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Ground granulated blast furnace slag and fly ash concrete

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Abstract. Utilization of ground granulated blast furnace slag (GGBFS) and fly ash (FA) to resolve the problem of increasing discharged and total accumulated industrial waste has attracted public concern. This article presents the research results on the effect of the replacement of up to 60 wt.% cement with GGBFS and FA, separately and in combination. It shows that mineral admixtures improve the workability of concrete mixture and reduce the required water-reducing admixture to reach a defined slump, prolonging the setting time of fresh concrete. The compressive strength of concrete with GGBFS at an early age decreases while increasing at 60 days and 90 days with the GGBFS content from 20 wt.% to 40 wt.%. The compressive strength of concrete with FA well develops at a later age, but it decreases at all ages as the FA replacement ratio increases. Cement replacement with a combined mineral admixture of 20 wt.% GGBFS and 20 wt.% FA does not significantly change the compressive strength at 28 days and later. Based on test results, the efficiency factor of mineral admixtures was calculated to use for selecting the proportion of concrete.

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1. Introduction

The development of the economy and industries in Vietnam inevitably causes environmental problems due to the discharging of large amounts of waste. According to the latest estimates, up to now, Vietnam has 30 coal-fired thermal power plants in operation, discharging about 16 million tons of ash and slag annually. The total amount of ash and slag accumulated over the years is about 100 million tons, of which, by the end of 2021, 48.4 million tons have been treated and reused. Blast furnace slag waste from steel production also reaches about 4.3 million tons per year. In that context, the utilization of industrial wastes, including fly ash (FA) and ground granulated blast furnace slag (GGBFS), is an inevitable development trend of building material production in general and concrete production in particular.

Industrial wastes, such as FA and GGBFS, have been used in concrete to replace aggregate, cement, or both. Studies on the separate use of FA [1–8], GGBFS [9–14], or a combination of the two above admixtures [15–23] in concrete all over the world show that with the appropriate replacement ratio, the mineral admixtures improve the properties of fresh and hardened concrete, especially the durability of concrete in some aggressive environments. When added to concrete, the active mineral admixture, on the one hand, has the filling effect and makes the structure denser, and on the other hand, reacts with $Ca(OH)_2$ to create binding minerals. The combining effect of the two above processes depends on many factors, such as the composition, properties, and amount of the admixture, the using ratio, the cement content, and other factors. The optimum admixture's content is usually determined based on actual test results with specific material.

Y. Cho et al. [3] study the influence of the 25 wt.% replacement of cement by 16 types of FA on the compressive strength of cement mortar. The results show that chemical parameters based on the amorphous chemical composition of FA have higher correlations with the compressive strength of the FA cement mortars than the chemical parameters based on crystalline components. The chemical parameters correlate with the 91-day strength better than the 28-day strength of FA cement mortars, as the pozzolanic reaction progressed further after 91 days. A. Oner et al. [2] investigate the strength development of concrete containing FA and the optimum use of FA in concrete. This study showed that strength increases with increasing amounts of FA up to an optimum value, beyond which it starts to decrease with further addition of FA. The optimum value of FA for the four test groups is about 40 wt.% of cement. The FA to cement ratio is an important factor determining the efficiency of FA. C. Luan et al. [4] study the effect of fly ashes, including low-calcium and high-calcium, on C-S-H structure, hydration products, hydration heat, and compressive strength of UHPC. The results showed that FA reduced the early-age compressive strength, but it increased middle- and late-age compressive strength, reduced the drying shrinkage and chloride impermeability coefficient of UHPC, and the effect of high-calcium FA was better than that of low-calcium FA.

Concerning GGBFS, A. Oner et al. [9] show the improvement of the 7-day to 365-day compressive strength with the increasing GGBS content. After an optimum point, at around 55 wt.% of the total binder content, further increasing GGBFS content does not improve the compressive strength. It is caused by the unreacted GGBFS acting as a filler material in the paste. S.C. Pal et al. [10] conclude that the reactivity of GGBFS depends on the source of slag, type of raw material, method, and cooling rate. The hydraulic index strongly correlates with the SiO_2, CaO, MgO, Al_2O_3, glass content, and Blaine's fineness of GGBFS at both 7 days and 28 days. S.C. Pal also develops the equations to determine the reactivity of slag based on the physical and chemical properties of slag. This equation accounts for the variations of the slag characteristics, which predict the hydraulic index and the strength performance of slag at 7 days and 28 days.

The combined utilization of FA and GGBFS has also been attracting the attention of researchers. The study of A. Szczesniak et al. [15] shows that adding FA to slag cement concrete in amounts of up to 33 wt.% by weight of cement is beneficial. The FA addition of 33 wt.% compared with the addition of 25 wt.% by the weight of cement in concrete based on CEM IIIA 42.5 cement does not significantly affect compressive strength and, in the case of concrete based on CEM IIIA 32.5 cement, even causes an increase in this strength. The possibility of using the k-value at XD1-3 exposure conditions for CEM IIIA cement classes should be carefully considered. A. Phul et al. [21] investigate the effect of cement replacement with up to 30 wt.% mineral admixtures, including GGBFS and FA, in concrete with a constant water-to-cement ratio of 0.47 and show that the workability of concrete increases initially with increasing replacement percentage up to an optimum limit but then decreases partially. The cement replacement with 20 wt.% GGBFS and 10 wt.% FA gives the highest compressive strength. The study of Z. Qu et al. [22] shows the reduction of the early-age mechanical properties of concrete with various FA and GGBFS at different cement replacement levels up to 40 wt.%. But at 28 days, the compressive strength of FA concrete is not lower, while GGBFS concrete is higher than that of reference concrete. C.U. Juang et al. [16] investigate the cement replacement by FA and GGBFS as long-term 40 wt.%, 50 wt.%, and 60 wt.%. The results showed that at high volumes of replacement, increasing GGBFS by 10% can increase the strength by 37 %. R. Rivera et al. [17] carried out the full factorial design for the 2 days, 7 days, and 28 days compressive strength of mortar with 25 wt.% and 40 wt.% of GGBFS and/or FA. The finer the GGBFS, the better the performance of ternary cement was achieved. It shows the more effective synergistic effect of the finer GGBFS due to a more adequate particle size distribution. This study also develops a relationship between compressive strength, fineness, GGBFS content, and FA content for each age.

When studying mineral additives, researchers pay great attention to quantifying the effectiveness of mineral additives. To evaluate the influence of mineral admixture on concrete strength, many researchers use the efficiency factor of additive k-value. The efficiency factor k-value represents the cement substitution capacity of mineral admixtures in equation (1), which correlates the compressive strength of concrete with the ratio of water to the binder.

$$f_C = b \times \left(\frac{1}{W/\left(C + k \times P\right)} \right) - a, \tag{1}$$

where f_C is the compressive strength of concrete; C, W, and P are the cement, water, and mineral admixture contents; a and b are the regression coefficients; k is the efficiency factor of mineral admixture.

The efficiency factor k-value is standardized in the European standard EN 206 "Concrete – Specification, performance, production, and conformity" as a k-factor concept. Based on the research in

Europe, EN 206 also recommends k-values for some admixtures. However, studies show that, in practice, there is a certain fluctuation of this value.

L. Wang et al. [24] consider the threshold value of the effective replacement ratio as the turning point of the strength curve with the replacement ratio. The threshold value of the effective replacement ratio by FA decreased with increasing curing temperature, whereas the reaction efficiency of FA increased with increasing curing temperature. The reaction efficiency of FA can be described more intuitively and quantitatively. G.K. Babu et al. [25] established the "overall cementing efficiency" (k) of FA through a "general efficiency factor" (k_e), dependent on the age, and a "percentage efficiency factor" (k_p), dependent on the replacement percentage. Meanwhile, K. Hwang et al. [5] develop an estimation equation for compressive strength development. The equation can express coefficient α, which indicates the activity of FA as a binder, in the form of a function of age, FA content, and Blaine-specific surface area of FA. Further, the coefficient α can be a product of α_1, which takes account of the effect of FA to cement ratio, and α_2, which expresses the effect of the specific surface area by Blaine.

M.S. Magalhães et al. [26] investigate the effect of the FA fineness and content, the water content, and the concrete age on the k-value. The results indicate that the k-values of Brazilian FA are higher than the one recommended by EN 206. Furthermore, the k-value depends on FA content and decreases when the content in the mixture increases. Water-to-binder ratio and hydration time significantly influence the k-value, too. The results also indicate an improvement in the k-value and relationship between compressive strength, Young's modulus, and the FA amount in the mixture with an increase in FA fineness.

Until now, EN 206 still does not specify the k-value of GGBFS due to its variation. R. Härdtl [27] confirms the broad range of performance of GGBFS from different sources and the strong influence of the interaction with Portland cement, which requires a conservative approach when defining the limits of a prescriptive k-value for GGBFS. In a recent study, B. Boukhatem et al. [28] used an artificial neural network to predict the efficiency factor of GGBFS in concrete based on published test results. He developed a mathematical model for predicting the value of GGBFS in terms of percentage replacement (from 0 % to 80 %) and concrete age (from 2 days to 90 days).

The utilization of GGBFS and FA in concrete has been studied and implemented for many years in Vietnam and has achieved encouraging results. However, the current technical documents in Vietnam still do not have specific guidance on evaluating the effectiveness of using mineral additives in concrete. The efficiency factor of Vietnamese mineral admixtures depends on its original, type, replacement ratio, the age of the concrete, and other factors and can be determined experimentally. This paper presents the results of research on the effects of partial replacement of cement with local mineral admixtures, including FA, GGBFS, and a combination of FA and GGBFS, on the properties of fresh concrete as well as the compressive strength of concrete.

2. Materials and Method

In this study, we used PC40 Portland cement from But Son Cement Plant with a specific gravity of 3.11 g/cm³, a standard consistency of 29.0 %, and initial and final setting times of 135 min and 195 min. The compressive strength of cement at 3 days and 7 days is 34.2 MPa and 51.9 MPa, respectively.

Fine aggregate is the Lo River yellow sand with a bulk specific gravity (dry) of 2.62 g/cm³, a bulk density of 1480 kg/m³, the mass of particles coarser than 5 mm of 2.2 wt.%, clay silt and dust content of 0.6 wt.%, and a fineness modulus of 2.6. The coarse aggregate used in the study is crushed stone from Hoa Binh with a bulk specific gravity (dry) of 2.72 g/cm³, a bulk density of 1420 kg/m³, clay silt and dust content of 0.3 wt.%, and a maximum particle size of 20 mm. The grading of the aggregate fulfills the standard requirements.

SilkRoad SPR1500, a high-range water-reducing chemical admixture based on polycarboxylate, has a 17.6 % water reduction ability, and the properties meet the requirements for type F admixture.

We use coal FA from the Pha Lai Thermal Power Plant. FA after treatment (floated) has a total content of SiO2+Al2O3+Fe2O3 of 88.52 wt.%, SO3 content of 0.14 wt.%, dissolved alkali content of 0.63 wt.%, chloride content of 0.01 wt.%, loss on ignition of 1.15 wt.%, specific gravity of 2.23 g/cm³, mass of particles on sieve 0.045 mm of 22 %. FA has a required water content of 98.3 % and a strength activity index of 92.7 % at 28 days.

We also use the GGBFS S95 of Hoa Phat Hai Duong Steel Factory with a specific gravity of 2.89 g/cm³, a specific surface area of 5120 cm²/g, a strength index at the age of 7 days of 76.2 %, 28 days of 101.4 %, a consistency ratio of 97.5 %, MgO content of 7.88 wt.%, SO3 content of 0.37 wt.%, a chloride content of 0.02 wt.%, and a loss on ignition of 0.45 wt.%.

We mix the concrete mixture in a free-falling laboratory mixer and determine the properties of fresh concrete. We cast the cylindrical test specimens with a diameter of 150 mm and a height of 300 mm in a series, each consisting of 3 cylinders. We cure the standard specimens in the laboratory until the testing ages. Testing to determine the properties of fresh and hardened concrete was carried out according to active national standards.

3. Results and Discussions

We study the effect of GGBFS and FA on the properties of fresh and hardened concrete in the mixtures with a constant content of cementitious materials. We used mineral admixtures, including GGBFS, FA, and GGBFS+FA, to partially replace cement by weight at the ratios of 20 wt.%, 40 wt.%, and 60 wt.% of the total content of cementitious materials. When using a mixture of GGBFS+FA, the replacement ratio of each admixture is 20 wt.% and 40 wt.%. To maintain a constant cementitious materials-to-water ratio and water content, we selected the appropriate dosage of high-range water-reducing chemical admixture so that the slump of the fresh concrete varied from 150 mm to 200 mm. Table 1 shows the actual concrete proportions.

Table 1. Proportion of fresh concrete.

No	ID	Material's content for 1m³ of concrete (kg)							Parameters		
		Cem.	GGBFS	FA	Fine agg.	Coarse agg.	Water	Adm., (%)	W/CM	GGBFS/CM, %	FA/CM, %
1	S0.F0	357	0	0	829	1062	178	1.0	0.51	0	0
2	S2.F0	286	71	0	825	1063	179	0.9	0.51	20	0
3	S4.F0	215	143	0	823	1065	179	0.7	0.51	40	0
4	S6.F0	142	214	0	815	1060	178	0.6	0.51	60	0
5	S0.F2	287	0	71	810	1063	179	0.8	0.51	0	20
6	S0.F4	217	0	144	795	1070	181	0.6	0.51	0	40
7	S0.F6	146	0	220	783	1080	182	0.0	0.50	0	60
8	S2.F2	216	72	72	809	1067	179	0.5	0.50	20	20
9	S2.F4	146	72	145	794	1073	181	0.4	0.50	20	40
10	S4.F2	144	143	72	803	1064	179	0.5	0.50	40	20

The test results for fresh concrete including, density, slump, air content, and setting time are presented in Table 2.

Table 2. Properties of fresh concrete.

No	ID	Density, kg/m³	Slump, mm	Air content, %	Setting time, min	
					Initial	Final
1	S0.F0	2434	150	2.0	455	585
2	S2.F0	2432	180	1.9	480	615
3	S4.F0	2435	160	1.8	505	635
4	S6.F0	2419	160	1.9	620	745
5	S0.F2	2418	160	2.2	505	640
6	S0.F4	2416	200	2.3	650	820
7	S0.F6	2420	180	1.8	810	985
8	S2.F2	2425	150	2.4	515	665
9	S2.F4	2420	190	2.1	720	935
10	S4.F2	2413	160	2.5	675	805

The experimental results in Table 2 show that, as there is an increase in the cement replacement ratio of mineral admixtures, the dosage of water-reducing admixture needed for the concrete mixture to reach the same slump decreases. It proves that both GGBFS and FA improve the slump of the concrete mixture, in which FA was able to improve the slump more than GGBFS. The spherical shape of FA particles and increasing binder volume when replacing cement are the reasons for this phenomenon.

Although the specific gravity of GGBFS and FA is less than that of cement, with a total cementitious materials content of about 360 kg/m³, replacing cement with GGBFS, FA, or GGBFS+FA at a ratio up to 60 wt.% does not significantly change the density of the concrete. The air content of concrete with mineral admixtures varies from 1.8 % to 2.5 % compared to 2.0 % of the concrete without it. The variation of air content is within the statistical error.

Partial cement replacement with a mineral admixture prolongs the setting time of fresh concrete, both initial and final. The initial setting time increases from 455 minutes of reference concrete to 620 minutes and 810 minutes of concrete with GGBFS and FA, respectively. The final setting time increases from 585 min to 745 min and 985 min for concrete using GGBFS and FA, respectively. Thus, FA increases the setting time of fresh concrete more than GGBFS. Increasing the setting time of concrete using GGBFS+FA has an intermediate value compared with concrete using FA or GGBFS separately.

Table 3 shows the compressive strength of concrete at 3 days of age to 90 of days age and the ratio of compressive strength at the different ages to those of the 28 days of the same proportion. Fig. 1 to Fig. 4 visualizes the effect of the cement replacement ratio of mineral admixtures on concrete compressive strength.

Table 3. Compressive strength of concrete.

No	ID	Compressive strength, MPa at the age, days / Ratio to the 28 days strength, %				
		3	7	28	60	90
1	S0.F0	29.0 / 64	38.9 / 85	45.6 / 100	49.3 / 108	51.3 / 112
2	S2.F0	24.6 / 57	35.2 / 82	43.0 / 100	50.9 / 118	54.3 / 126
3	S4.F0	20.0 / 50	28.3 / 70	40.3 / 100	49.5 / 123	53.5 / 133
4	S6.F0	15.2 / 40	25.4 / 68	37.6 / 100	44.3 / 118	47.0 / 125
5	S0.F2	22.4 / 58	29.7 / 77	38.5 / 100	45.4 / 118	50.1 / 130
6	S0.F4	16.3 / 50	22.5 / 69	32.7 / 100	40.3 / 123	45.5 / 139
7	S0.F6	7.9 / 40	13.1 / 66	20.0 / 100	25.9 / 130	28.0 / 140
8	S2.F2	14.9 / 38	25.3 / 64	39.7 / 100	48.3 / 122	49.5 / 125
9	S2.F4	10.5 / 31	20.4 / 60	33.8 / 100	37.1 / 110	40.8 / 121
10	S4.F2	10.4 / 30	20.1 / 58	34.7 / 100	38.3 / 100	42.6 / 123

Research results show that, at the age of up to 28 days, partly replacing cement with mineral admixtures, including GGBFS, FA, and GGBFS+FA, reduces the compressive strength of concrete. However, this trend changes significantly at longer ages. At 60 days and 90 days, with the GGBFS replacement ratio up to 40 wt.%, the strength of concrete hardly decreased but somehow improved. However, when combined with FA, the strength can be unchanged only at the GGBFS replacement ratio of up to 20 wt.%. With an FA replacement ratio of 40 wt.%, the addition of GGBFS results in a significant decrease in the strength of the concrete at any age.

Unlike GGBFS, partly replacing cement with FA causes the strength of concrete to decrease at all replacement ratios at all ages. The strength reduction rate increases rapidly at a high FA ratio. The use of FA in combination with GGBFS did not change this trend. This effect can be explained by the fact that, unlike GGBFS, the FA admixture has low activity, so using it instead of cement, especially at a high ratio, while the water content and cementitious materials to water ratio remain unchanged, decreases the hydration products as well as the CSH minerals and causes strength reduction.

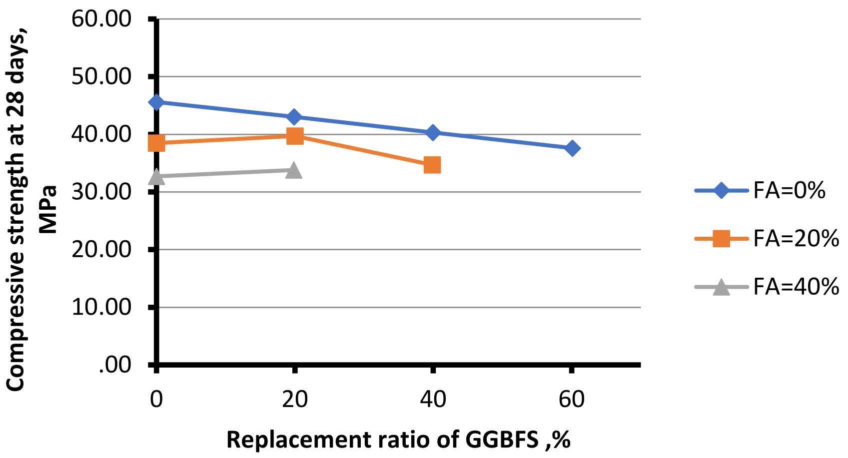

Figure 1. Effect of GGBFS on the compressive strength of concrete at 28 days.

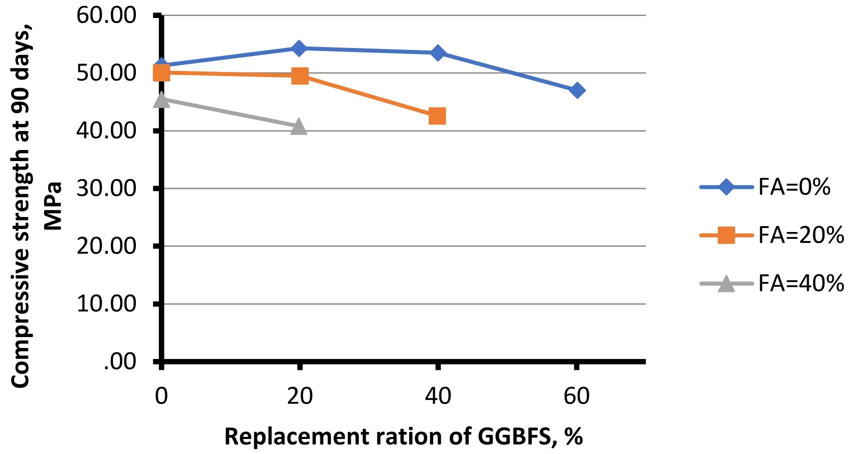

Figure 2. Effect of GGBFS on the compressive strength of concrete at 90 days.

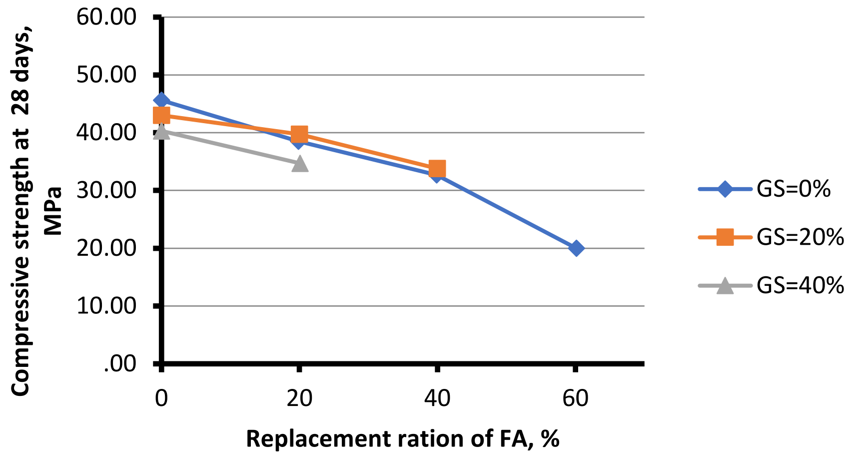

Figure 3. Effect of FA on the compressive strength of concrete at 28 days.

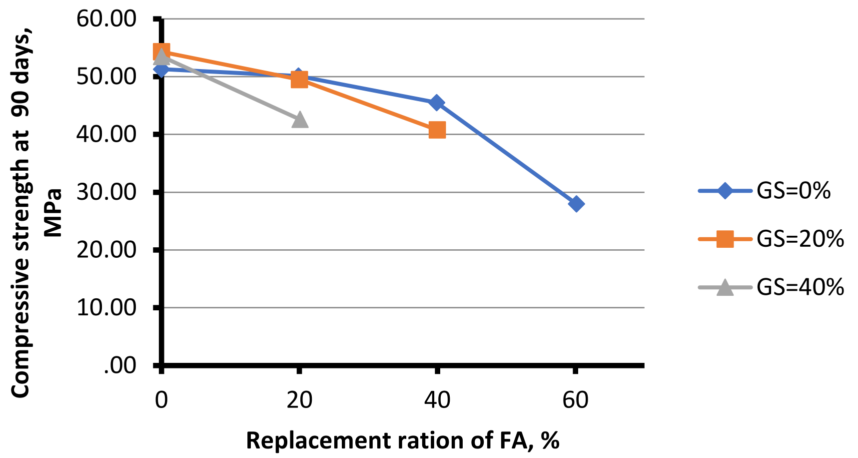

Figure 4. Effect of FA on the compressive strength of concrete at 90 days.

The above data shows that when replacing a part of the cement with mineral additives, the absolute value of the strength may decrease, but the strength development at longer ages is greater than that of the control mixture without mineral admixture. When replacing cement with GGBFS at the ratio of 20 wt.% to 60 wt.% of cementitious materials, the compressive strength at 90 days can increase from 25 % to 33 %, while replacing with FA increases from 30 % to 40 %. Replacement of cement with the mixture of GGBFS+FA can increase strength by 25 %. The above results are similar to studies [10, 16, 17] and show that concrete using mineral admixtures will be effective in structures where the strength is specified at longer ages.

Table 4 presents the ratio of the compressive strength of concrete at each age to the compressive strength of reference concrete (without mineral admixtures) at 28 days.

Table 4. The compressive strength ration at 28 days.

No	ID	Ratio of strength of concrete to the strength of reference concrete at 28 age, % at age, days				
		3	7	28	60	90
1	S0.F0	64	85	100	108	113
2	S2.F0	54	77	94	112	119
3	S4.F0	44	62	88	109	117
4	S6.F0	33	56	82	97	103
5	S0.F2	49	65	84	100	110
6	S0.F4	36	49	72	88	100
7	S0.F6	17	29	44	57	61
8	S2.F2	33	55	87	106	109
9	S2.F4	23	45	74	81	89
10	S4.F2	23	44	76	84	93

The data in Table 4 shows that concrete using mineral admixtures can achieve strength not less than 28 days strength of reference concrete when the GGBFS replacement ratio is up to 40 wt.% at 60 days and up to 60 wt.% at 90 days. These ratios of FA were 20 wt.% at 60 days and 40 wt.% at 90 days. When using the combination of GGBFS+FA, the concrete strength only reaches the reference concrete strength at the age of 28 days when the replacement ratio of each type is 20 wt.% (total replacement ratio 40 wt.%). The results obtained in the study are different from some studies in the world. The reason may be due to differences in local raw material characteristics, different chemical compositions, and fineness.

To evaluate the contribution effect on concrete's strength of the mineral admixture, we estimate the k-value in Equation (1) at different ages. To calculate the k factor, we determine the regression between compressive strength and the cement-to-water ratio in concrete without using mineral admixture at different ages. Based on the actual strength of concrete with mineral admixture and established regression, we calculate the equivalent amount of binder, thereby determining the k-value. Table 5 presents the estimated k-value.

Table 5. Efficiency factor k-value.

No	ID	Efficiency factor k-value at age, days				
		3	7	28	60	90
1	S2.F0	0.60	0.70	0.78	1.16	1.28
2	S4.F0	0.57	0.54	0.75	1.00	1.09
3	S6.F0	0.56	0.61	0.75	0.84	0.86
4	S0.F2	0.37	0.20	0.34	0.64	0.89
5	S0.F4	0.40	0.29	0.40	0.59	0.74
6	S0.F6	0.32	0.24	0.20	0.28	0.29
7	S2.F2	0.31	0.39	0.70	0.92	0.89
8	S2.F4	0.40	0.46	0.62	0.62	0.67
9	S4.F2	0.40	0.45	0.65	0.66	0.73

Obviously, in Table 5, the k-value for both admixtures tends to increase over time from 3 days to 90 days. The increase of the k-value depends on the type of admixture and the replacement ratio. Previous studies have also noted this upward trend [18, 27, 29, 30]. Compared with the recommended value in EN 206, the determined k-value has a certain difference as mentioned in the studies [1, 26, 29]. It shows that in practice, to improve the efficiency of mineral admixture, it is advisable to determine and apply the k-value for each different local source of raw materials.

The k-value of mineral admixtures depends on the replacement ratio. Regarding the GGBFS and GGBFS+FA, the k-value at a replacement ratio of 20 wt.% is higher than that of 40 wt.% and 60 wt.% at all ages from 3 days to 90 days. FA has a different behavior. The FA k-value at a replacement ratio of 40 wt.% is highest only at the ages of 3 days to 28 days. At 60 days and 90 days, the FA k-value at a replacement ratio of 20 wt.% is higher than that of 40 wt.% and 60 wt%.

The efficiency of GGBFS is higher than that of FA. When the replacement ratio increased from 20 wt.% to 60 wt.%, the efficiency factors of both admixtures tended to decrease. At a replacement ratio of 60 wt.%, the efficiency factor of FA is dramatically reduced, indicating that, for materials used in the study, a replacement ratio of FA of more than 40 wt.% may not be beneficial in the strength aspect.

Regarding the use of a combination of two admixtures, the efficiency factor of the combined admixture has an intermediate value between these values of each admixture at the corresponding replacement ratio. When replacing cement with GGBFS at the ratio of 20 wt.% and 40 wt.%, the k-value at 60 days and 90 days is greater than 1.00, showing that the efficiency of GGBFS in strength is more than that of cement. These results can be used for selecting concrete proportions using GGBFS and FA admixtures.

4. Conclusions

Partial cement replacement with GGBFS and FA at a ratio of up to 60 wt.% improves concrete slump as shown by reducing the required water-reducing admixture to maintain the same slump when the water content remains unchanged. The effect on slump improvement of FA is greater than that of GGBFS.

GGBFS and FA replacement increases the initial and final setting time of concrete mixtures. In particular, the increase in setting time when using FA is more than when using GGBFS.

Replacing up to 40 wt.% of cement with GGBFS improves concrete strength at 60 days and 90 days, even in combination with 20 wt.% FA. Replacing cement with FA at the replacement ratio in the study decreases concrete strength at all ages. Based on the experimental results, the mineral admixture efficiency factor k-value was calculated at specific replacement ratios and different ages. These values can be used for selecting concrete proportions using mineral admixtures.

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