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The Application of Alkali Activator and Admixture for High Early Concrete Compressive Strength with GGBFS Substitution

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ABSTRACT

Concrete with high early compressive strength is designed to reach at least 20 MPa within the first 24 hours after casting. However, achieving this generally requires increased cement content, which unfortunately leads to higher carbon emissions and production costs. To reduce this impact, cement can be partially substituted with pozzolans such as ground granulated blast furnace slag (GGBFS), which has a chemical composition similar to cement. Nevertheless, GGBFS exhibits a slow hydration process; therefore, an alkali activator is required to accelerate the reaction. On the other hand, alkali activation can reduce concrete workability, making the addition of admixtures such as superplasticizers necessary to maintain adequate workability. This study investigates the effect of adding alkali activators and admixtures on concrete's early compressive strength and workability of concrete incorporating GGBFS as a cement substitute. Ordinary Portland cement and GGBFS were used at a ratio of 70:30. The alkali activator consisted of NaOH and Na_2SiO_3, with a Na_2SiO_3/NaOH ratio (R) of 1.5 and a total alkali-to-GGBFS ratio (A) of 0.45. The superplasticizer was Sika® ViscoCrete®-1050 HE at at dosages of 0.5% and 1%. The alkali activator contents tested were 0%, 2.5%, 5%, 7.5%, and 10%. The paste-to-fine aggregate void ratio (R_m) and the mortar-to-coarse aggregate void ratio (R_b) were both set at 1.4. Workability was evaluated using the slump test, while compressive strength was measured at 24 hours. The results showed that the addition of an alkali activator led to a substantial improvement in the compressive strength of the concrete, reaching up to 114.8% of the minimum required early compressive strength. The compressive strength peaked at 43 MPa when 10% alkali activator was added to the mixture. However, increasing the alkali activator content significantly reduced workability, with the slump value reaching zero at the 10% dosage. The addition of a superplasticizer was proven to be necessary to maintain a balance between early strength and concrete workability.

1. Introduction

The construction sector contributes around 40% of global carbon dioxide emissions [1]. The production of cement clinker generates carbon dioxide (CO_2) emissions, which represent one of the main contributors to total global emissions [2]. Therefore, to reduce the use of cement, partial substitution using pozzolan has been implemented [3]. Additionally, pozzolans can enhance concrete quality by making it more uniform, cohesive, and dense, thereby contributing to improved mechanical performance [4].

According to ASTM D6868, pozzolanic materials can be formed by the accumulation of chemical compounds such as silica, calcium, alumina, magnesia, and iron with a combined concentration exceeding 70%. One of the most commonly used pozzolans is ground granulated blast furnace slag (GGBFS) [5]. GGBFS is an industrial solid waste product derived from the iron and steel industry [6]. It consists of silicate, calcium aluminosilicate, and other base compounds which are similar to the chemical composition of cement [7]. As a result, GGBFS is often used as a partial replacement for ordinary Portland cement

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(OPC) in concrete, helping to reduce cement consumption and lower the demand for clinker production.

Amid increasing demands for faster and more efficient construction, high early-strength concrete has become an important option. This type of concrete can reach a minimum compressive strength of 20 MPa in just 24 hours [8], allowing formwork to be removed more quickly and construction activities to proceed with minimal interruption. This directly contributes to time and cost savings [9]. However, mixtures with low water content are typically used to achieve such strength, which can reduce workability and increase cement consumption [10]. To maintain efficiency and workability, part of the cement must be replaced with alternative materials without compromising the concrete quality.

Previous studies have investigated the effect of using GGBFS as a substitute for OPC on concrete compressive strength at curing ages of 28, 90, 150, and 300 days, with GGBFS substitution levels of 0%, 20%, 40%, and 60%. The research results indicate that at 90 days, concrete containing 40% GGBFS exhibits higher compressive strength than concrete with 0%, 20%, and 60% GGBFS. Concrete with 60% GGBFS shows lower strength than concrete with 0%, 20%, and 40% GGBFS at all curing ages [11]. The initial hydration process of GGBFS with water alone occurs more slowly than that of OPC. To accelerate the reaction process, an alkali activator—typically a solution composed of sodium silicate and sodium hydroxide—is commonly used [12].

Several factors, including sodium hydroxide molarity, alkali solution/slag content, and sodium-silicate-to-sodium hydroxide ratio, must be considered [13]. Studies show that increasing sodium hydroxide molarity enhances compressive strength, tensile strength, elastic modulus, and porosity. Alkali-activated slag concrete can achieve approximately 90% of its compressive strength and tensile strength within 7 days, indicating high early strength development [14]. However, increasing sodium hydroxide molarity and the ratio of sodium silicate to sodium hydroxide can reduce the setting time of the paste. This occurs because a higher level of alkalinity alkali activator solution accelerates slag hydration, thereby reducing the setting time [15][16].

Alkali-activated GGBFS-based concrete cured at room temperature has shown no deterioration due to poor workability [17]. This is due to the higher water absorption capacity of GGBFS compared to natural fine aggregates; therefore, the use of retarders or chemical admixtures is recommended to achieve the desired slump value [18].

The addition of viscocrete can improve concrete workability and reduce water demand as the percentage of Viscocrete increases. The workability of concrete must be considered to facilitate the construction process in the field. The addition of Viscocrete increases compressive strength at concentrations up to 0.5%, but compressive strength decreases when used in higher concentrations [19]. Another study showed that adding 1% sika can increase the setting time [20]. Therefore, in this study, OPC was partially replaced with GGBFS and an alkali activator, and Sika Viscocrete admixture was incorporated. Through this approach, the resulting concrete is expected to achieve high early strength while maintaining good workability.

This study reviews the development of high early-strength concrete based on OPC with the addition of GGBFS, alkali activators, and admixtures through room temperature curing. This study aims to determine the optimal material requirements for concrete with high early compressive strength, specifically a minimum of 20 MPa within 24 hours, as well as adequate workability indicated by a slump value of 18–20 cm. The findings of this study are expected to advancements in concrete technology and support efforts to reduce cement consumption through the utilization of environmentally friendly materials such as GGBFS while achieving high early strength.

2. Methods

2.1 Ordinary Portland Cement dan GGBFS

The ordinary portland cement (OPC) used in this study was supplied by PT. Solusi Bangun Indonesia, as shown in Figure 1. The cement was type I, with a specific gravity of 3.15. The ground granulated blast furnace slag (GGBFS) used in this study was sourced from PT. Krakatau Semen Indonesia, with specifications based on ASTM C989 [21], a specific gravity of 2.77, and chemical composition as shown in the Table 1. GGBFS is a non-metallic product in the form of very fine grayish-white granules, as shown in the Figure 2. Based on initial trials, the optimal ratio between OPC and GGBFS was determined to be 70:30.

Figure 1. Ordinary portland cement

Figure 2. Ground granulated blast furnace slag

Figure 3. Silica sand

Figure 4. Optima sand

Figure 5. Coarse aggregate

Table 1. Chemical content of GGBFS

Components	Chemical content (%)
Aluminum Trioxide (Al_2O_3)	15.75
Silicon Dioxide (SiO_2)	37.03
Iron Trioxide (Fe_2O_3)	0.67
Magnesium Oksida (MgO)	1.52
Calcium Oxide (CaO)	42.61
Sulfur Trioxide (SO_3)	1.83
Potassium Oxide (K_2O)	0.30

2.2 Superplasticiser

The admixture used in this study was Sika® ViscoCrete®-1050 HE type E with a specific gravity of 1.07, hereinafter referred to as a superplasticizer. The superplasticizer can improve flowability, reduce water demand, and increase early strength.

2.3 Alkali Activator

The alkali activator consisted of a combination of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). The molarity of NaOH is set at 10 M based on the optimum concentration reported in previous studies [22]. Previous studies found that the optimum Na2SiO3/NaOH ratio (*R*) was 1.5, with an alkali-to-cement ratio (*A*) of 0.45 [23].

The NaOH solution was prepared by mixing NaOH pellets with 98.5% purity and distilled water, followed by stirring until the pellets were completely dissolved. The 10 M NaOH solution was then allowed to stand for 24 hours or until it reached room temperature. Subsequently, sodium silicate (Na_2SiO_3) was added, and the solution was left to stand for approximately 1 hour or until it reached room temperature before use.

2.4 Aggregate

The fine aggregate consisted of silica sand from Tayan, as shown in the Figure 3, and optima sand from Rumpin, Bogor, as shown in the Figure 4. The ratio of fine aggregate used was 70:30, composed of 70% silica sand and 30% optima sand. The coarse aggregate used comes from Rumpin, Bogor, with a particle size ranging from 10 to 20 mm, as shown in Figure 5. The characteristics of the aggregates are presented in the Table 2.

Table 2. Aggregate Characteristics

No	Description	Silica Sand	Optima Sand	Split 10/20
1	Fineness modulus (FM)	2.498	3.28	-
2	Spesific gravity (SG)	2.66	2.53	2.58
3	Absorption (%)	0.4	2.04	2.08
4	Material finer than 200 microns (%)	1	2.3	1.7
5	Unit weight (ton/m^3)	1.39	1.43	1.48
6	Organic impurities	No. 5	No. 1	-
7	Los Angeles (%)	-	-	17.88

2.5 Mix Design

There are no established standards for geopolymer paste mix design. Therefore, the calculation of paste, mortar, and concrete mixtures was determined based on the absolute volume proportions of each constituent material in 1 m^3 [24]. The absolute volume of the paste was calculated using Equation (1).

$$V_s+V_{ggbfs}+V_{sv}+V_a+V_{ac} = 1m^3 \tag{1}$$

Where, V_s is the absolute volume of hydraulic cement, V_{ggbfs} is the absolute volume of GGBFS, V_{sv} is the absolute volume of Sika® Viscocrete®-1050 HE, V_a is the absolute volume of water, V_{ac} is the absolute volume of alkali activator. Equation (1) was then expanded into Equation (2) to calculate the weight of each material. W_s represent the weight of cement, W_{ggbfs} represent the weight of GGBFS, W_{sv} represent the weight of Sika® ViscoCrete®-1050 HE, W_a represent the weight of water, W_{ac} represent the weight of alkali activator, G_{ss} is the specific gravity of cement, G_{sggbfs} is the specific gravity of GGBFS, G_{ssv} is the specific gravity of Sika® ViscoCrete®-1050 HE, G_{sa} is the particular gravity of water, and γ_w is the density of water.

The OPC and GGBFS mixture ratio was determined to be 70:30 based on trial-and-error testing. The water-to-cementitious ratio (*FASm*) was set at 0.25. The weight of Sika® ViscoCrete®-1050 HE was calculated based on the cement weight (W_{sm}), which is the addition of OPC and GGBFS weight. The use of alkali activators was calculated based on the percentage of GGBFS, not cement, and the amount of alkali activators used was then subtracted from the amount of water. This calculation was performed using Equation (3), where, X represent the percentage of GGBFS, Y represent the percentage of Sika® ViscoCrete®-1050 HE, and Z represent the percentage of alkali activator towards GGBFS.

The volume of voids between fine aggregate particles (V_{ragh}) in 1 m^3 can was calculated using Equation (4).The composition of the mortar mixture is determined according to the composition of the paste mixture. By modifying Equation (2), the mortar mixture composition was calculated using Equation (5). The composition of the mortar mixture was obtained by assuming that the volume of the paste fills the volume of the fine aggregate voids. Thus, the absolute volume ratio of the paste to the volume of the fine aggregate voids was determined (R_m). Weight of fine aggregate (W_{agh}) was calculated using Equation (6).

The volume of voids between coarse aggregate particles (V_{ragk}) in 1 m^3 was calculated by Equation (7). The composition of the concrete mix is determined by modifying the composition of the paste and mortar and was calculated using Equation (8). It was assumed that the voids between fine aggregate particles (V_{ragh}) is filled with the volume of the paste (Vp), while the volume of voids between coarse aggregate particles (V_{ragk}) is filled with mortar volume (V_m). So that the ratio of mortar volume to coarse aggregate void volume is determined (R_b). The weight of fine aggregate (W_{agh}) and coarse aggregate (W_{agk}) were calculated using Equation (9) and Equation (10), respectively.

Based on Equation (7), the proportions of the concrete mixture presented in the Table 1**.** The concrete sample code BSV0.5AC0 was used to simplify the identification of the concrete mix composition, where B represents the concrete code, SV0.5 indicates 0.5% superplasticizer, and AC0 indicates 0% alkali activator.

$$\frac{W_s}{G_{ss}\,\gamma_w}+\frac{W_{ggbfs}}{G_{sggbs}\,\gamma_w}+\frac{W_{sv}}{G_{ssv}\,\gamma_w}+\frac{W_a}{G_{sa}\,\gamma_w}+\frac{W_{ac}}{G_{sac}\,\gamma_w} = 1m^3 \tag{1}$$

$$\frac{(1-X)W_{sm}}{G_{ss}\,\gamma_w}+\frac{XW_{sm}}{G_{sggbs}\,\gamma_w}+\frac{YW_{sm}}{Gs_{sv}\,\gamma_w}+\frac{(FASm-ZAX)W_{sm}}{G_{sa}\,\gamma_w}+\frac{ZAXW_{sm}}{G_{sac}\,\gamma_w} = 1m^3 \tag{2}$$

$$V_{ragh} = 1-\frac{B_{sagh}}{G_{sagh}}\gamma_w \tag{3}$$

$$\frac{(1-X)W_{sm}}{G_{ss}\,\gamma_w}+\frac{XW_{sm}}{G_{sggbs}\,\gamma_w}+\frac{YW_{sm}}{Gs_{sv}\,\gamma_w}+\frac{(FASm-ZAX)W_{sm}}{G_{sa}\,\gamma_w}+\frac{ZAXW_{sm}}{G_{sac}\,\gamma_w} = R_m V_{ragh} \tag{4}$$

$$V_{ragh}R_m+\frac{W_{agh}}{G_{sagh}\gamma_w} = 1\,m^3 \tag{5}$$

$$V_{ragk} = 1-\frac{B_{sagk}}{G_{sagk}}\gamma_w \tag{6}$$

$$\frac{(1-X)W_{sm}}{G_{ss}\,\gamma_w}+\frac{XW_{sm}}{G_{sggbs}\,\gamma_w}+\frac{YW_{sm}}{Gs_{sv}\,\gamma_w}+\frac{(FASm-ZAX)W_{sm}}{G_{sa}\,\gamma_w}+\frac{ZAXW_{sm}}{G_{sac}\,\gamma_w} = R_m V_{ragh} R_b V_{ragk} \tag{7}$$

$$R_m V_{ragh} R_b V_{ragk}+\frac{W_{agh}}{G_{sagh}\gamma_w} = R_b V_{ragk} \tag{8}$$

$$R_b V_{ragk}+\frac{W_{agk}}{G_{sagk}\gamma_w} = 1\,m^3 \tag{9}$$

Table 3. Concrete mix design proportions in m^3

Label	Weight (kg/m^3)												
	OPC	GGBFS	SV	W	SS	SH	Silica Sand	Optima Sand	Course Aggregate	R_m	R_b	*Vragh*	*Vragk*
BSV0.5AC0	464.9	199.2	3.3	166	0	0	0.0	0.0	1040	1.4	1.4	0.47	0.43
BSV0.5AC2.5	465.9	199.7	3.3	164.1	1.3	0.9	382.1	163.7	1040	1.4	1.4	0.47	0.43
BSV0.5AC5	466.8	200.1	3.3	162.2	2.7	1.8	382.1	163.7	1040	1.4	1.4	0.47	0.43
BSV0.5AC7.5	467.8	200.5	3.3	160.3	4.1	2.7	382.1	163.7	1040	1.4	1.4	0.47	0.43
BSV0.5AC10	468.8	200.9	3.3	158.4	5.4	3.6	382.1	163.7	1040	1.4	1.4	0.47	0.43
BSV1.0AC5	463.1	198.5	6.6	160.9	2.7	1.8	382.1	163.7	1040	1.4	1.4	0.47	0.43

Label: *OPC* = ordinary portland cement, *GGBFS* = ground granulated blast furnace slag, *SV* = sika viscocrete, *W* = water, *SS* = sodium silicate, *SH* = sodium hydroxide, R_m = the absolute volume of paste of the absolute volume of fine aggregate voids, R_b the absolute volume of mortar of the absolute volume of coarse aggregate voids, V_{ragh} = the volume of voids between fine aggregate particles, V_{ragk} = the volume of voids between coarse aggregate particles

Figure 1. Compressive strength test on concrete

2.6 Mixing, casting, and testing

The mixing process is carried out by dry mixing OPC and GGBFS. At this stage, it is highly recommended to wear a mask, as the mixing process of dry materials such as GGBFS and OPC can easily disperse into the air and enter the respiratory tract. Water mixed with the superplasticizer was then added. Mixing was conducted for approximately 5 minutes until a homogeneous mixture was obtained, as GGBFS and water require time for the mixture to stop clumping.

Subsequently, the alkali activator was added and mixed for approximately 3.5 minutes or until the alkali activator reacts with the cement. The fine aggregate was then added and mixed for approximately 3.5 minutes, followed by the addition of coarse aggregate and further mixing for approximately 3.5 minutes.

The workability of fresh concrete was evaluated using the slump test in accordance with SNI 1972:2008 [25]. The concrete was then cast into 100 × 200 mm cylindrical molds in three layers, with compaction performed according to SNI 4810:2013 [26].

Compressive strength testing was conducted at 24 hours ± 30 minutes in accordance with SNI 1974:2011 [27]. The compressive strength of concrete was calculated using the Equation (11), where P is the compressive load, and A represents the the cross-sectional area of the test specimen. The compressive strength test setup is shown in Figure 6**.**

$$f'_c = \frac{P}{A} \tag{10}$$

3. Results and Discussion

3.1. Compressive Strength

The compressive strength test results at 24 hours showed that the BSV1.0AC5 sample had a compressive strength of 30.6 MPa. However, segregation occurred at high superplasticizer percentages, where white spots could be seen on the concrete, as shown in Figure 7**.** This indicates that the concrete is not homogeneous, so the percentage of superplasticizer is reduced to 0.5%. Figure 8 BSV0.5AC5 shows that when using 0.5% superplasticizer with the same percentage of activator, namely 5%, the concrete appears more homogeneous with the disappearance of white spots on the cylinder sample with a compressive strength of 34.5 MPa. Increasing the percentage of superplasticizer does not directly affect compressive strength [28]. The results of concrete compressive strength testing at 24 hours with a superplasticizer percentage of 0.5% show an increase in compressive strength with the addition of alkali activators. The compressive strength of the concrete increased by 62% with the addition of 2.5%

alkali activator. It increased to 114.8% by adding 10% alkali activator from the required compressive strength for high-strength concrete, which is 20 MPa at 24 hours [8]. An increase in the percentage of alkaline activator tends to enhance compressive strength, as higher doses of alkaline activator can elevate the pH of the activator solution. An increase in pH can accelerate the dissolution process of silica (Si) and aluminum (Al) compounds, which has an impact on the increase in compressive strength [29]. However, sample BSV0.5AC7.5 in Figure 9 and sample BSV0.5AC10 in Figure 10 shows porosity due to poor compaction during the casting process. An increase in the chemical composition of the alkali activator causes the reaction to accelerate, causing the concrete to harden more quickly [30]. The results of concrete compressive strength testing with various alkali activator variations can be seen in Figure 11**.**

Figure 2. BSV1.0AC5

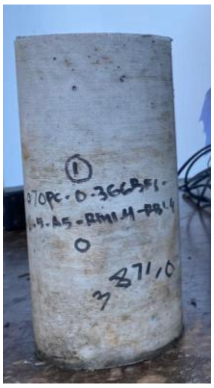

Figure 3. BSV0.5AC5

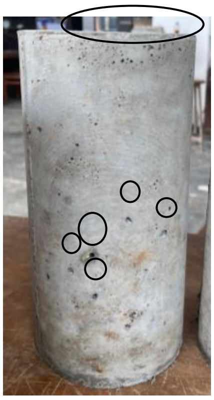

Figure 4. BSV0.5AC7.5

Figure 5. BSV0.5AC10

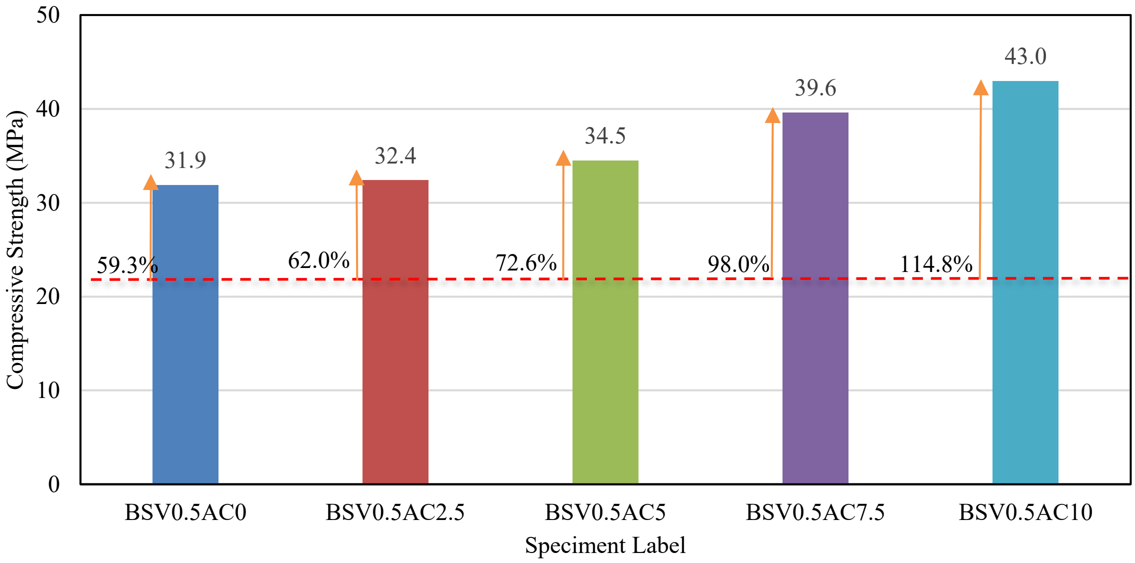

Figure 6. Compressive strength of concrete with various alkali activators.

3.2 Workability of Concrete

The slump test results show that the higher the percentage of alkali activator, the lower the slump value, as seen in Figure 12**.** A low slump value results in high compressive strength, but the mixture cannot be worked, causing construction problems [31]. The slump value of sample BSV0.5AC0 was 21.5 cm, and segregation occurred with water separation in the mixture, as shown in Figure 13**.** The BSV0.5AC0.25 was a 20.5 cm sample's slump value still showed segregation with the paste's separation, as seen in Figure 14. However, adding 2.5% alkali activator produces concrete with a denser consistency, as seen in a 4.7% decrease in slump value compared to concrete without alkali activator. Segregation occurs when there is an uneven concentration of components in concrete or mortar mix, or an uneven distribution of sizes in the aggregate mass [32]. Concrete segregation is influenced more by the ratio of volume to surface area and the density difference between the coarse aggregate and the mortar, rather than by individula material properties [33]. Based on the target slump value of 18-20 cm, the slump value of the BSV0.5AC5 sample is the most optimal slump value, which is 19.5 cm. The BSV0.5AC5 sample experienced a 9.3% decrease in slump value compared to the BSV0.5AC0 sample, which did not use an alkali activator. The BSV0.5AC5 sample in Figure 15 shows that the concrete mix is homogeneous with no separation between the concrete components. Controlling concrete segregation is very important to ensure the strength and durability of concrete [34]. Based on Figure 16, the slump value of sample BSV0.5AC7.5, which was 5 cm, decreased significantly compared to using alkali activators by up to 5%. Compared to the sample BSV0.5AC0, there was a decrease of 76.7%. As illustrated in Figure 17, the slump value of the BSV0.5AC10 sample was 0 cm, with no slump at all. Concrete mixtures that absorb higher amounts of mixing water harden faster, decreasing workability [35].

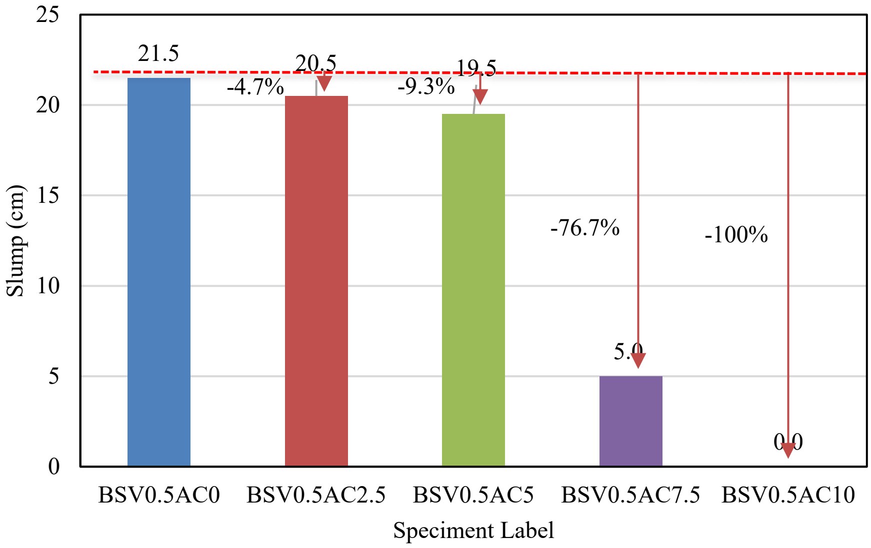

Figure 7. Slump values of various alkaline activators.

Figure 8.
BSV0.5AC0

Figure 9.
BSV0.5AC2.5

Figure 10.
BSV0.5AC5

Figure 11.
BSV0.5AC7.5

Figure 12.
BSV0.5AC10

4. Conclusions

The study's results indicate that the initial compressive strength of concrete at 24 hours increases with the addition of alkali activator. This is evidenced by adding 10% alkali activator, which can increase compressive strength to 114.8% of the required specification of 20 MPa in 24 hours. Meanwhile, the mixture without adding alkali activator only experienced an increase of 59.3% from the requirement. However, increasing the alkali activator percentage can reduce concrete workability. At a 10% alkali activator percentage, there was no deterioration in the slump test, with a slump value of zero. The most significant decrease in workability begins at an alkali activator addition of 7.5%, reaching 76.7% compared to the mixture without alkali activator addition. Based on this study, the most optimal concrete mix design occurs with a 30% substitution of GGBFS, 0.5% superplasticizer, and a 5% addition of alkali activator, resulting in a slump value of 19.5 cm and compressive strength of 34.5 MPa.

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