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STRENGTHENING EFFECTS OF FINELY GROUND FLY ASH, GRANULATED BLAST FURNACE SLAG, AND THEIR COMBINATION

Kefeng Tan[1]* and Xincheng Pu[†]
*Southwest Institute of Technology, Mianyang, Sichuan, People's Republic of China
[†]Chongqing Jianzhu University, Chongqing, People's Republic of China

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ABSTRACT

The effect of finely ground fly ash (FGFA), finely ground granulated blast furnace slag (FGGBS), and their combination on the compressive strength of concrete was studied. Test results showed that incorporating 20% FGFA or FGGBS can significantly increase the compressive strength of concrete after 3 days. The compressive strength of concrete incorporating the combination of FGFA and FGGBS is higher than both FGFA concrete and FGGBS concrete, and is quantitatively similar to that of silica fume concrete. Scanning electron microscopic analysis showed that, after the incorporation of the combination of FGFA and FGGBS, a great quantity of a stick-like substance exist in the surface of hardened paste being investigated. The electron probe x-ray microanalyzer analysis showed that the stick-like substance was most probably the sheet C-S-H rolled up during specimen preparation for scanning electron microscopic analysis, which may be the mechanism of the strengthening effect of the combination of FGFA and FGGBS. *© 1998 Elsevier Science Ltd*

Introduction

High-strength concrete is a construction material that has been used increasingly in the past decade (1,2). It is popular for two reasons: it is economical purely on the basis of cost to resist a specified load, and it allows the use of smaller columns.

Generally, to make a concrete mix with compressive strength exceeding 80 MPa, incorporation of silica fume is required (3). In China, however, the quantity of silica fume is limited and its price is too high to be accepted for the concrete users (4). Thus, it is necessary to find other mineral admixtures instead of silica fume to make high-strength concrete. Investigation of the mechanism of strengthening effects of those mineral admixtures is also essential.

It is well known that the incorporation of fly ash and granulated blast furnace slag at normal fineness can reduce the early strength of concrete. The objective of this study is to investigate the behavior of finely ground fly ash (FGFA) and finely ground granulated blast

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[1]To whom correspondence should be addressed.

TABLE 1
Chemical composition of binders.

	Oxides (% by weight)								
	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	MgO	K_2O	Na_2O	LOI
Cement	64.38	20.71	4.93	4.38	2.3	1.68	0.58	0.33	—
FGFA	5.16	45.10	29.42	16.68		1.67	2.31	1.21	2.01
FGGBS	35.32	36.88	14.18	1.05		7.33	0.45	0.31	1.73
SF	1.62	90.11	1.60	0.63					

furnace slage (FGGBS) and their combination in concrete and to determine the possibility of their acting as strengthening agents of concrete.

Experimental

Materials

Ordinary Portland cement was used. The fly ash and granulated blast furnace slag were finely ground in a ball mill to a Blaine fineness of 6021 cm^2/g and 5923 cm^2/g, respectively, to produce FGFA and FGGBS. The silica fume was supplied as dry powder. The chemical composition of all the binders is given in Table 1.

The superplasticizer was a sulfonated naphthalene formaldehyde condensate. The coarse aggregate was 15-mm maximum size crashed gravel. The fine aggregate was river sand with a fineness modulus of 3.1.

Specimen preparation and testing

The compositions of five concrete mixes included in the test program are shown in Table 2. After demolding, the 100 × 100-mm cube specimens were kept in water at 20°C until time of compressive strength testing.

TABLE 2
Mix proportions of concrete (kg/m^3).

Mix no.	Cement	Fly ash	Slag	SF	W/B	Sand	Gravel	Super-plasticizer	Slump (cm)
1	500	0	0	0	0.30	703	1147	7.5	18
2	400	100	0	0	0.30	703	1147	7.5	15
3	400	0	100	0	0.30	703	1147	7.5	16
4	400	50	50	0	0.30	703	1147	7.5	16
5	467	0	0	33	0.30	703	1147	7.5	17

TABLE 3
Compressive strength of concretes
at different ages (MPa).

	Age (days)			
Mix no.	1	3	28	56
1	39.0	53.8	60.6	73.8
2	37.3	51.4	79.3	81.1
3	37.7	57.4	79.9	82.3
4	41.6	60.7	80.7	86.0
5	44.7	60.8	81.2	86.4

To investigate the strengthening effects of mineral admixtures, binder pastes with the same binder-to-water ratio and quantities of mineral admixture incorporation with those in concrete were prepared. After mixing, the fresh pastes were filled in plastic bottles and then sealed, vibrated, and put into water at the same temperature as that for concretes. After 28 days, the specimens were taken out and treated for scanning electronic microscope (SEM) analysis.

Results and Discussion

Compressive strength

The compressive strength of concretes with and without mineral admixtures at different curing age is shown in Table 3. It can be seen that for the concretes incorporating FGFA (mix 2) or FGGBS (mix 3), the 1- and 3-day strengths are similar to those of control mix (mix 1). For 28- and 56-day strengths, however, incorporating FGFA or FGGBS increases the compressive strength significantly, from 60.6 MPa to 79.3 and 79.9 MPa and from 73.8 MPa to 81.1 and 82.3 MPa, respectively. The results are consistent with another observation (5), which also showed that FGGBS had a much higher activity. No big difference is observed for the concretes incorporating FGFA and FGGBS at all ages. The activity of fly ash at normal fineness being much lower than granulated blast furnace slag implies that finely grinding the former is more effective in improving its activity than that of the latter.

As can be seen from Table 3, compared to control mix, incorporating the combination of FGFA and FGGBS (mix 4) increases compressive strength significantly at all ages, quantitatively similar to that of silica fume concrete. The compressive strength of this concrete at all ages is also higher than that of FGFA concrete and FGGBS concrete, implying that the combination of FGFA and FGGBS has a much higher activity than each itself. Thus, it can be said that, like silica fume, the combination of FGFA and FGGBS can act as a concrete strengthening agent. The reason for this behavior will be discussed later.

Microstructure

The results obtained from the SEM analysis of five pastes cured for 28 days are shown in Figures 1 to 5. The water-to-binder ratios and mineral admixture incorporations are the same

FIG. 1.
SEM image of hydrated plain cement paste.

with that in concrete. It can be seen that all the hardened pastes are very dense because of the low water-to-binder ratios.

Something unusual was found when FGFA and the combination of FGFA and FGGBS were incorporated. From Figure 2 it can be seen that a great quantity of well-crystallized cubic crystals is formed when FGFA was incorporated. Electron probe x-ray microanalyzer

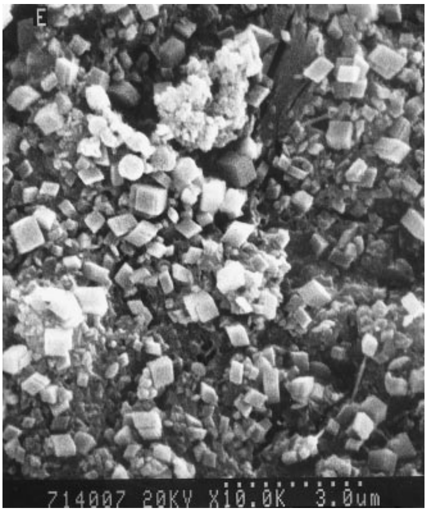

FIG. 2.
SEM image of hydrated cement pastes containing FA.

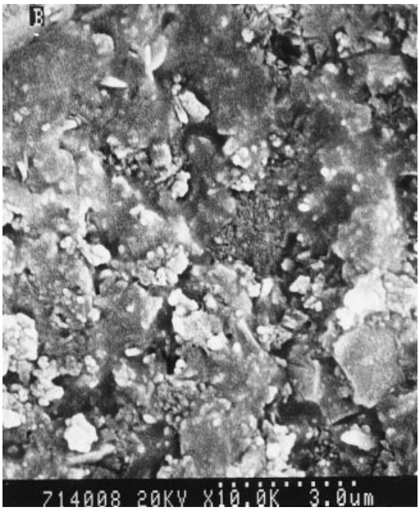

FIG. 3.
SEM image of hydrated cement paste containing GBS.

(EPXM) analysis showed that the crystals mainly consist of Ca, Si, and Al. It can be concluded that the cubic crystals are hydrogarnet ($C_3AS_2H_n$), which is formed by the reaction of Al_2O_3 and SiO_2, the main composition of fly ash, with $Ca(OH)_2$ liberated from C_3S and C_2S hydration. The reaction would be:

FIG. 4.
SEM image of hydrated cement paste containing FA and GBS.

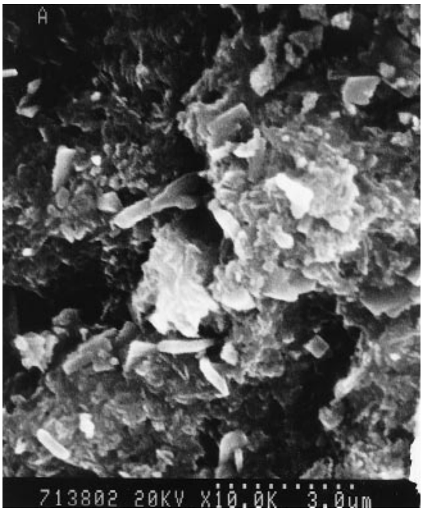

FIG. 5.
SEM image of hydrated cement paste containing SF.

$$3Ca(OH)_2 + Al_2O_3 + 2SiO_2 + mH_2O \rightarrow 3CaO{\cdot}Al_2O_3{\cdot}2SiO_2{\cdot}nH_2O$$

Figure 4 shows the microstructure of paste incorporating both FGFA and FGGBS. It was found that a large quantity of a stick-like substance exists in the investigating surface. EPXM analysis showed the main elements of the stick-like substance are Ca and Si, revealing it to be the sheet-like C-S-H rolled up during drying for SEM analysis. This C-S-H is most likely, or at least partly, the reaction product of SiO_2, CaO, and $Ca(OH)_2$, which are from FGFA, FGGBS, and C_3S, C_2S hydration, respectively. The formation of this C-S-H is beneficial for the strength of concrete, and this may be the reason why the strength of concrete incorporating the combination of FGFA and FGGBS is higher than those of plain, FGFA, and FGGBS concretes. Thus, the combination of FGFA and FGGBS, like silica fume, can be used as strengthening agent to produce very high-strength concrete.

Conclusions

1. Incorporating 20% FGFA or FGGBS can significantly increase the compressive strength of concrete after 3 days. However, no big difference in compressive strength was found between themselves.
2. Incorporating the combination of 10% FGFA and 10% FGGBS can increase the compressive strength of concrete at all ages. The compressive strength is higher than that incorporating FGFA and FGGBS singly, quantitatively similar to that of SF concrete. Thus, the combination of FGFA and FGGBS, like silica fume, can be used as a strengthening agent of concrete.
3. It was certified by SEM and the EPXM analysis that a large quantity of sheet-like C-S-H

was formed when incorporating the combination of FGFA and FGGBS into concrete, and this may be the mechanism of its strengthening effect on concrete.

4. Much well-crystallized hydrogarnet ($C_3AS_2H_n$) is formed when FGFA is incorporated into concrete.

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