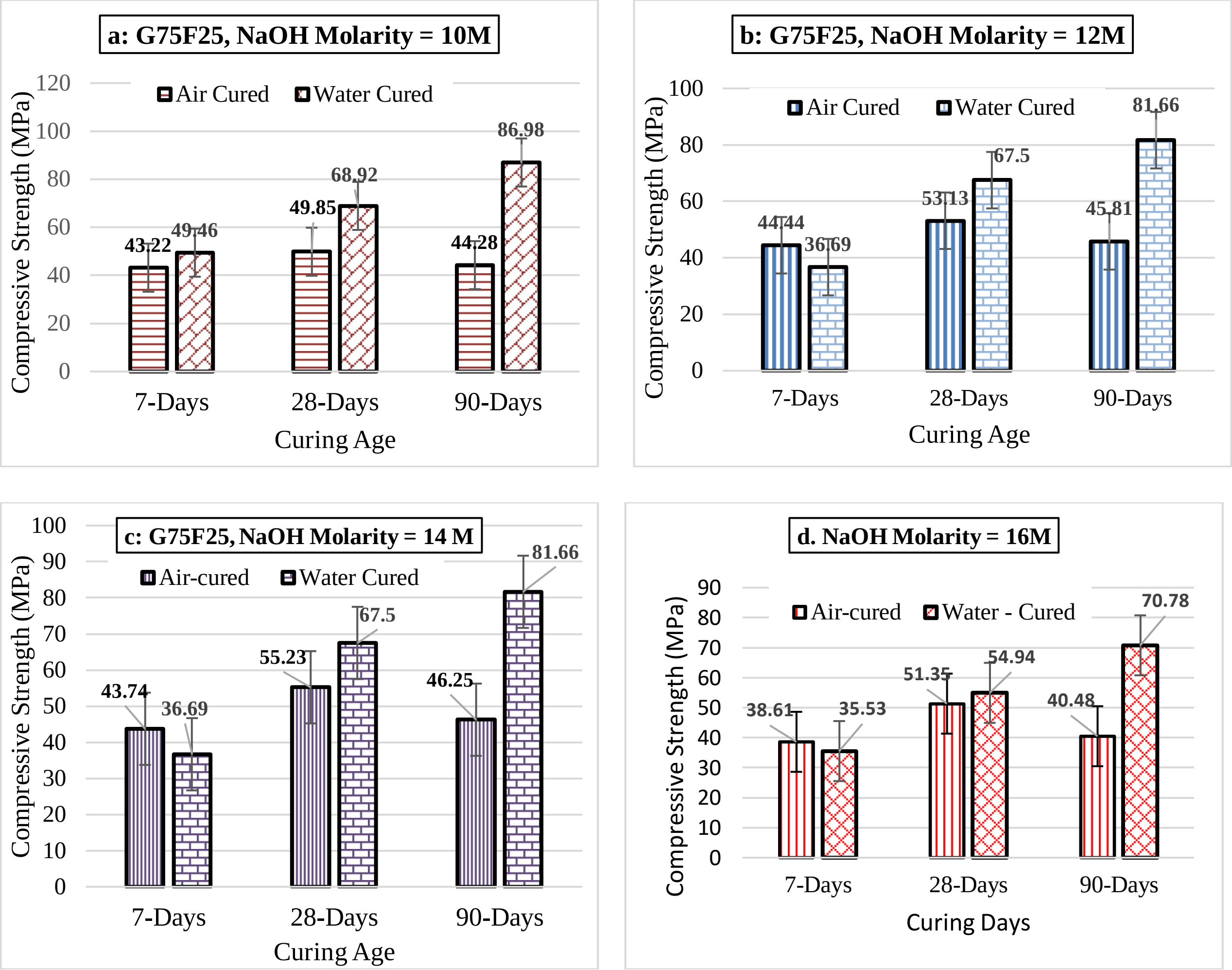

Fig. 3: Strength development is samples with GGBS:fly ash ratio of 3:1 (G75F25) cured in air or immersed in water containing sulfuric acid.

Comparing Fig. 3 and 2, it is clear that after 28 and 90 days of curing, the G75F25 mix developed higher compressive strength for NaOH concentrations of 10 M, 12 M, and 14 M compared to the G50F50 mix. This indicates that GGBS not only continued to hydrate rapidly but also accelerated the polymerization of the 25% fly ash in the G75F25 mixes, leading to an increased formation of both hydration and geopolymerization products. The high compressive strengths at 28 and 90 days, even with a relatively high liquid-to-binder ratio of 0.55, are attributed to the optimal compactness of the system—characterized by dense, less porous C-A-S-H due to the high GGBS content, combined with a smaller proportion of the more porous N-A-S-H matrix. The larger, more permeable voids in N-A-S-H compared to the denser, finer pore system of C-A-S-H have been extensively documented in the literature.

4. Conclusion

This paper evaluated the effect on compressive strength development of curing mortar—prepared with alkali-activated GGBS and fly ash binders—in air versus in water containing sulfuric acid. The effects of relative binder composition and NaOH concentration on compressive strength development were also evaluated. The alkaline activator consisted of NaOH (with concentrations ranging from 10 mol/L to 16 mol/L) and sodium silicate (water glass), with a sodium silicate-to-sodium hydroxide ratio of 1.5. The following observations were observed:

- Although immersing samples in water containing sulfuric acid is known to adversely affect compressive strength, it did not inhibit the development of geopolymerization products, and strength continued to increase with curing age from 7 to 90 days.
- Mortar cured in water developed consistently higher compressive strength than mortar cured in air, irrespective of NaOH concentration, for binders with both GGBS:fly ash ratios of 1:1 and 3:1.
- Mortar cured in air increased in strength from 7 to 28 days but decreased at 90 days for all samples with a 3:1 GGBS:fly ash ratio and most NaOH activator concentrations (10, 12, and 14 mol/L). The loss in strength is possibly due to water evaporation leaving behind solid activator deposits within the samples. In contrast, samples cured in water retained the activator solution within their pores, which facilitated the ongoing geopolymerization reaction and the development of additional C-A-S-H.
- Water-cured mortar with a GGBS:fly ash ratio of 3:1 exhibited consistently higher compressive strength than mortar with a 1:1 ratio for NaOH concentrations of 10, 12, and 14 mol/L. This pattern remained consistent after 7, 28, and 90 days of curing. The only exception was at 90 days with a NaOH concentration of 16 mol/L, where the strength for the 3:1 ratio was slightly lower than for the 1:1 ratio. The higher strength for the 3:1 ratio indicates a more effective interaction in the formation of C-A-S-H and N-A-S-H products along with a more refined pore system.
- Increasing the NaOH concentration from 10 mol/L to 16 mol/L decreased the compressive strength in water-cured mortar with a GGBS:fly ash ratio of 3:1. This suggests that 10 mol/L is the optimum NaOH concentration within the range evaluated for this ratio. An excessively high NaOH concentration may lead to overly high alkalinity that accelerates the reaction of the fast-reacting GGBS. This rapid reaction can cause overly fast polymerization and the precipitation of products on the binder particles, which may slow down or impede further polymerization. Further research is needed to fully understand the reasons behind the optimum NaOH concentration, especially in systems with high GGBS content.

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