construction materials

Article

The Influence of Molarity Activity on the Green and Mechanical Properties of Geopolymer Concrete

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Abstract: The usage of geopolymer-based materials (GPBMs) in concrete structures has been broadly promoted by the current construction sector. GPBMs have an outstanding influence on enhancing concrete mechanical properties. Geopolymers (GPs) also have a potential impact on reducing the carbon dioxide emissions emitted by the current cement production procedure. Therefore, this paper aims to evaluate the impact of some variables that affect green and mechanical properties of fly ash-based geopolymer concretes (FA–GPCs), i.e., different silica fume (SF) contents, alkaline activator solution (AAS) percentages, sodium silicate-to-sodium hydroxide (SS/SH) ratios, sodium hydroxide (NaOH) molarity, and additional water. A slump test was used to evaluate the concrete workability to assess the green properties of the designed fly ash-geopolymer concrete mixes (FA–GPCMs). The 14- and 28-day compressive strengths were used to evaluate the concrete's mechanical properties. Results indicate that the workability of prepared FA–GPCMs reduced with improving SF content (5% to 30%), SS/SH ratio (1% to 3%), and NaOH molarity (10 M to 16 M), while reducing alkaline activator percentages to 35% resulted in a decrease in the FA–GPCMs' workability. Also, increasing SF replacement percentages from 5% to 15% in FA–GPCMs resulted in significant 14- and 28-day FA–GP compressive strength enhancements compared to FA–GPCM produced with 0% SF, while SF contents of 20%, 25%, and 30% led to a decline in the 14- and 28-day FA–GPC compressive strength compared to that of G1–SF15%.

Keywords: geopolymer; alkaline activators; silica fume; fly ash; compressive strength; workability

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1. Introduction

The constant surge in concrete demand for several applications in the construction field has led to a corresponding increase in cement production [1,2]. Cement possesses various favorable physical and hardened properties in addition to being available and affordable [3–5]. Nonetheless, it is an undeniable fact that the current construction industry is considered to be one of the main sources contributing to generating carbon dioxide emissions (CDEs) [6,7]. It is highly reliant on using Portland cement (PC) as a primary building material. In particular, the current production practices of cement are extremely energy-intensive, and each ton releases approximately a ton of carbon dioxide emissions (CO_2) [8–11]. It was reported that 1.6 tons of raw constituents are used globally to manufacture 1 ton of cement, and that causes 1 ton of CO_2 [2]. Data have also reported that 13,500 million tons of CO_2 are generated globally from cement production. Thus, around

7–8% of the overall CDEs are annually emitted by the cement industry [12–14]. Accordingly, to eliminate the detrimental impact associated with the cement production procedure, sustainable materials (SMs) can be incorporated as alternatives to conventional cement (CC). Most SMs have been the result of industries as a different form of waste constituents which can be applied as cementitious materials. Hence, the application of such wastes into concrete mixtures can contribute to a significant reduction in carbon dioxide emissions (CDEs) and the depletion of natural raw resources linked with CC, as well as offer efficient waste control [1,15].

Thus, realizing the detrimental impact of the cement production process has created global pressure toward the utilization of sustainable building materials such as geopolymers (GPs). GPs are cementitious materials; the term was first devised in 1978 by Davidovits and was applied to a certain type of source material created by reacting an alkaline activator solution (AAS) with aluminosilicate-based materials [16,17]. Several cementitious replacement materials (CRMs) are presently applied in producing GP concrete. Basically, CRMs are classified into two main groups. Natural pozzolans (NPs) are the first group, and they are typically obtained from volcanic magma. NPs are a mixture of silica/silica-alumina-based amorphous glasses. Organic materials (OMs) are the second group of CRMs, which are created as a result of industrial waste, i.e., slag, red mud, metakaolin, and fly ash, and rice husk ash [17]. The application of such sustainable cementitious materials (SCMs), i.e., fly ash (FA), ground granulated blast slag (GGBS), silica fume (SF), rice husk ash (RHA), eggshell powder (ESP), and palm oil fuel ash (POFA), can contribute to conserving environment sustainability [18–20]. Hence, the matrix development and the strength of geopolymer concrete (GPC) do not demand a calcium–silicate hydrate (C–S–H) gel but highly depend on the polycondensation of alumina and silica precursors [17,21,22]. It was reported that the substitution of CCs by GPCs results in a reduction of up to 80% in CO_2 based on the applied precursor and alkaline activator solutions [23].

GPs have recently gained massive attention in both the construction industry and research. Since geopolymer-based materials (GPMs) involve considerable impact on improving the physical, chemical, as well as mechanical properties of concrete, their usage has been promoted [24,25]. For instance, GPs have been employed as a substitute for OPC composites in several specific applications, i.e., fiber-reinforced composites, fire-resistant coatings, and waste control [1,26]. Specifically, SCMs have a beneficial impact on concrete's hardened properties, i.e., compressive, flexural, and tensile strengths, and this is primarily due to the chemical composition of the GP binder. Hence, the incorporation of SCMs results in concrete with a dense microstructure [27,28]. Basically, concrete produced with geopolymers has a shorter setting time, a superior initial strength, a higher fire resistance, lower permeability, and excellent acid resistance compared to those achieved with traditional PC [29]. Thus, applying geopolymers (GPs) in concrete structures has been broadly promoted by the current construction sector due to their outstanding properties.

Alumina–silicate-based constituents and alkali-silicate activator solution (ASAS) are the principal elements of geopolymer concrete (GPC). GPs are created through mixing materials involving aluminum (Al_2O_3) and silica (SiO_2) with alkali–silicate activator solution (ASAS). ASAS, in turn, breaks the connections of Al_2O_3 and SiO_2 in the aluminosilicate powder. Then, the major inorganic polymer chain is formed after the dissolution and activation of the Ai and Si particles in a quick polymerization interaction [15,16]. The silicate alkali solvent includes calcium hydroxide ($Ca\ (OH)_2$), potassium hydroxide (KOH), sodium hydroxide (NaOH), alone or a mixture of these ASASs, involving a silicate solution with either potassium silicate (K_2SiO) or sodium silicate (Na_2SiO_3) [18,30].

The strengthening development in GPC is highly influenced by the polymerization reactions between the aluminosilicate precursors and alkaline activators [31,32]. Thus, the effect of different built-up geopolymer materials on the hardened concrete properties has been thoroughly inspected. Particularly, silica fume (SF) has been the most inspected aluminosilicate precursor [33]. The particle size of SF is very small, allowing it to fill the micro cavities existing in the concrete matrix. Thus, it has a considerable role in improving the hardened properties of concrete by strengthening the bond between the cement paste and unreacted components [34,35]. Previous papers have restricted the dosage of silica fume (SF) and other parameters that influence the bond strength of the concrete matrix, i.e., NaOH concentration, ASAS percentages, and SS/SH weight ratios [36–38]. However, prior investigations have stated controversial findings concerning the optimum percentages of mentioned variables. Some papers indicated that the incorporation of above 5% of SF into concrete mixtures increases the permeability of concrete, as the high silicon dioxide content of SF hinders the polymerization [39–41]. With improving silica fume dosage, sodium oxide, which is required for the dissolution process, might be unavailable in ASAS. Thus, some unreacted SEMs stay in the GP gel, which leads to an increase in concrete's permeability and then reduces the concrete's durability. On the other hand, other publications stated that the best substitution percentages of SF can be 10% and 7% [25,42].

To expand sustainability awareness in the construction domain, extensive research works have been conducted to study GPCs' properties. In particular, the mechanical properties of GPCs are highly affected by several variables, i.e., the applied geopolymer-based materials (GPBMs), mixture proportions, Si/Al ratio, and (SiO_2 + Al_2O_3), in addition to other important parameters, i.e., content of di-hydrogen monoxide, used alkaline activators, and the applied curing process [31,43]. As mentioned earlier, previous knowledge concerning the influence of those mentioned factors on the fresh and hardened properties of fly ash-based geopolymer (FA-GPCs), including SF, is mostly controversial and limited. Therefore, this paper involves a comprehensive study to evaluate and compare the green and mechanical properties of FA-GPC produced with different silica fume (SF) percentages, alkaline activator solution (AAS) contents, and sodium hydroxide solution (NaOH) molarity, sodium silicate/sodium hydroxide (SS/SH) ratios, and additional water. The effects of those mentioned parameters on the fresh and mechanical properties were assessed based on workability and compressive strength, through applying slump tests and compression tests, respectively.

2. Materials and the Experimental Procedure

2.1. Materials

In this paper, the utilized cementitious materials were low-calcium fly ash (FFA), and silica fume (SF) (Figure 1). The physical and chemical properties of FFA and SF are presented in Table 1. Coarse aggregate (CA) and sand (S) were applied with the max particle sizes of 9.5 and 4.0 mm, respectively (Figure 2). The specific gravity and water absorption of the utilized coarse aggregate and sand were 2.67, 0.68%, 2.63, and 1.3%, respectively. The utilized alkaline activator solution (AAS) was a combination of sodium silicate solution (D-Grade-Na_2SiO_3) (Figure 1i) and sodium hydroxide (NaOH) of 98% purity (Figure 1e). The chemical components of Na_2SiO_3-D-Grade were 14.8% Na_2O and 29.3% SiO_2 by weight. The specific gravity of the used D-Grade-Na_2SiO_3 was 1.5. Sodium hydroxide solution was prepared with four different concentrations, i.e., 10, 12, 14, and 16 M. They were made by disintegrating NaOH solid pellets with a purity of 98% with tap water [22].

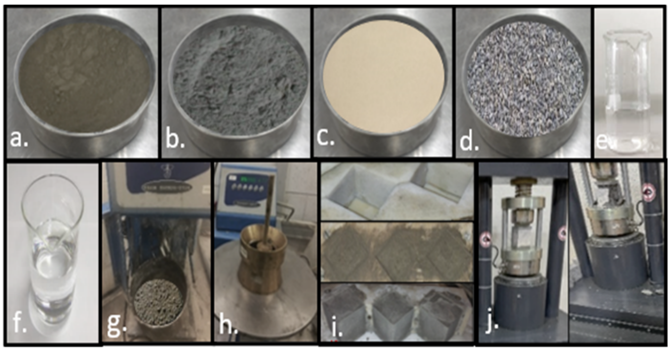

Figure 1. (**a**) Fly ash, (**b**) silica fume, (**c**) sand, (**d**) coarse aggregate, (**e**) sodium hydroxide, (**f**) sodium silicate, (**g**) mixing machine, (**h**) a slump test, (**i**) cubic GPC specimens, (**j**) compression test.

Table 1. Chemical composition of fly ash (FFA) and silica fume (SF).

Chemicals	**FFA%**	**SF%**
SiO_2	51.23	91.9
Al_2O_3	25.65	0.67
CaO	4.36	0.42
Fe_2O_3	12.7	1.23
MgO	1.48	1.69
Na_2O	0.81	0.43
SO_3	0.24	—
K_2O	0.73	1.19
LOI	0.58	1.18
P_2O_5	0.87	—
Color	Gray	Dark gray

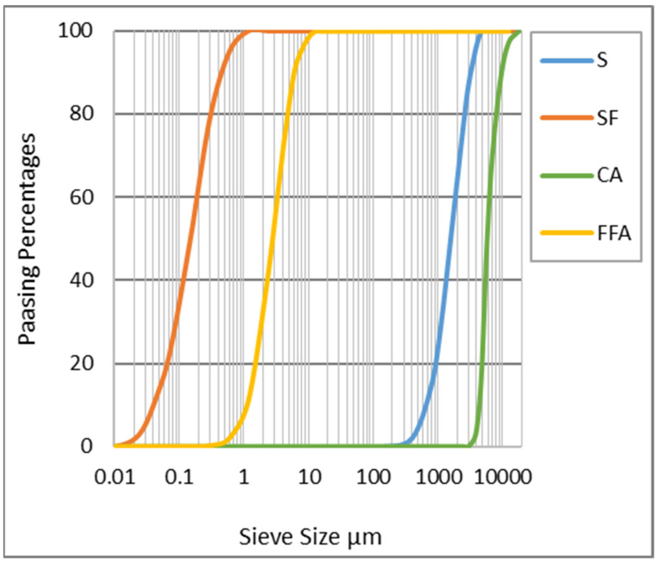

Figure 2. Particle size distribution of FA, SF, sand (S), and coarse aggregate (CA).

2.2. Mixture Proportions

In this paper, FA–GPC mixes were categorized into six main groups based on the studied parameters, i.e., different SF contents, AAS percentages, NaOH molarity, SS/SH ratios, and additional water, as revealed in Table 2. In total, forty-eight different fly ash-based geopolymer concrete mixes (FA–GPCMs) were included in the experimental program of this paper. They were mainly designed to evaluate the effect of the five mentioned variables on the fresh and hardened properties of FA–GPCs. The involved FA–GPC mixes were one reference mix (RM) with 100%FFA, and the rest of FA–GPCMs involved different substitution percentages of SF. All FA–GPCMs comprised FFA, coarse aggregate (1110 kg/m^3), as well as sand (580 kg/m^3) with 9.5 mm and 4 mm maximum particle size, respectively, AAS (a mixture of sodium hydroxide solution and D-grade sodium silicate), additional water (AW), and superplasticizer (%4 SP). The forty-eight FA–GPCMs were designed by varying the studied mix parameters, i.e., SF contents (5%, 10%, 15%, 20%, 25%, and 30%), SS/SH ratio (1, 1.5, 2.0, 2.5 and 3.0), AAS percentages (35%, 40%, and 45%), and NaOH molarity (10, 12, 14, and 16 M). For further information, Table 2 includes the mixture proportions of designed FA–GPCMs in this paper.

Table 2. Mixture proportions of FA–GPCMs.

Group No.	Mix No.	Mix ID	FA	S	CA	SF%	AAS%	SS/SH%	M	AW%	SP%	The Studied Factor
			Unit Content (kg/m^3)									
	1	G1–SF0%	500	580	1110	0	40	1	10	-	4	
	2	G1–SF5%	475	580	1110	5	40	1	10	-	4	Effect of SF Content
	3	G1–SF10%	450	580	1110	10	40	1	10	-	4	
1	4	G1–SF15%	425	580	1110	15	40	1	10	-	4	
	5	G1–SF20%	400	580	1110	20	40	1	10	-	4	
	6	G1–SF25%	375	580	1110	25	40	1	10	-	4	
	7	G1–SF30%	350	580	1110	25	40	1	10	-	4	
	8	G2–SF0%	500	580	1110	0	45	1	10	-	4	
	9	G2–SF5%	475	580	1110	5	45	1	10	-	4	
	10	G2–SF10%	450	580	1110	10	45	1	10	-	4	Effect of AAS Content
2	11	G2–SF15%	425	580	1110	15	45	1	10	-	4	
	12	G2–SF20%	400	580	1110	20	45	1	10	-	4	
	13	G2–SF25%	375	580	1110	20	45	1	10	-	4	
	14	G2–SF30%	350	580	1110	25	45	1	10	-	4	
	15	G3–SF0%	500	580	1110	0	35	1	10	-	4	
	16	G3–SF5%	475	580	1110	5	35	1	10	-	4	
	17	G3–SF10%	450	580	1110	10	35	1	10	-	4	
3	18	G3–SF15%	425	580	1110	15	35	1	10	-	4	
	19	G3–SF20%	400	580	1110	15	35	1	10	-	4	
	20	G3–SF25%	375	580	1110	20	35	1	10	-	4	
	21	G3–SF30%	350	580	1110	25	35	1	10	-	4	
	22	G4–10M–SF5%	475	580	1110	5	40	1	10	-	4	
	23	G4–12M–SF5%	475	580	1110	5	40	1	12	-	4	
	24	G4–14M–SF5%	475	580	1110	5	40	1	14	-	4	
	25	G4–16M–SF5%	475	580	1110	5	40	1	16	-	4	
	26	G4–10M–S10%	450	580	1110	10	40	1	10	-	4	
4	27	G4–12M–S10%	450	580	1110	10	40	1	12	-	4	Effects of NaOH Molarity
	28	G4–14M–S10%	450	580	1110	10	40	1	14	-	4	
	29	G4–16M–S10%	450	580	1110	10	40	1	16	-	4	
	30	G4–10M–S15%	425	580	1110	15	40	1	10	-	4	
	31	G4–12M–S15%	425	580	1110	15	40	1	12	-	4	
	32	G4–14M–S15%	425	580	1110	15	40	1	14	-	4	
	33	G4–16M–S15%	425	580	1110	15	40	1	16	-	4	

Table 2. *Cont.*

Group No.	Mix No.	Mix ID	FA	S	CA	SF%	AAS%	SS/SH%	M	AW%	SP%	The Studied Factor
			Unit Content (kg/m^3)									
5	34	G5–SS/SH1%	450	580	1110	10	40	1	10	-	4	Impact of SS/SH Ratio
	35	G5–SS/SH1.5%	450	580	1110	10	40	1.5	10	-	4	
	36	G5–SS/SH2%	450	580	1110	10	40	2	10	-	4	
	37	G5–SS/SH2.5%	450	580	1110	10	40	2.5	10	-	4	
	38	G5–SS/SH3%	450	580	1110	10	40	3	10	-	4	
6	39	G6–SF0%	500	580	1110	0	35	1	10	14.5	4	Impact of additional water
	40	G6–SF5%	475	580	1110	5	35	1	10	14.5	4	
	41	G6–SF10%	450	580	1110	10	35	1	10	14.5	4	
	42	G6–SF15%	425	580	1110	15	35	1	10	14.5	4	
	43	G6–SF20%	400	580	1110	15	35	1	10	14.5	4	
	44	G6–SF25%	375	580	1110	20	35	1	10	14.5	4	
	45	G6–SF30%	350	580	1110	25	35	1	10	14.5	4	
	46	G6–16M–SF5%	475	580	1110	5	40	1	16	14.5	4	
	47	G6–16M–S10%	450	580	1110	10	40	1	16	14.5	4	
	48	G6–16M–S15%	425	580	1110	15	40	1	16	14.5	4	

2.3. Mixing Process and Specimen Preparation

The mixing process of FA–GPCMs started with preparing alkaline activator solution (AAS). To prepare AAS, sodium hydroxide (SH) solution with a determined concentration (10, 12, 14, or 16 M) was first prepared in advance by mixing NaOH pellets of 98% purity with tap water. Then, sodium hydroxide (SH) and sodium silicate (SS) were mixed in a predetermined ratio (1%, 1.5%, 2%, 2.5%, or 3%) to produce AAS. The next step of the mixing process was mixing dry constituents (S, CA, FA, and SF); it lasted for 2–4 min. After that, the wet mixing step started through adding liquid materials (AAS, AW, and SP) gradually to the dry mixture in the mixing machine, and it was run for 5 min (Figure 1g). During this step, the prepared alkaline solutions began to bind unreacted ingredients, i.e., sand and coarse aggregate, to create GPC. The mixing process was applied at a room temperature of 23 °C. The mixing process, temperature, as well as time were kept the same for of all FA–GPCMs. The preparation procedure of fly ash-based geopolymer concrete samples (FA–GPCSs) was started by preparing molds previously and then applying FA–GPCM in the specified standard molds. Then, FA–GPCSs were compacted for 3 min by using the electrical vibrant table to attain a high compaction level and reduce existing air voids. Then, the FA–GPC specimens were left inside a plastic sheet to preserve their moisture level and avoid passive reaction between GPs and airborne particles. The warped GPCSs were left in an ambient temperature of 23 °C for 24 h. After that, the GPCSs were demolded and cured with an oven curing temperature of 60 °C for 24 h [44]. Then, GPCSs were kept at a room temperature of 23 °C until the specified testing day.

2.4. Testing Procedure

Slump tests were applied in accordance with ASTM C143/C143M to assess the effect of some important parameters, i.e., different SF dosages, alkaline activator solution (AAS) percentages, sodium hydroxide molarity, sodium silicate-to-sodium hydroxide (SS/SH) ratios, and additional water (AW), on the FA–GPCs' workability (Figure 1h) [45]. Compression tests were also applied to assess the impact of mentioned variables on the FA–GPCs' 14- and 28-day compression strength. A compression test was performed on cubic FA–GPCSs for each FA-based geopolymer concrete mixture in accordance with ASTM C39/C39M [46]. Cubic molds with dimensions of 50 × 50 × 50 mm were utilized to form testing specimens

(Figure 1i). Compressive strength results of incorporated FA–GPCSs were the average strength of three FA-GPC specimens for each FA–GPCM.

3. Result and Discussion

3.1. Workability

The green properties of FA–GPCMs were evaluated in terms of concrete workability. The flowability of incorporated FA–GPCMs was assessed by conducting a number of slump cone tests in accordance with the ASTM C143/C143M [45]. Basically, this section discusses the impact of five significant parameters (i.e., SF content, AAS percentages, NaOH dosage, SS/SH ratio, and additional water) on the workability of the designed FA–GPCMs, as listed below:

3.1.1. The Effect of Silica Fume Content

The effect of different SF replacement percentages on the slump value of FA–GPCMs is shown in Figure 3. In this part, FA–GPCMs of group 1 (G1) were utilized to assess the impact of the SF content on the FA–GPCMs' flowability. FA–GPCMs of group 1 were produced with different SF replacement percentages, i.e., 5%, 10%, 15%, 20%, 25%, and 30%, while keeping the rest of the parameters constant, i.e., 40%AAS, 10 M NaOH, and 1% SS/SH. According to the slump test outcomes, the flowability of FA–GPCMs was extremely affected by the replacement percentages of SF in the prepared GPCMs. More specifically, the workability of FA–GPCMs gradually declined by increasing SF percentages from 5% to 30%. For instance, G1–SF30% showed the lowest slump value of 96 mm compared to the rest of the FA–GPCMs of group 1, produced with lower SF contents. More particularly, the slump values of FA–GPCMs–G1 declined by 49% (G1–SF30%), 40% (G1–SF25%), 32% (G1–SF20%), 25% (G1–SF15%), 16% (G1–SF10%), and 9% (G1–SF5%), respectively, compared to that of the reference mixture (G1–SF0%). The decline in the slump values of FA–GPCMs produced with high percentages of SF can highly contribute to the physical and chemical properties of silica fume. Namely, the reactivity of SF is high due to its fine particle size, approximately 0.1 µm, and average surface area, around 30 m^2/gm. Thus, a high surface area necessitates additional AAS, SP, or water. The same findings were drawn from previous investigations [47–49].

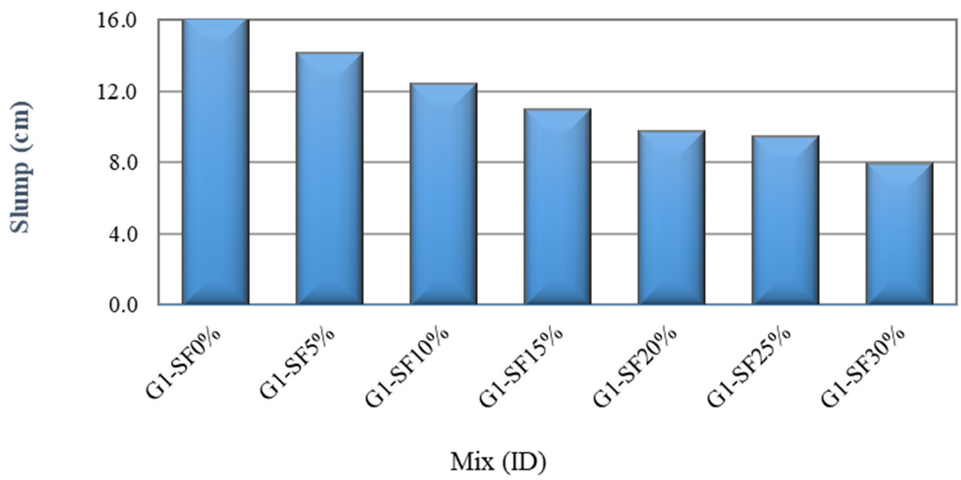

Figure 3. Influence of SF content on the slump value of FA–GPCMs.

3.1.2. Effect of Alkaline Activator Solution Content

The impact of alkaline activator solution content on the slump value of FA–GPCM is represented in Figure 4. In this part, three groups of GPCMs were prepared with three different AAS percentages. Group 1 (G1), group 2 (G2), and group 3 (G3) had percentages of 40%, 45%, and 35%, respectively. FA–GPCMs of each group were produced with different SF replacement percentages (i.e., 5%, 10%, 15%, 20%, 25%, and 30%) while keeping the rest of the parameters constant, i.e., 10 M NaOH, and 1%SS/SH. The effect of AAS on the FA–GPCMs' flowability was evaluated through comparing the slump test results of the three incorporated groups. The slump test outcomes of G1 mixes ranged between 161 and 83 mm, whereas the slump outcomes of G2 and G3 mixes were between 229 and 109 mm and between 99 and 40 mm, respectively. It was indicated that slump test results of group 1 FA–GPCMs (40% AAS) were lower than those of group 2 (45% AAS) and higher than those of group 3 (35% AAS), as seen in Figure 4. More specifically, the slump value of (G1–SF10%) was lower by 33% than that of (G2–SF10%) and higher by 41% than that of (G3–SF10%). The decrease in the FA–GPCMs' workability can be attributed to the high friction between the dry material particles initiated by the insufficient AAS content, resulting in a sticky system, which in turn decreased the total consistency of FA–GPCMs [50]. Thus, it is essential to maintain the AAS dosage, because it is essential to complete the dissolution process [51].

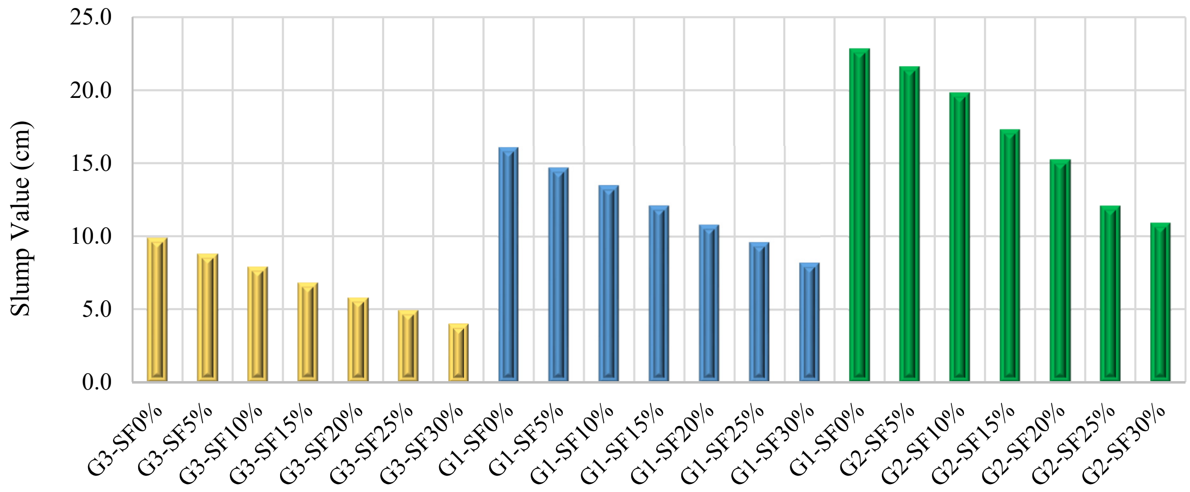

Figure 4. The effect of AAS on slump value of FA–GPCMs.

3.1.3. Effect of Sodium Hydroxide Molarity

In this section, FA–GPCMs of group 4 (G4) were used to inspect the effect of NaOH molarity on the workability of fly ash-based geopolymer concrete mixes (FA–GPCMs). The applied mixes were produced with different NaOH concentrations, i.e., 10, 12, 14, and 16 M, and SF contents (5, 10, and 15) with keeping the rest of the parameters constant, i.e., 40% AAS, and 1% SS/SH. Figure 5 involves the impact of different NaOH concentrations on the slump values of FA–GPCMs. Outcomes indicated that the flowability of FA–GPCMs decreased with rising NaOH molarity. For instance, the slump values of some G4 FA–GPCMs produced with 10%SF and NaOH molarity of 10, 12, 14, and 16 M were 135, 111, 82, and 61 mm, respectively. This indicated that the decrease in the slump values of FA–GPCMs prepared with 16 M NaOH (G4–16M–S10%) was lower by 56%, 44%, and 28% compared to those of 10, 12, and 14 M, respectively. Moreover, this decline increased with rising SF replacement percentages in FA–GPCMs. For example, the slump value of mix G4–14M–S15% was lesser by 23% and 30% than those of mix G4–14M–S10% and mix G4–14M–S5%, respectively. The reason behind the decline in the slump values of FA–GPCMs due to improving NaOH molarity is closely correlated to the increase in the GPCMs' viscosity, which in turn produces less workable and stickier mortar [52]. Thus, most previous investigations recommended using 8 M or 10 M to maintain the workability of FA–GPCMs [15,42,44].

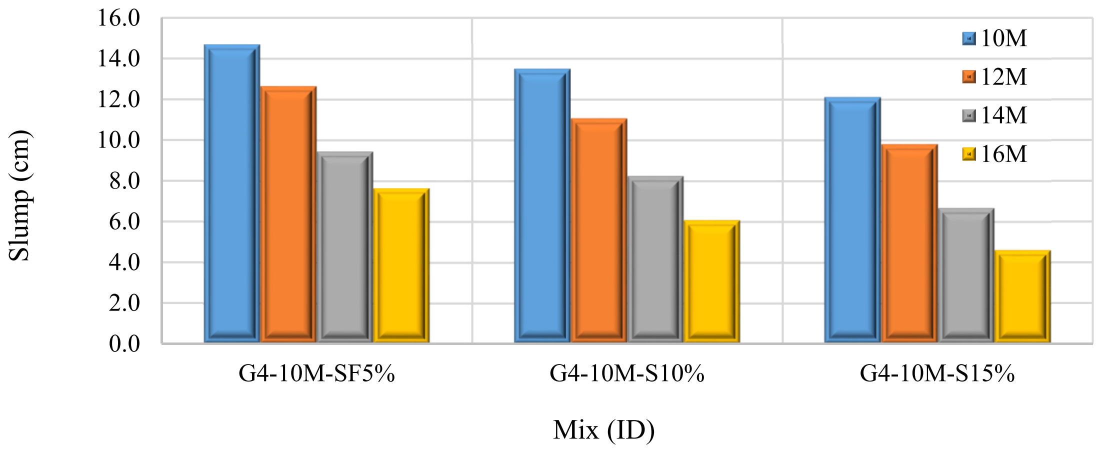

Figure 5. The effect of NaOH molarity on the slump value of FA–GPCMs.

3.1.4. Impact of Sodium Silicate-to-Sodium Hydroxide Ratio

In this part, FA–GPCMs of group 5 (G5) were utilized to evaluate the influence of different SS/SH ratios on the FA–GPCMs' workability. G5 Mixes were made with various SS/SH ratios (i.e., 1, 1.5, 2, 2.5 and 3.0) and constant percentages of 10%SF, 40%AAS, and 10 M NaOH molarity. The slump test results of G5 FA–GPCMs are shown in Figure 6. The outcomes presented that slump outcomes of G5 FA–GPCMs declined with increasing SS/SH ratios from 1% to 3%. For instance, the slump test result of mix G5–3% SS/SH was less than those of G5–2.5%SS/SH, G5–2%SS/SH, G5–1.5%SS/SH, and G5–1%SS/SH by 19%, 30%, 39%, and 48%, respectively. This decrease can belong to the high sodium silicate's viscosity which, in turn, produces a stiff, cohesive, and thick GPCM, thus reducing the mortar's consistency [50]. Furthermore, the higher soluble silica content could be induced by a high SS/SH ratio, which then accelerated the polymerization, and accordingly increased the total viscosity, resulting in lower slump outcomes of FA–GPCMs [53].

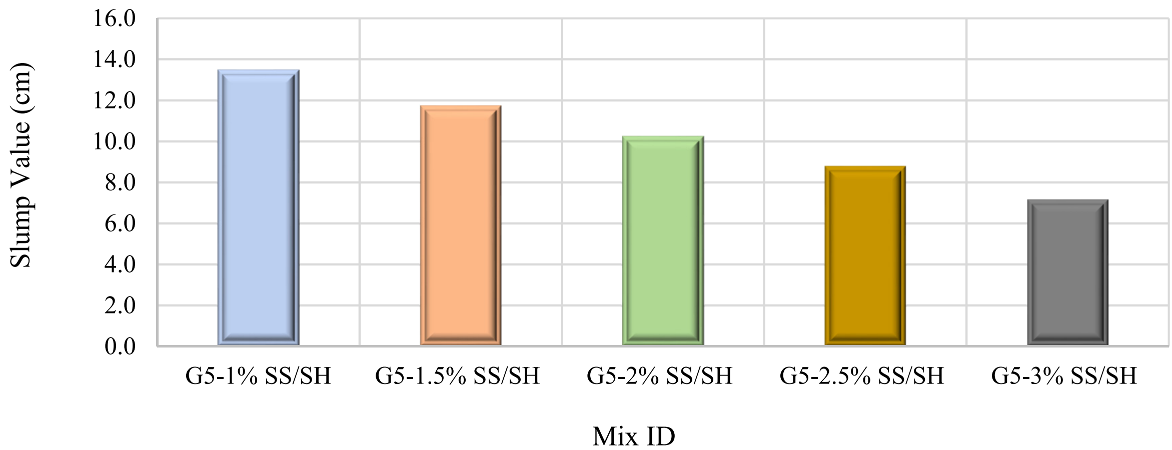

Figure 6. The impact of SS/SH ratio on slump value of FA–GPCMs.

3.1.5. Effect of Additional Water

FA–GPC mixes prepared with 35%AAS (group 3) and 16 M NaOH (group 4) showed poor flowability in comparison with mixes produced with 40%, 45%, and NaOH molarity less than 16 M. FA–GPCMs of group 6 included the same mixture proportions of mixes in group 3 and group 4, in addition to 14.5 kg/m^3 extra water. In this part, FA–GPC mixes of groups 3, 4, and 6 were used to evaluate the impact of additional water (AW) on the FA–GPCMs' workability. According to slump tests results, it is indicated that the FA–GPCMs' flowability increases by adding more water (AW) into FA–GPCMs. For instance, the rises in the slump results of the G6 mixes, with 14.5 kg/m^3 AW, were 94% (G6–16M–SF5%), 91% (G6–16M–S10%), and 88% (G6–16M–S15%) compared to G4 mixes produced with 16 M NaOH and without extra water (Figure 7). Similarly, the increases in the slump values of G6 FA–GPCMs, with 35% AAS and 14.5 kg/m^3 AW, were 97% (G6–SF5%), 94% (G6–SF10%), 91% (G6–SF15%), 88% (G6–SF20%), 87% (G6–SF25%), and 85% (G6–SF30%) compared to mixes of group 3 (Figure 8). The increase in the workability of FA–GPCMs is obviously because of the rise in the amount of free water, which serves no role in the chemical reaction [54].

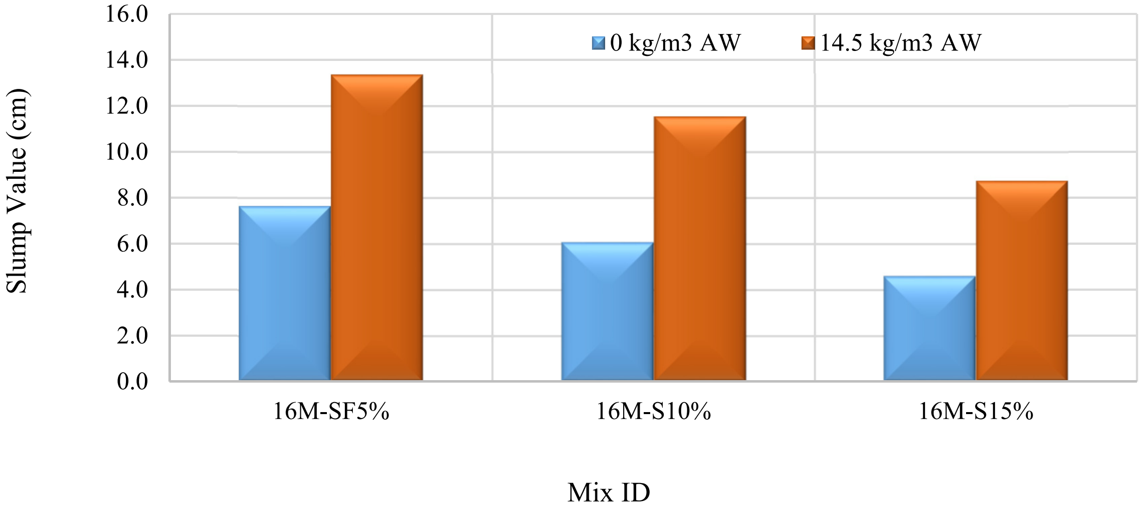

Figure 7. The effect of additional water (AW) on slump values of FA–GPCMs produced with 16 M NaOH.

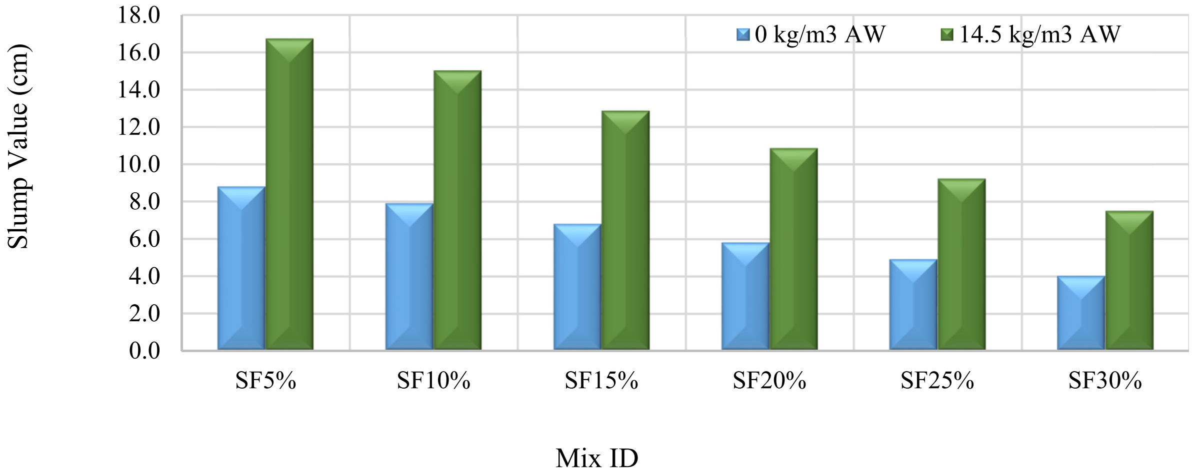

Figure 8. The influence of additional water (AW) on slump values of FA–GPCMs prepared with 35% AAS.

3.2. Compressive Strength

Compression tests were performed on cubic concrete specimens with dimensions of 50 × 50 × 50 mm for each FA–GPCM at the 14 and 28 days, in accordance with ASTM C39/C39M [46]. The test was performed at an ambient temperature of 23 °C. Compressive strength outcomes were the average of three specimens' compressive strength for each FA–GPCM. The following sections will discuss the effect of the inspected parameters on the FA–GPC compressive strength.

3.2.1. Impact of Silica Fume Content

The effect of different SF replacement percentages on the fly ash-based geopolymer concrete compressive strength (FA–CCS) is represented in Figure 9. In this test, FA–GPCMs of group 1 were used to assess the effect of the SF content, i.e., 5%, 10% 15%, 20%, 25%, and 30%, on FA–CCS. According to the results, it is indicated that improving SF dosage to 15% led to a noteworthy enhancement in the FA–CCS up to 147%, as well as 140% at 28 and 14 days, respectively, in comparison with that of the reference mixture (RM) produced with 0% SF. More specifically, the 28-day compressive strengths of the FA–GPC samples produced with mix 2 (G1–SF5%), mix 3 (G1–SF10%), and mix 4 (G1–SF15%) were 31.4, 41.2, and 51.6 MPa, respectively. Based on the outcomes, it was observed that the 14- and 28-day compressive strength improvements realized by concrete samples (FA–GPCSs) prepared with G1–SF15% (15%SF) of 142% and 147%, respectively, were approximately more than twice that realized with G1–SF5% of 45% and 50%. The compressive strength enhancement attained by the inclusion of SF into concrete mixtures could be due to the C–S–H gel, which is formed by reacting SF and AAS. This gel enables the geopolymer concrete matrix to be hardened at room temperature and provides a denser concrete microstructure [12]. Fundamentally, the incorporation of SF into concrete mixtures leads to lowering the permeability of concrete by improving the bond strength between the cement paste and aggregates, and that has an advantageous effect on the compressive strength outcomes [55–57]. On the other hand, the addition of more than 15%SF (i.e., 20%, 25%, and 30%) showed a decrease in the 28-day and 14-day FA–GPC compressive strengths compared to that of G1–SF15% (the optimum value). For instance, the decline in the 14-day FA–CCS was 15% (GPSF20%), 23% (GPSF25%), and 30% (GPSF30%) compared to that of G1–SF15%. This decline may be highly attributed to the increase in the permeability of the FA–GPC structure [25]. More specifically, with increasing SF percentages, sodium oxide, necessary for complete dissolution, might be insufficient in AAS. Accordingly, some unreacted SF remained in the provided GP gel, which then might be responsible for the GPC's high permeability and the decline in the concrete strength [44]. Hence, some researchers have restricted the dosages of additions into GPCMs owing to the applied supplementary materials, i.e., SF, MK, etc. [25,42,58].

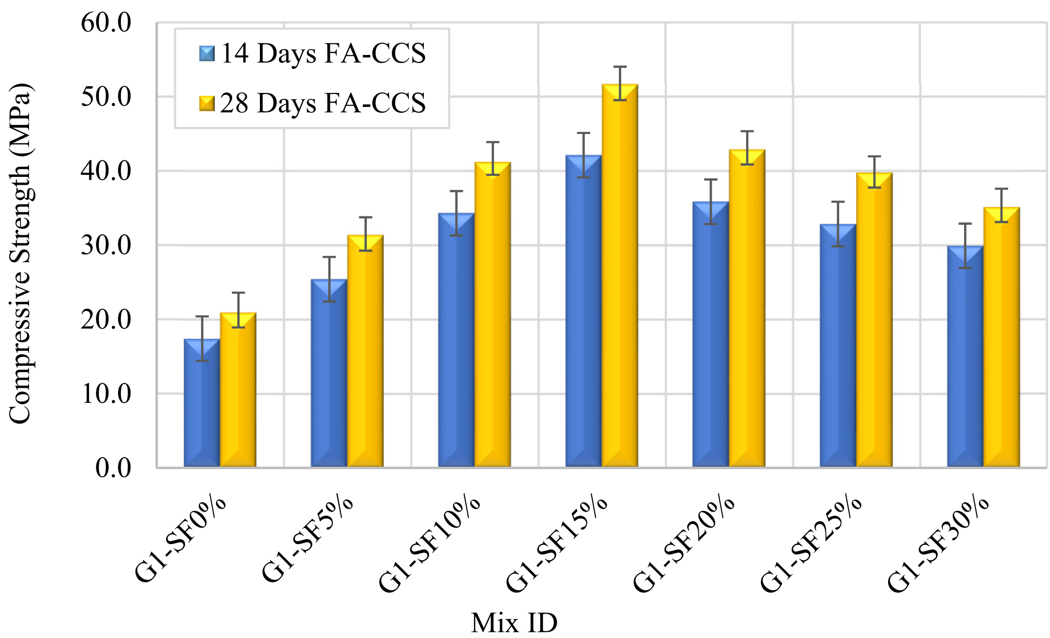

Figure 9. The influence of SF content on concrete compressive strength.

3.2.2. Effect of Alkaline Activator Solution Content

The impact of different AAS percentages was evaluated through using FA–GPCSs manufactured with GPCMs of group 1, group 2, and group 3. Figure 10 demonstrates the effect of AAS ratio on the of FA–GPCS's compressive strength at 14 and 28 days. According to the results, improving AAS percentages up to 0.45 resulted in the highest 14- and 28-day FA–CCSs of 45.32 MPa (G2–SF30%) and 55.69 MPa (G2–SF30%), respectively. It was also observed that the compressive strength enhancement of FA–GPC was highly influenced by the AAS percentage and SF content. For instance, the highest 28-day FA–CCSs of 55.69, 51.6, and 40.2 MPa were realized in the FA–GPC specimens produced with mix 14 (30%SF and 45%AAS), mix 4 (15%SF and 40%AAS), as well as mix 18 (10%SF and 35%AAS), respectively. The reason behind these results could be attributed to the sufficient content of AAS, which was adequate to realize the effective dissolution process of aluminosilicate. As a result, this reflected positively on the compressive strength of FA–GPC specimens. On the other hand, FA–GPCSs produced with the rest of the GPCMs showed lower compressive strength results, because sodium oxide, required for the dissolution process, might be unavailable in AAS. Thus, some unreacted particles of SF might stay in the GP gel, leading to an increase in the concrete permeability and reducing the concrete compressive strength [41].

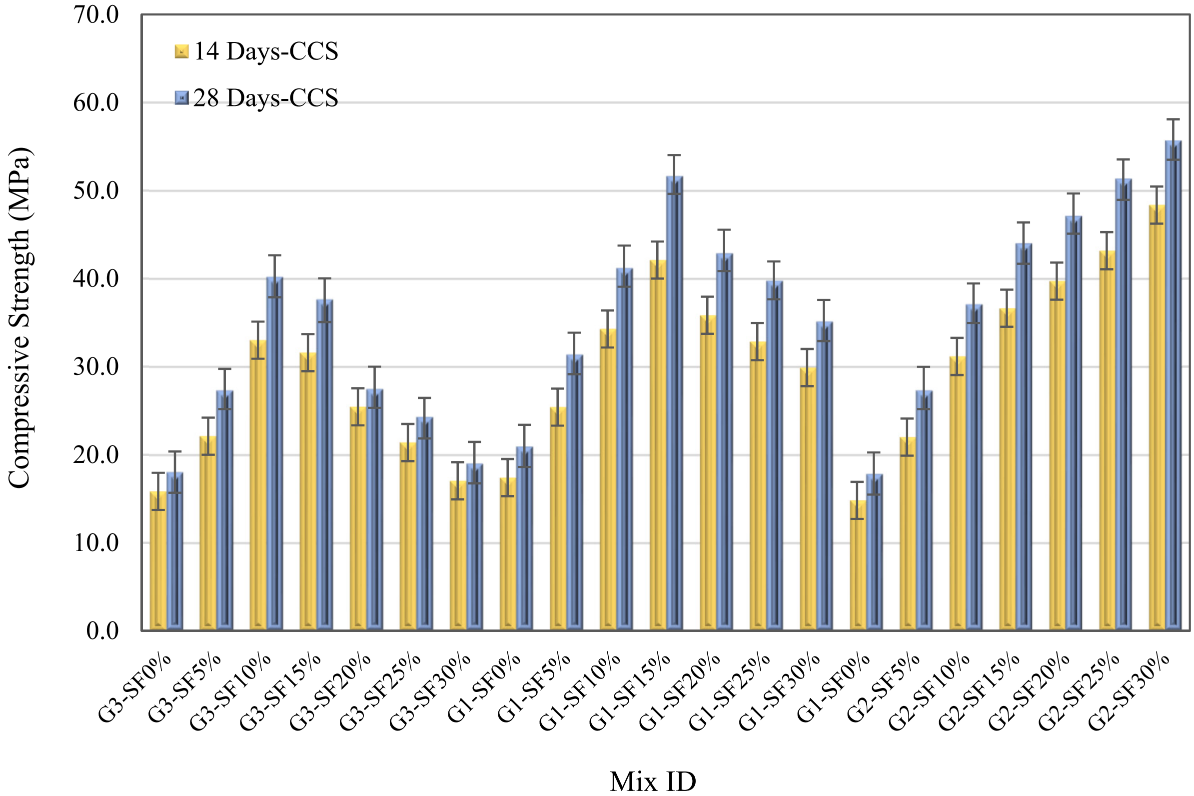

Figure 10. The influence of AAS content on FA–GPCS's compressive strength.

3.2.3. Effect of NaOH Molarity

The impact of different NaOH concentrations on the 14- and 28-day FA–GPC compressive strengths is shown in Figure 11. Based on the outcomes, it can be indicated that the molarity of NaOH includes a vital impact on the FA–CCS, where improving concentration from 10 to 14 M increased the 14- and 28-day FA–CCSs. For instance, the compressive strength results of FA–GPCSs produced with mixes (G4–10M–S10%, G4–12M–S10%, and G4–14M–S10%) were 34.3, 40.4, and 43.2 MPa, respectively. As can be seen, 14 M and 12 M NaOH led to compressive strength enhancements of 19% and 27% in comparison with that of 10 M NaOH. Basically, NaOH concentration involves a noteworthy influence on the geopolymerization process, as OH ions aid in dissolving the aluminosilicates of GP-based materials and then lead to the creation of stronger bonds in the concrete matrix [42,48]. Also, the rapid reaction between the components of the source materials, i.e., Si, Al, and Ca, is another reason behind the growth in FA–CCS. However, it was indicated that increasing NaOH concentration up to 16 M had an adverse effect on the 14- and 28-day FA–GPC compressive strengths in comparison with the FA–CCS of 14 M NaOH. For instance, 16 M NaOH resulted in the 14-day FA–CCS decrease of 21% (G4–16M–S15%), 18% (G4–16M–S10%), and 14% (G4–16M–SF5%) compared to those of mixes G4–14M–S15%, G4–14M–S10%, and G4–14M–SF5%, respectively. It can be observed that the reduction in FA–CCS was caused by 16 M NaOH, and it was also affected by the SF content. Namely, the drop in the FA–GPC compressive strength increased with improved silica fume percentages. The excessive concentration of hydroxide ions led to the precipitation of aluminosilicate gel at very initial ages, which hindered the subsequent geopolymerization, and then led to low compressive strength results. Accordingly, GPC compressive strength highly depends on the NaOH molarity, and thus, the GPC matrix should include an adequate quantity of OH ions for a complete geopolymerization process [52,59].

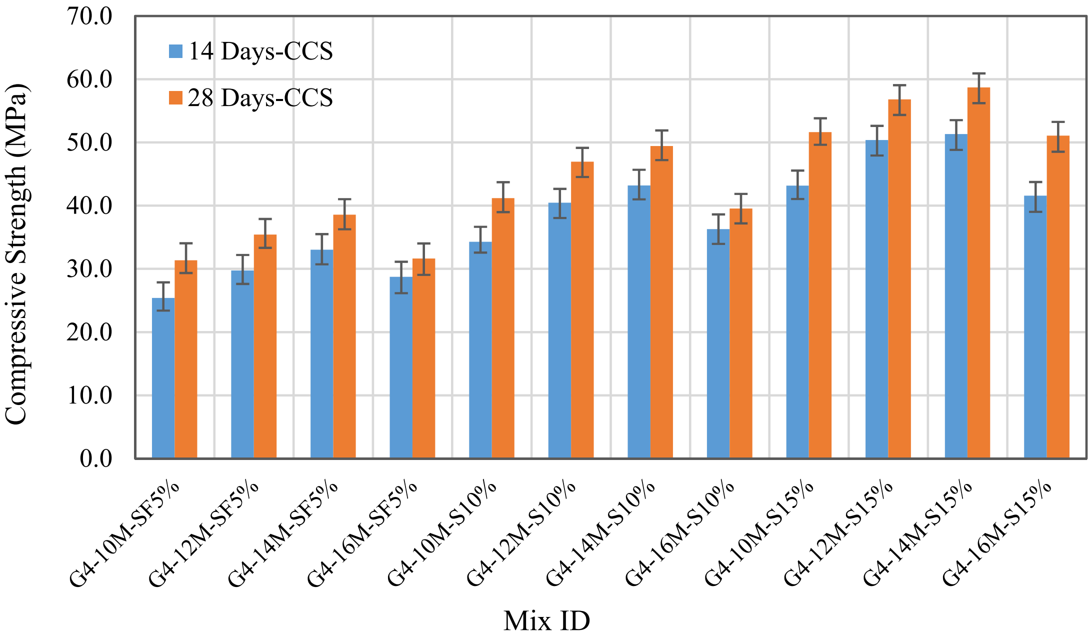

Figure 11. The impact of NaOH molarity on the FA–GPCS compressive strength.

3.2.4. Influence of Sodium Silicate-to-Sodium Hydroxide Ratio

The effect of (Na_2SiO_3/NaOH) ratio on the compressive strength development of FA–GPCs at 14 and 28 days is presented in Figure 12. In this section, GPCSs were produced with different Na_2SiO_3/NaOH ratios, i.e., 1%, 1.5%, 2%, 2.5%, and 3%, while keeping the rest of the parameters constant, i.e., 15% SF, 40% AAS, and 10 M NaOH. The outcomes indicate that the improvement in the Na_2SiO_3/NaOH ratio led to enhancing the 14- and 28-day concrete compressive strength of incorporated FA–GPSs. For instance, the 14-day FA–CCS enhancements of mixes G5–SS/SH3%, G5–SS/SH2.5%, G5–SS/SH2%, and G5–SS/SH1.5% were 31%, 25%, 20%, and 13%, respectively, compared to that produced with G5–SS/SH 1%. The 14-day compressive strength trend of the involved FA–GPCSs was the same as those of the 28-day FA–CCS trend. However, the compressive strength enhancements at 14 days were higher than those achieved at 28 days. For instance, the 14- and 28-day CCS developments of FA–GPCS produced with mix G5–SS/SH3% were 31%, and 18%, respectively, compared to the compressive strength results of specimens produced with G5–SS/SH1% at 14 and 28 days. Basically, the strength development can be attributed to the modification of the FA–GPC matrix microstructure owing to increasing silica content (SS) in a proportion that is compatible with the NaOH content to ensure an effective dissolution process [56].

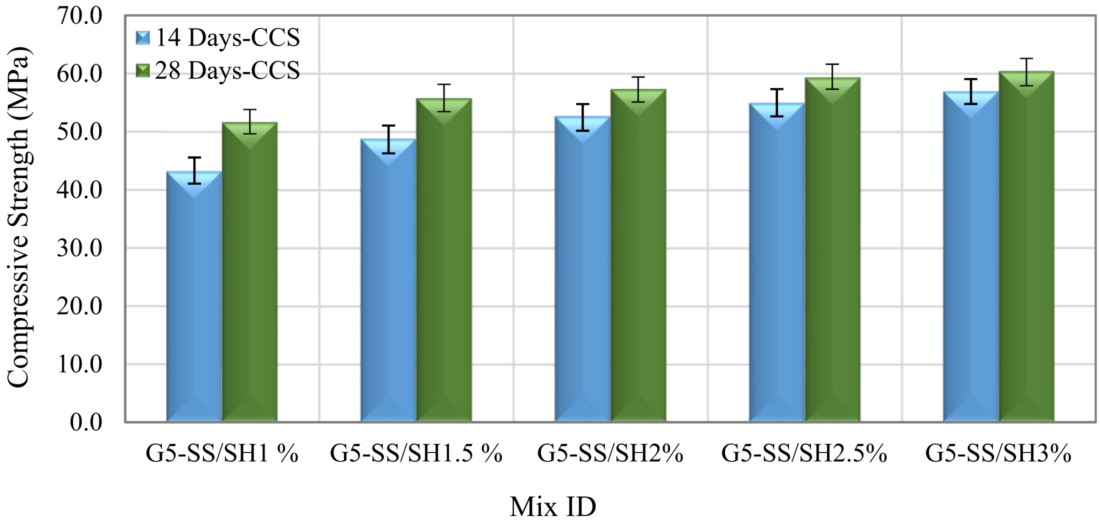

Figure 12. The impact of sodium hydroxide-to-sodium silicate ratio on FA–GPCS's compressive strength.

3.2.5. Impact of Additional Water

In FA–GPC mixes of group 6, 14.5 kg/m^3 additional water was utilized to improve the flowability of FA–GPCMs produced with 35% AAS (group 3) and 16 M NaOH (group 4). The influence of additional water (AW) on the FFA-based concrete compressive strength is revealed in Figure 13 (group 6 vs. group 3) and Figure 14 (group 6 vs. group 4). According to the results, it was observed that FA–CCS declined with extra water added into FA–GPCMs. For instance, 14.5 kg/m^3 AW resulted in a 14-day FA–CCS decrease of 25% (G6–SF0%), 20% (G6–SF5%), 18% (G6–SF10%), 14% (G6–SF15%), 12% (G6–SF20%), 9% (G6–SF25%), 7% (G6–SF30%), 21% (G6–14M–SF5%), 18% (G6–14M–S10%), 11% (G6–14M–S15%), 19% (G6–16M–SF5%), 15% (G6–16M–S10%), and 9% (G6–164M-S15%) compared to equivalent mixes of group 3 and group 4. The 14-day compressive strength decrease trend of FA–GPCSs due to the extra water was the same after 28 days but in different percentages. It was also noticed that the impact of AW was less important in the FA–GPCMs produced with high percentages of SF and NaOH concentrations. The presence of SF in the GPCM caused the formation of C–S–H gel in the GPC matrix, which, in turn, resulted in a noteworthy improvement in the FA–GPC strength. However, the strength reduction due to the extra water could be due to the decrease in the AAS and NaOH molarity and thus less SH ions existing in the FA–GPCMs to dissolve the aluminosilicates.

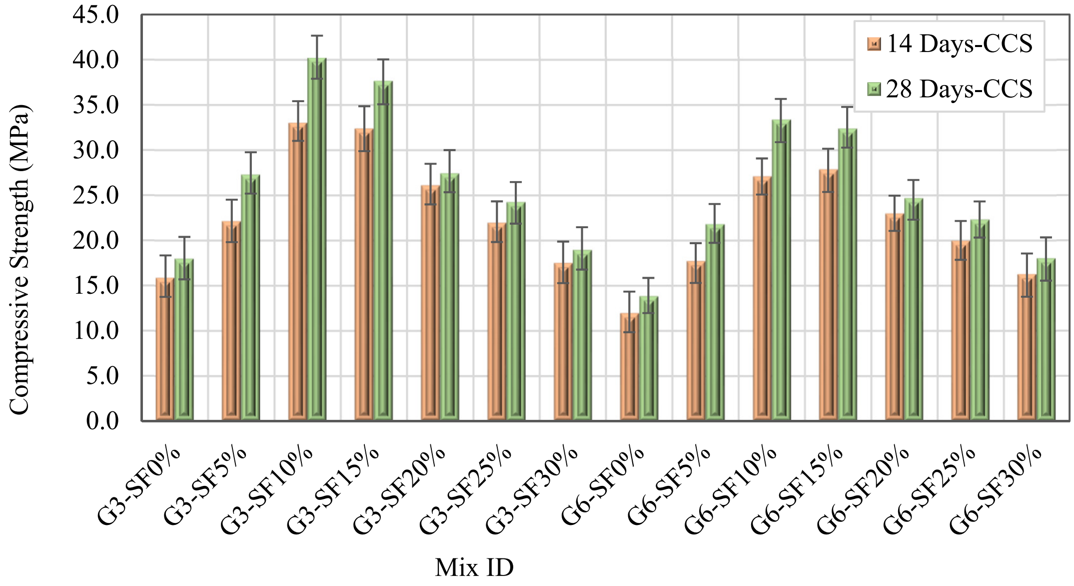

Figure 13. The impact of additional water on FA–GPCS compressive strength (group 6 vs. group 3).

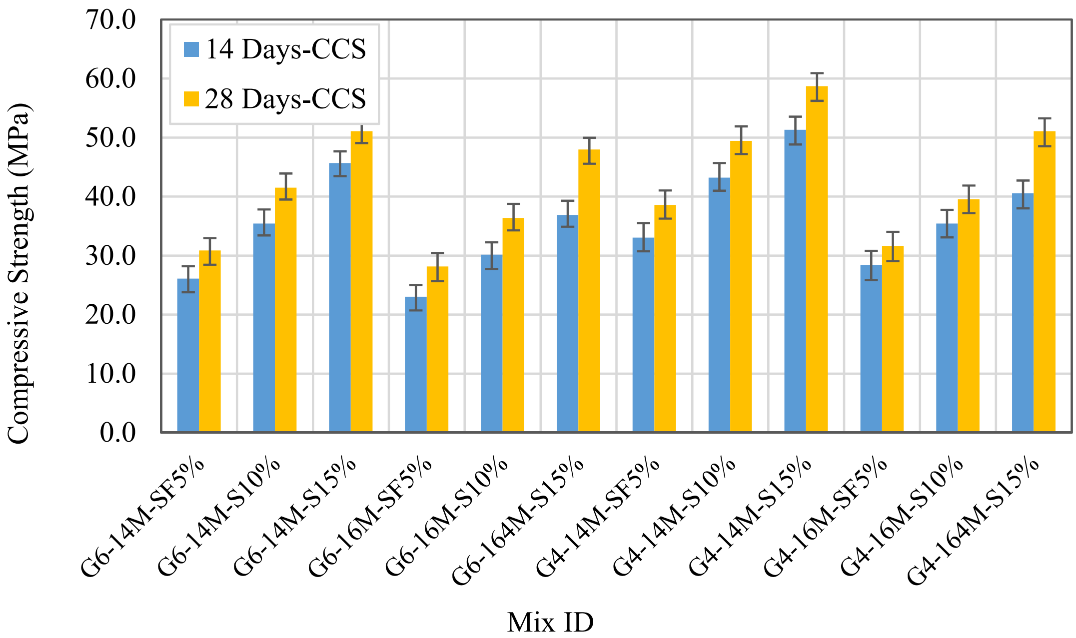

Figure 14. The effect of additional water on FA–GPCS compressive strength (group 6 vs. group 4).

4. Conclusions

In this paper, forty-eight fly ash-based geopolymer concrete mixes divided into sixes groups were prepared to evaluate the impact of five main variables, i.e., SF content, AAS percentages, sodium silicate-to-sodium hydroxide solution ratio, NaOH molarity, and additional water on the FA–GPC green and hardened properties. Key conclusions from this paper can be outlined as follows:

1. Increasing the SF content (5% to 30%), SS/SH ratio (1% to 3%), and NaOH molarity (10 M to 16 M) declines the workability of FA–GPCMs. On the other hand, reducing alkaline activator percentages to 35% results in a decrease in the FA–GPCM's workability. The impact of low AAS content (35%) and high NaOH molarity (14 M and 16 M) on the FA–GPCM's workability is more obvious in FA–GPCMs prepared with higher SF percentages.

2. Increasing the SF replacement percentages from 5% to 15% in FA–GPCMs leads to significant 28- and 14-day compressive strength enhancements compared to FA–GPCM produced with 0% SF.
3. The FA–GPC compressive strength development depends on the AAS percentages and SF content. The highest 28-day FA–CCS results can be realized from GPC samples produced with mixes SF30% and 45%AAS, SF15% and 40%AAS, as well as SF10% and 35%AAS.
4. NaOH concentration involves a significant impact on the FA-GPC compressive strength. Increasing NaOH molarity from 10 to 14 M improves the FA–CCS. On the other hand, increasing NaOH concentration up to 16 M results in an adverse impact on the FA–GPC compressive strengths.
5. Increasing the SS/SH (Na_2SiO_3/NaOH) ratio from 1% to 3% results in improving the 14- and 28-day FA–GPS concrete compressive strength due to modification of the FA-GPC matrix microstructure owing to improving silica content (SS) in a proportion that is compatible with the NaOH content to ensure an effective dissolution process.
6. The 14- and 28-day compressive strengths of FA–GPC decline with additional water added to FA–GPCMs. The impact of extra water is less noticeable on FA–GPCMs produced with high SF content and NaOH molarity.

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