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Effects of flue gas desulphurization sludge on the pozzolanic reaction of reject-fly-ash-blended cement pastes

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Abstract

Reject fly ash (rFA), a coarse portion of the pulverized fuel ash (PFA) produced from coal-fired power plants and rejected from the ash classifying process, has remained unused due to its high carbon content and large particle size (>45 μm). However, the reject ash may have potential uses in chemical stabilization/solidification (S/S) processes that require relatively low strength and low chemical reactivity. Flue gas desulphurization (FGD) sludge is a by-product of the air pollution control process in coal-fired power plants. Its chemical composition is mainly gypsum. As there is no effective usage of both of these materials, it was of interest to conduct research on the possible activation of rFA using FGD. This paper presents experimental results of the effect of FGD on the pozzolanic reaction of rFA-blended cement pastes with or without $Ca(OH)_2$ and chemical activators. The results show that FGD take effect as an activator only at late curing ages. Adding $Ca(OH)_2$ activates the hydration of rFA. Chemical activator, such as alkali sulphate, is more effective in enhancing the strength development and degree of hydration of rFA than $CaCl_2$ in the rFA-$Ca(OH)_2$-cement system. But $CaCl_2$ is more effective in the rFA-$Ca(OH)_2$-FGD-cement system. The chemical activators speed up the reaction of the rFA through the formation new hydration products and elevating the pH value.

Keywords: Reject fly ash; Compressive strength; Hydration; Flue gas desulphurization sludge, FGD; Acceleration

1. Introduction

Pulverized fuel ash (PFA) is a by-product generated from burning coal during the generation of electricity. The finer fraction of PFA (< 45 μm) produced by passing the raw ash through a classifying process is being increasingly used in building construction [1,2]. But the reject of the classifying process (i.e., coarse fraction) is not suitable for use as a construction material due to its high carbon content and large particle size (>45 μm). In Hong Kong, this material is currently being dumped in large ash lagoons. However, the reject ash may have potential uses in the chemical stabilization/solidification (S/S) process, which requires a relatively low strength to be achieved.

Studies on the activation of fine fly ash have been widely reported [3–12]. These studies involved alkali activation and sulfate activation. The former breaks down the glass phase of the ash particles in an elevated alkaline environment to accelerate the hydration reaction [3–7]. The latter is based on the ability of sulfates to react with the aluminum phase in the ash particle to produce ettringite (AFt), which contributes to the early strength of the cementitious [8–12]. Shi et al. [3–5] reported that Na_2SO_4 was effective in enhancing the early strength development of fly-ash-blended cement paste and $CaCl_2$ was more useful to the later strength development. NaOH was also considered as an effective activator but the chemical was too expensive [5] for any real application. For sulfate activation, Xu and Sarkar [8] reported that the addition of gypsum appeared to be beneficial in terms of assisting the dissolution of the glass phase of the fly ash particle. Poon et al. [9] found that anhydrite was more effective than gypsum in increasing the early age strength of the cement/fly ash system. Results of Ma et al. [10] showed that the pore sizes of untreated fly ash/cement pastes were almost the same as that of $CaSO_4 \cdot 2H_2O$ activated fly ash/cement pastes. Hyde [11] reported that the addition of 10% anhydrite by mass can double the strength of a cement/PFA paste. All of the above studies were conducted using the fine (classified) portion of the fly ash. Few studies have been conducted on the activation and potential application of the coarse (reject) ash.

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Flue gas desulphurization (FGD) sludge is generated as a by-product by the air pollution control equipment in coal-fired power plants. The process uses lime to remove sulphur dioxide and generates low-grade gypsum as a by-product. This FGD process is adopted in many coal-fired power plants including the Lamma Power Plant operated by the Hong Kong Electric. But in Hong Kong, at present, there is no effective use of the FGD sludge produced.

The objective of this paper is to study the influence of FGD on the pozzolanic reactions of reject fly ash (rFA)-blended cement pastes, with and without the addition of other chemical activators. The results of the strength and microstructure developments of pastes and the hydration degree of the fly ash are presented.

2. Experimental details

2.1. Materials

The rFA and the FGD were obtained from the local coal-fired power plants. Fig. 1 shows their X-ray diffraction (XRD) patterns. Besides gypsum, there are some $CaCO_3$ and $Ca(OH)_2$ contents in the FGD sludge. The rFA corresponds to ASTM class F and its particle size distribution is shown in Fig. 2. Commercially available ordinary Portland cement equivalent to ASTM Type I and hydrated lime ($Ca(OH)_2$) were used as binders. Reagent grade Na_2SO_4, K_2SO_4, $CaCl_2$, NaOH, and KOH were used as chemical activators as required. The chemical and physical properties of the fly ash, FGD, and cement are given in Tables 1 and 2.

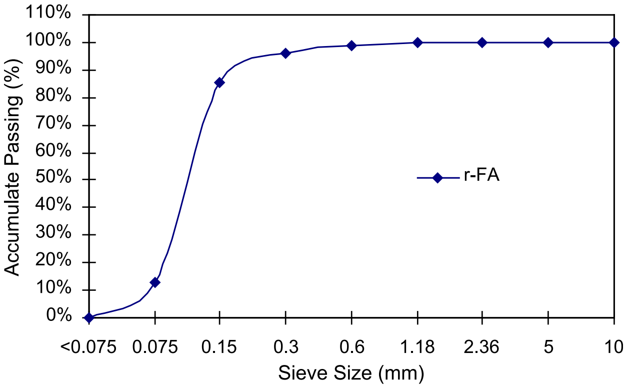

Fig. 2. Particle size distribution of rFA.

2.2. Preparation of specimens

Twenty-seven mixes were prepared with a water–total solid ratio (w/b) of 0.35 according to Table 3. The proportion of rFA to cement was kept at 100:25 in each mix. The chemicals added into the mixes were all at 4% by mass of the total binder (rFA, $Ca(OH)_2$, FGD, and cement). In the F group, the $Ca(OH)_2$ content in the mixes was increased from 10% to 30% by mass of rFA. In the G group, the FGD content was varied from 10% to 30% by mass of rFA.

Because mix F3 in the F group showed the highest compressive strength and degree of hydration, it was chosen as the base of other mixes. In the FG group, based on the proportion of mix F3, FGD was added from 10% to 30% by mass of rFA. In the FC group, 4% of Na_2SO_4, K_2SO_4, and $CaCl_2$ by mass of total binders (rFA, $Ca(OH)_2$, and cement), respectively, was added.

Considering all the results of the G group and the FG group, mixes H3 and P3 were selected as the base of HG group and PG group, respectively. Moreover, to assess the effect of using NaOH and KOH instead of sulphates, the two alkaline solutions were used in mix PNH and mix PKH, which were formulated by keeping the same mole ratio of Na and K as in mix PNS2 and mix PKS2, respectively.

All the pastes (shown in Table 3) were mixed for 10 min in a mechanical mixer at room temperature and were cast into plastic vials and compacted with a plastic rod until no air bubbles were observed. Water was added at the first 1 min. As for the chemical activators, they were first dissolved into

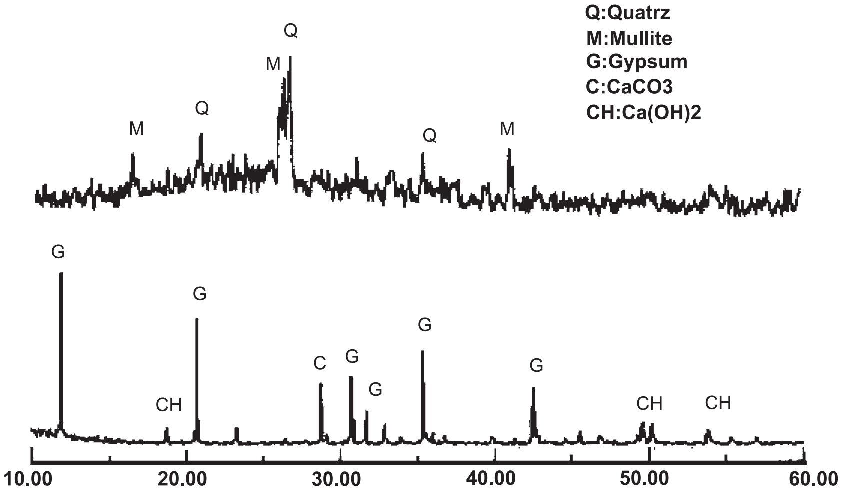

Fig. 1. XRD patterns of rFA and FGD (CuK radiation).

Table 1
Chemical compositions of materials used in experiment

	SiO_2	Fe_2O_3	Al_2O_3	TiO2	CaO	MgO	SO_3	K_2O	Na_2O	I.L
r-PFA	47.23	8.42	24.54	0.99	8.28	1.62	0.39	–	–	8.06
FGD	3.61	0.54	1.79	0.06	32.05	3.01	37.7	0	0	21.36
Cement	19.61	3.32	7.33	–	63.15	2.54	2.13	–	–	2.97

the required amount of water before mixing. All the prepared specimens were placed into a fog tank at 25 °C. The plastic vials were stripped and the specimens removed after the curing ages of 7, 28, and 90 days for the subsequent testing.

2.3. Compressive strength test

At the given ages, three specimens per mix underwent compressive strength testing, using a Denison compression machine. The ends of these specimens were first ground to ensure that the two surfaces were flat and parallel. The strength result per mix was the average of three specimens with a variation of no more than 10%. If a specimen's variation of strength exceeded the average, the result would be the average of two specimens.

The fractured pieces of the specimens after the compression testing were preserved for other tests. To stop the hydration reactions taking place, these pieces were soaked in acetone for a total of 14 days but with the acetone changed after 7 days. Then they were dried at a temperature of 60 °C for 48 h in a vacuum oven.

2.4. Hydration degree of the rFA

The degree of hydration was determined by a selective dissolution procedure using picric acid-methanol solution and water [13]. The method is based on the phenomenon that unreacted cement and fly ash cannot be removed by picric acid-methanol solution. The preserved samples obtained above were ground in a mortar to pass through a 75-μm sieve before testing.

2.5. XRD analysis

The ground samples prepared above were used for the XRD analysis. A Bruker D8 Advanced scanner using a Cu target was employed and run at a 2θ of 0.04° per step.

2.6. Mercury intrusion porosimetry (MIP)

Table 2
Physical properties of materials used in experiment

	Fineness (m^2/kg)	Density (kg/m^3)
r-PFA	119.0	2.19
Cement	352.0	3.16

Table 3
Mix proportions

		Binder				Chemical
		rFA	$Ca(OH)_2$	FGD	Cement	
	Control	100.0	/	/	25.0	/
F group	F1	100.0	10.0	/	25.0	/
	F2	100.0	15.0	/	25.0	/
	F3	100.0	20.0	/	25.0	/
	F4	100.0	25.0	/	25.0	/
	F5	100.0	30.0	/	25.0	/
G group	G1	100.0	/	10.0	25.0	/
	G2	100.0	/	15.0	25.0	/
	G3	100.0	/	20.0	25.0	/
	G4	100.0	/	25.0	25.0	/
	G5	100.0	/	30.0	25.0	/
FG group (Based on F3)	H3	100.0	20.0	10.0	25.0	/
	K3	100.0	20.0	15.0	25.0	/
	M3	100.0	20.0	20.0	25.0	/
	P3	100.0	20.0	25.0	25.0	/
	S3	100.0	20.0	30.0	25.0	/
FC group (based on F3)	FNS2	100.0	20.0	/	25.0	4.0% Na_2SO_4 of the binder
	FKS2	100.0	20.0	/	25.0	4.0% K_2SO_4 of the binder
	FCC2	100.0	20.0	/	25.0	4.0% $CaCl_2$ of the binder
HG group (based on H3)	HNS2	100.0	20.0	10.0	25.0	4.0% Na_2SO_4 of the binder
	HKS2	100.0	20.0	10.0	25.0	4.0% K_2SO_4 of the binder
	HCC2	100.0	20.0	10.0	25.0	4.0% $CaCl_2$ of the binder
PG group (based on P3)	PNS2	100.0	20.0	25.0	25.0	4.0% Na_2SO_4 of the binder
	PKS2	100.0	20.0	25.0	25.0	4.0% K_2SO_4 of the binder
	PCC2	100.0	20.0	25.0	25.0	4.0% $CaCl_2$ of the binder
	PNH	100.0	20.0	25.0	25.0	2.3% NaOH of the binder
	PKH	100.0	20.0	25.0	25.0	2.6% KOH of the binder

The samples used for the MIP test were the preserved fractured unground pieces. MIP was measured by a Pore Sizer 9320 mercury intrusion porosimeter with a maximum mercury intrusion pressure of 210 MPa. A cylindrical pore geometry and a contact angle θ of 140° were assumed [8]. The mercury intruded pore diameter by $dp = -4\gamma\cos\theta / P_{In}$ (where $\gamma = 0.483$ Nm^{-1}, the surface tension of mercury).

3. Results

3.1. Compressive strength

For the rFA/cement system, it can be found from Fig. 3 that the compressive strength decreases with the increase of $Ca(OH)_2$ content at 7 days. This may be attributed to the lower overall cement content when $Ca(OH)_2$ was added. At 28 days, the strength of the mix F3 shows the highest value, although it is still lower than the control (i.e., mix without

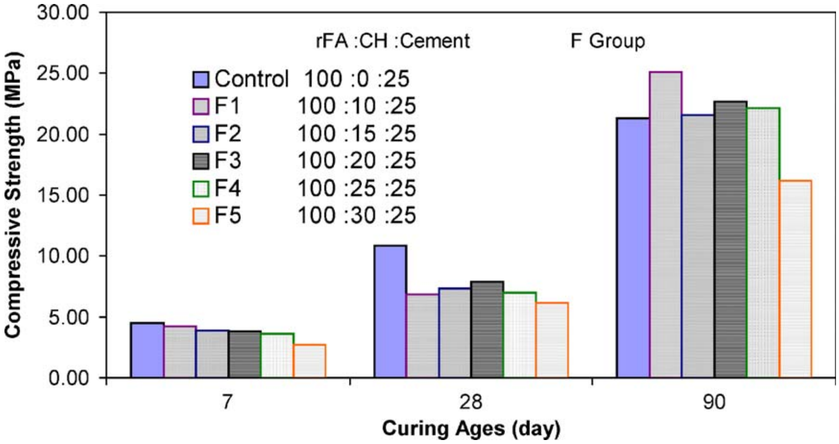

Fig. 3. Effects of different $Ca(OH)_2$ contents on compressive strength (CH: $Ca(OH)_2$).

$Ca(OH)_2$ addition). At 90 days, all the strength values of the F group (except mix F5) are higher than the control.

Fig. 4 shows that the compressive strength values of the G group decrease with the increase in FGD content at all curing ages. The strength values of the mixes with FGD addition are lower than the control at 7 and 28 days. But at 90 days, the strength of mix G1 is higher than the control.

Based on the mix proportions of mix F3, the effects of FGD on the compressive strength of the mixes with a constant level of $Ca(OH)_2$ are shown in Fig. 5a. It can be noticed that at 7 and 28 days, the strength values of the FG group decrease with increase in FGD content, which is similar to the results of the G group. Comparing with the results in the G group in Fig. 4, the mixes in the FG group generally have lower strength values.

The obvious effects of the addition of chemical activators (FC group) on the strength development (based on mix F3 again) are shown in Fig. 5b. Before 28 days, Na_2SO_4, among the three chemicals, is the most effective in enhancing the strength. The addition of $CaCl_2$ increases the strength significantly at 90 days.

Fig. 5c and d (HG and PG group, respectively) shows the effect of chemicals on the strength of the mix with $Ca(OH)_2$ and different levels of FGD addition. The strength values of HG group are higher than those of PG group. The effects of chemical activators on the strength development in the HG and PG are different from those in the FC group. It seems that $CaCl_2$ is most useful to strength development, whereas Na_2SO_4 retards the strength development.

It is interesting to note that when compared with Na_2SO_4 and K_2SO_4, the addition of the NaOH and KOH shows no obvious effect on the strength development, although the same Na and K molar ratios were used.

3.2. Hydration degree of the rFA

From the results in Fig. 6, it is obvious that the rate of hydration of rFA in the F group increase with increase of $Ca(OH)_2$ content at 28 and 90 days, although the hydration rates first decrease at 7 days. The results also show that the optimal amount of $Ca(OH)_2$ addition is 20% by mass of rFA. Fig. 6 also shows that the hydration degrees of rFA in the F group are lower than that in the control sample.

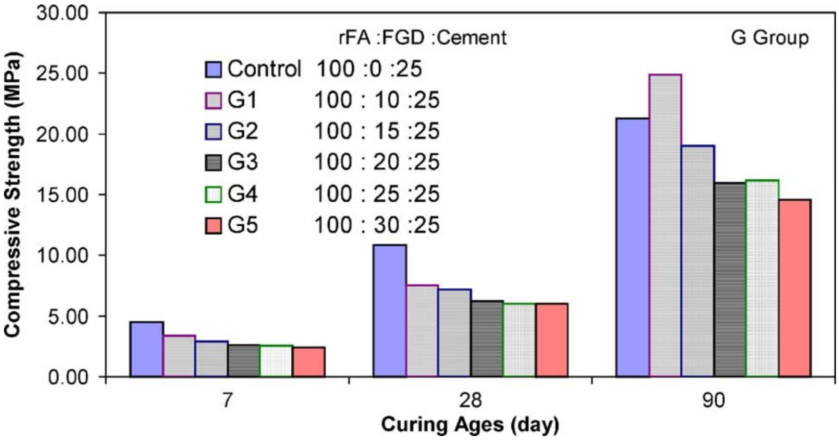

Fig. 4. Effects of different FGD contents on compressive strength.

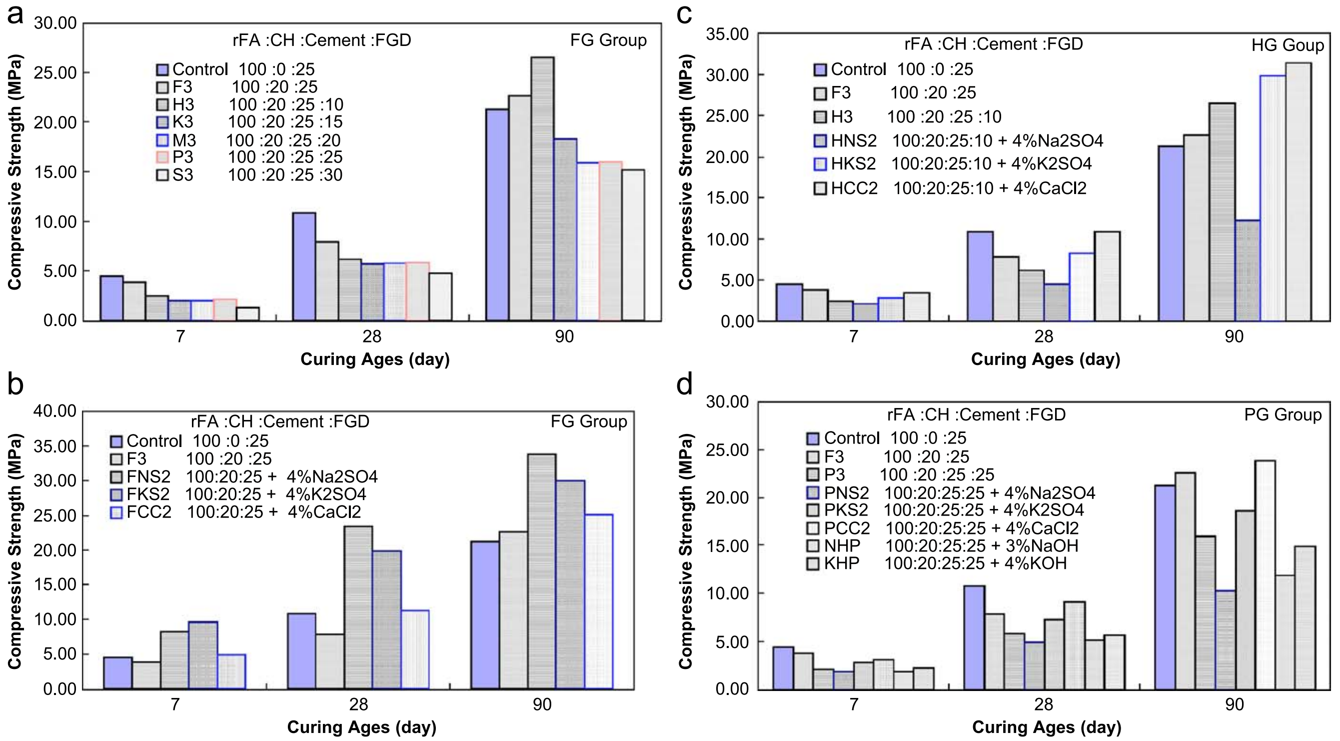

Fig. 5. (a) Effects of FGD on compressive strength of mixes with $Ca(OH)_2$ (CH: $Ca(OH)_2$). (b) Effects of chemical activators on compressive strength of mixes with $Ca(OH)_2$ (CH: $Ca(OH)_2$). (c) Effects of chemical activators on compressive strength of mixes with $Ca(OH)_2$ and 10% FGD (CH: $Ca(OH)_2$). (d) Effects of chemical activators on compressive strength of mixes with $Ca(OH)_2$ and 25% FGD (CH: $Ca(OH)_2$).

The hydration degrees of rFA in the G group are shown in the Fig. 7. Addition of FGD is useful to the hydration of rFA, which increases with increase of FGD content. The effect of FGD on the hydration degree of rFA in the rFA-$Ca(OH)_2$-cement system is shown in the Fig. 8a. The hydration degree of rFA in the FG group shows the same trend as that in the G group, but the simultaneous presence of FGD and $Ca(OH)_2$ is more effective in enhancing the hydration rate of rFA as the curing time increases. Fig. 8b shows that the addition of other chemicals is effective for activating the hydration of rFA. Na_2SO_4 is the most effective and $CaCl_2$ is the least. Fig. 8c and d shows that the addition of other chemical activators to the mixes with FGD results in higher hydration degrees than those without chemicals. However, the most useful chemical for the mixes with FGD is $CaCl_2$. The hydration degree of the mix with more FGD (PG group) is higher than that with less FGD (HG group) or without FGD (FC group) after adding the

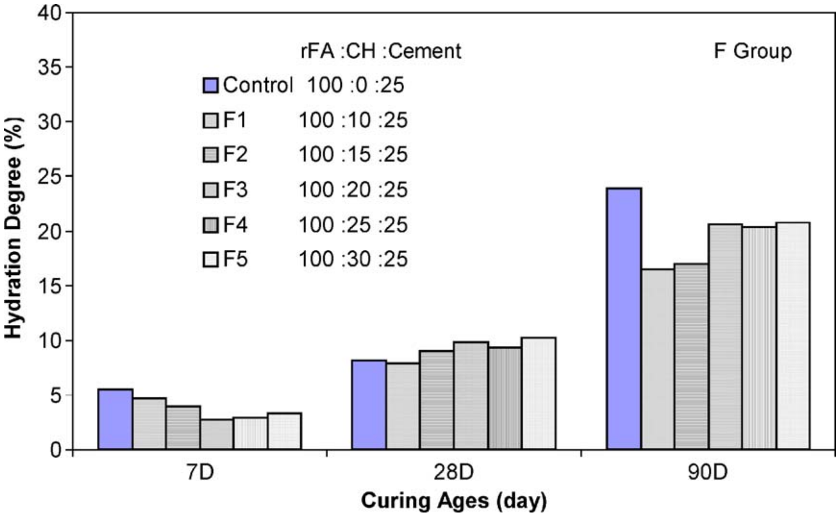

Fig. 6. Effects of different $Ca(OH)_2$ contents on degree of hydration (CH: $Ca(OH)_2$).

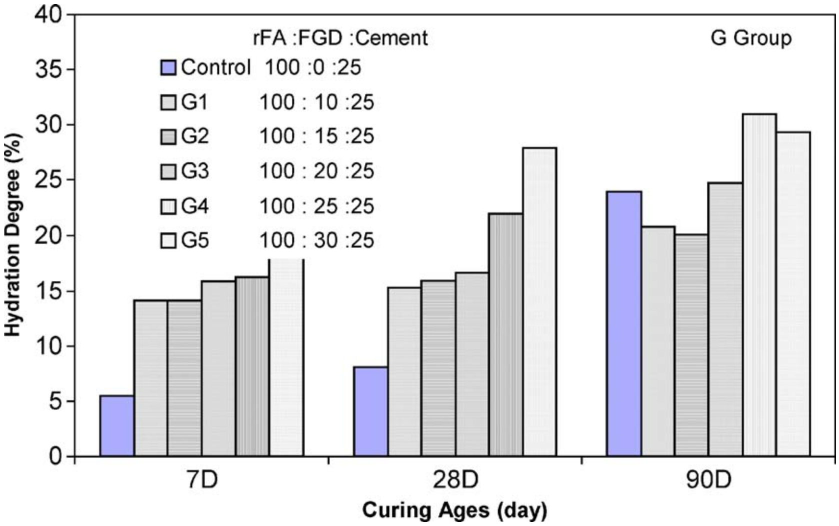

Fig. 7. Effects of different FGD contents on degree of hydration.

same chemical activators. Fig. 8d shows the addition of NaOH and KOH instead of Na_2SO_4, and K_2SO_4 have less effect on the hydration of rFA except for the mix with KOH at 90 days.

3.3. XRD analysis

Fig. 9 shows that the addition of $Ca(OH)_2$ alone (mix F3) has no obvious effects on the hydration of rFA, but the

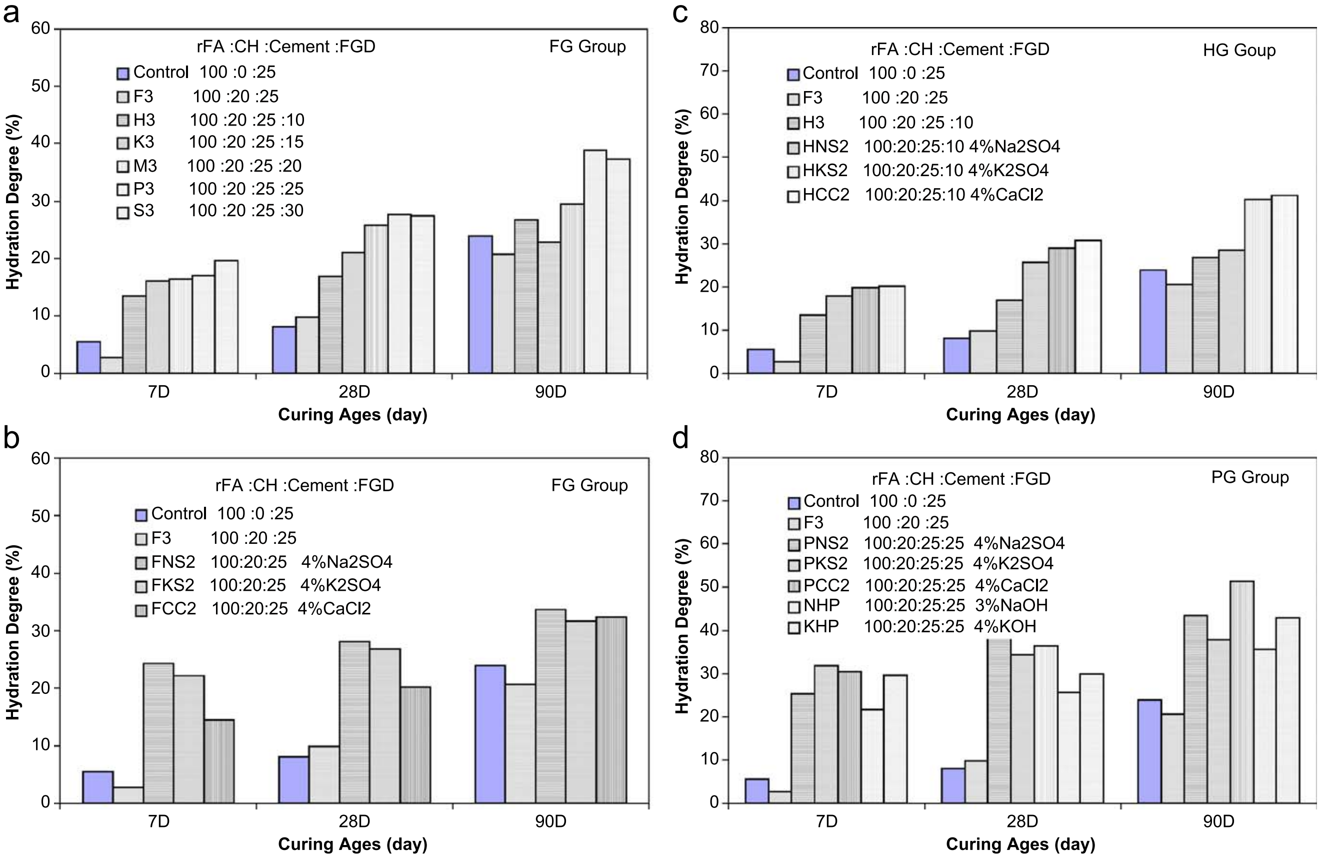

Fig. 8. (a) Effects of FGD on degree of hydration of mixes with $Ca(OH)_2$ (CH: $Ca(OH)_2$). (b) Effects of chemical activators on the degree of hydration of mixes with $Ca(OH)_2$ (CH: $Ca(OH)_2$). (c) Effects of chemical activators on degree of hydration of mixes with $Ca(OH)_2$ and 10% FGD (CH: $Ca(OH)_2$). (d) Effects of chemical activators on degree of hydration of mixes with $Ca(OH)_2$ and 25% FGD (CH: $Ca(OH)_2$).

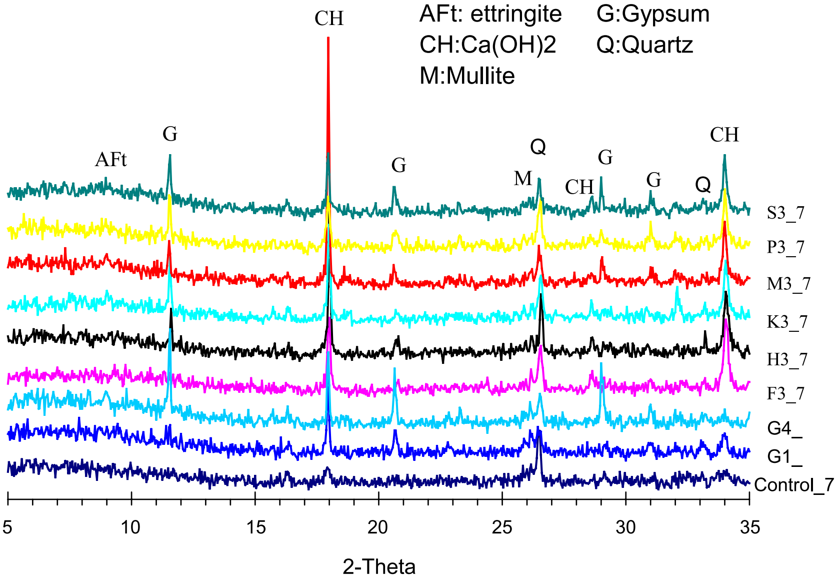

Fig. 9. XRD patterns of the mixes without chemical activators at 7 days (CuK radiation).

addition of FGD alone (mix G1 and G4) accelerates the reaction of both the cement and the rFA. The gypsum peaks almost disappear in mix G1 (Fig. 9). Using the mix proportions of mix F3, the addition of FGD (mixes H3, K3, M3, P3, and S3) weakens the main peak of the rFA's quartz and increases the gypsum peaks. The XRD patterns show that there is no obvious formation of AFt in all the mixes at 7 days.

Compared with mix F3, the addition of chemical activators to the rFA/cement/$Ca(OH)_2$ mixes reduces the $Ca(OH)_2$ significantly (Fig. 10), but there is still no obvious AFt or monochloroaluminate ($C_3A \cdot CaCl_2 \cdot 10H_2O$) [3]. With the addition of alkali sulphate, based on the mix proportion of P3 (rFA/cement/$Ca(OH)_2$/FGD), AFt begins to appear and the two main gypsum peaks are weakened. The two main peaks of $Ca(OH)_2$ in mix PCC2 decrease more than those in mixes PNS2 and PKS2. However, the two main peaks of gypsum in mix PCC2 seem to have been widened with no change in intensity. This is likely to be related to overlapping of the gypsum and monochloroaluminate peaks. It can be observed from Fig. 10 that the peak intensity of quartz in the PG group decreases in the following sequence: $CaCl_2$, K_2SO_4, and Na_2SO_4.

At 28 days, for mixes G1, G4, and the control, $Ca(OH)_2$ is increased after the addition of FGD (Fig. 11). At the

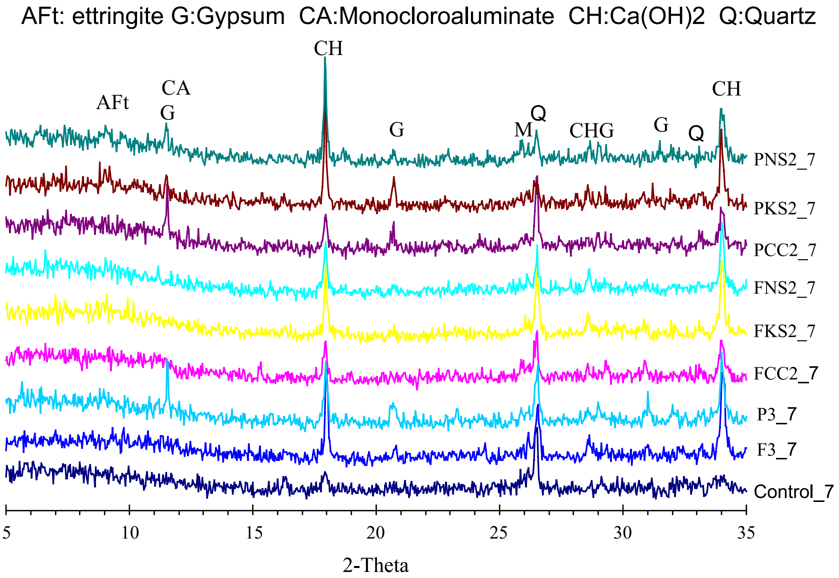

Fig. 10. XRD patterns of mixes with chemical activators at 7 days (CuK radiation).

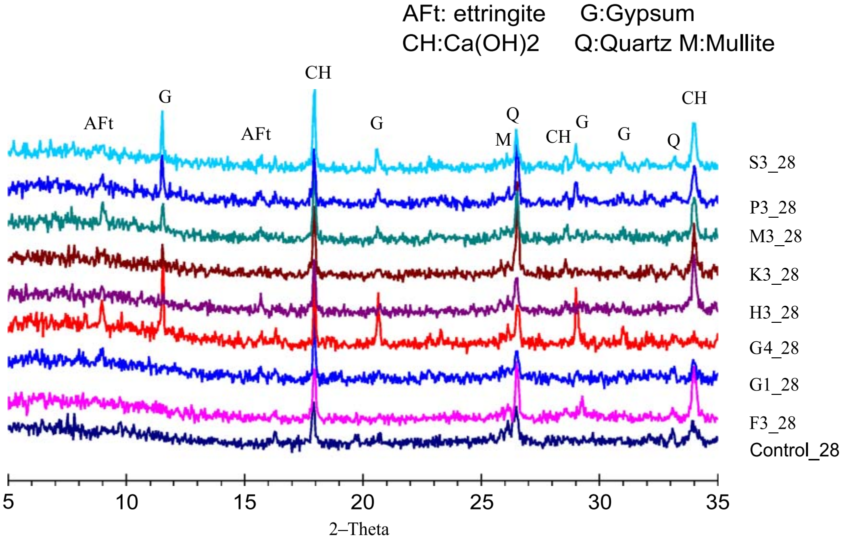

Fig. 11. XRD patterns of mixes without chemical activators at 28 days (CuK radiation).

same time, the AFt can also be observed. The peak intensity of AFt in the mix G4 is stronger than that of the mix G1. The formation of AFt in the FG group can only be found in mixes M3 and P3. This may mean that an appropriate ratio of $Ca(OH)_2$ to FGD is required for the formation of AFt.

In Fig. 12, the major effects of adding the chemical activators in the FC group are the weakening of the peak intensities of $Ca(OH)_2$ and quartz. The addition of alkali sulphate, especially Na_2SO_4, enhances the formation of AFt significantly. The peak of monochloroaluminate ($C_3A \cdot CaCl_2 \cdot 10H_2O$) can also be distinguished from gypsum at 28 days. For those mixes with both FGD and chemical activators, $CaCl_2$ is most effective in weakening the peak intensities of $Ca(OH)_2$ and quartz and the alkali sulphate renders the AFt peak sharper at 28 days.

The XRD patterns of the samples after 90 days of curing are not shown in this paper. Generally, they are consistent with those found at 28 days.

3.4. Pore size distribution

The influence of FGD and the chemical activators on the pore structure of the prepared pastes are shown in Fig. 13. When compared with the control, the addition of $Ca(OH)_2$ or FGD decreases the cumulative porosity of the samples (Fig. 13a), but the porosities of the samples with only FGD and no $Ca(OH)_2$ increase with increase in FGD content. With the presence of $Ca(OH)_2$, increase in FGD decreases the porosity.

Fig. 13b shows that the additions of the chemical activators can significantly decrease the porosity of paste

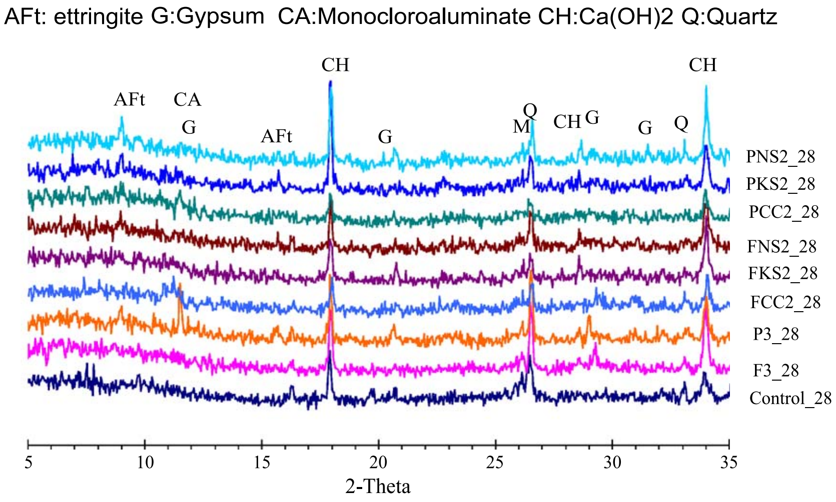

Fig. 12. XRD patterns of mixes with chemical activators at 28 days (CuK radiation).

prepared with rFA/$Ca(OH)_2$/cement. The sample with $CaCl_2$ shows higher porosity than the samples with the other two chemicals. It can be also noted from Fig. 13b–d the major effect of the chemical activators on reducing the pores within the pore sizes of 0.02–3.6 μm.

4. Discussion

The results of this study indicate that FGD plays an important role in the compressive strength development, hydration degree, formation of hydration products, and

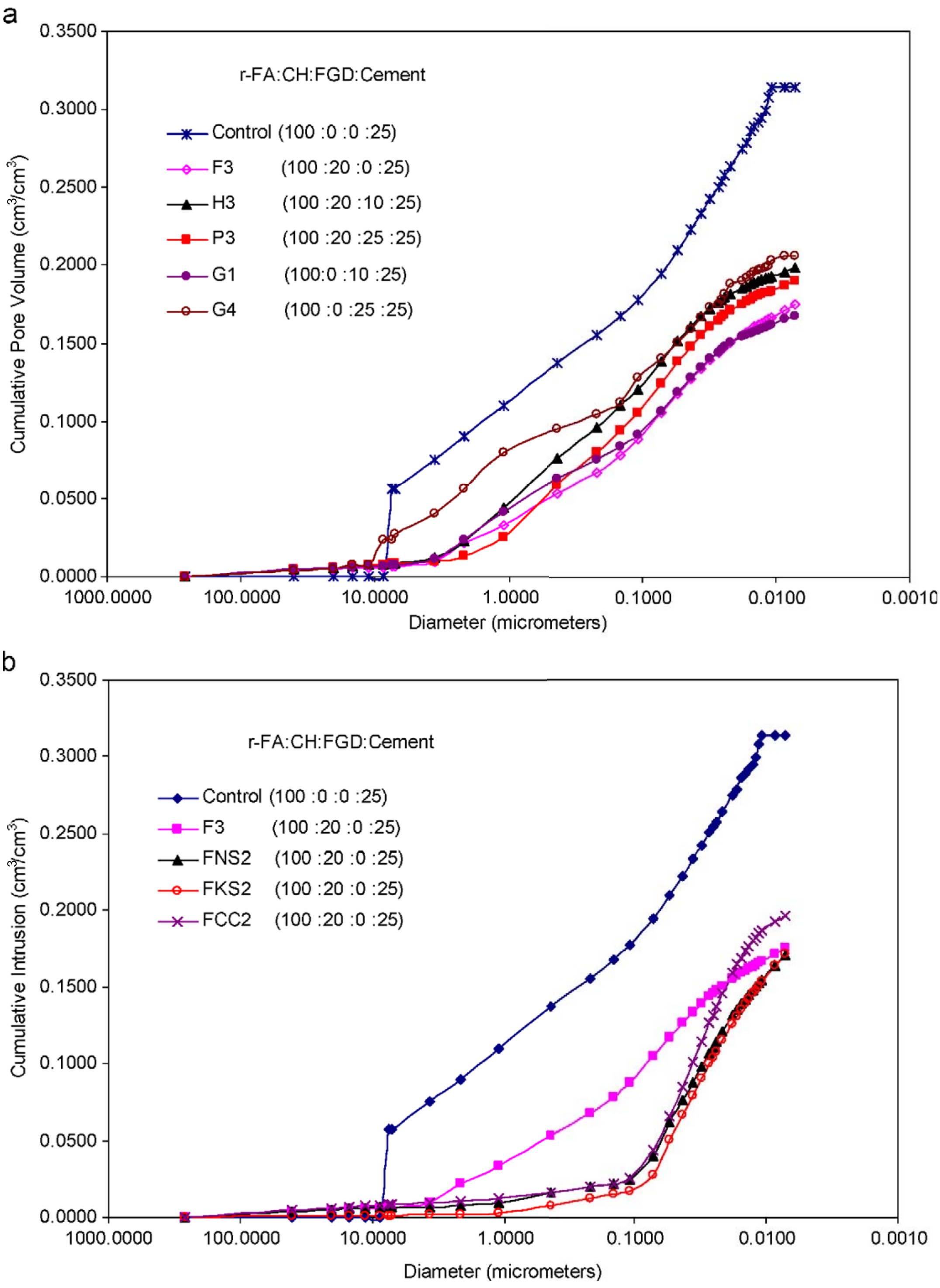

Fig. 13. Influence of FGD and chemical activators on the pore size distribution: (a) effect of different FGD contents, (b) effect of different chemical activators, (c) effect of different chemical activators at 10% FGD, (d) effect of different chemical at 25% FGD.

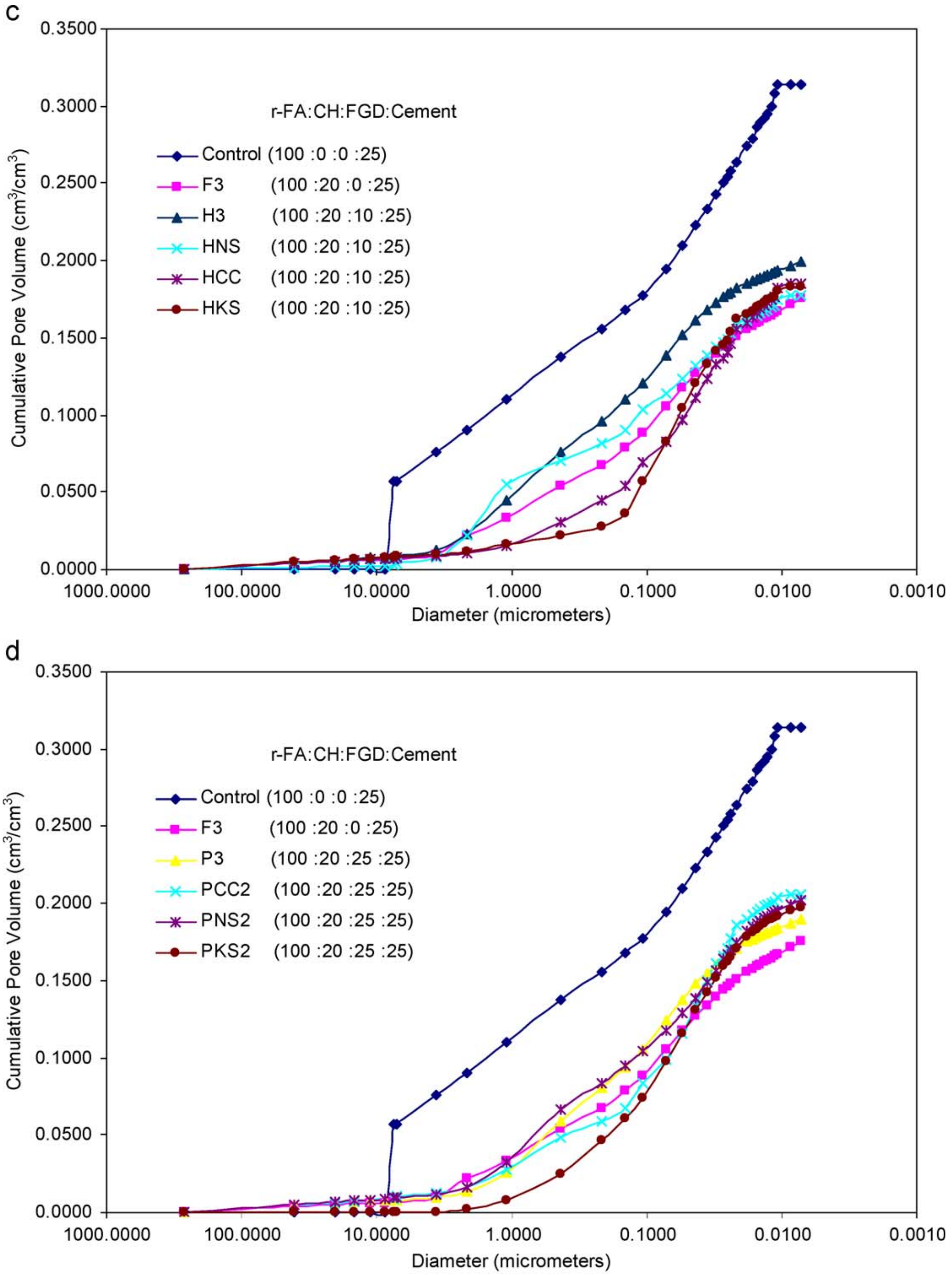

Fig. 13 (*continued*).

pore size distribution of the prepared pastes. The effect of FGD can be divided into three parts: effect on the rFA-cement system, effect on the rFA-Ca$(OH)_2$-cement system, and effect on the rFA-Ca$(OH)_2$-cement-chemical activators system.

4.1. Effect on the rFA-cement system

Xu and Sarkar [8] reported that gypsum is not an effective activator for fly ash hydration until it is dissolved in solution, which only occurs when Ca$(OH)_2$ formation has been slowed down. The rate of strength increase of the samples in the rFA-FGD-cement system is almost equal to the control sample (with only rFA and cement) at 28 days. This shows that FGD has little effect on the hydration of rFA before 28 days. From the small peak of AFt in mixes G1 and G4 at 28 days, it can be concluded that FGD begins to take effect as an activator only after 28 days in the rFA-FGD-cement system. This is supported by the increase in the strength development of all the samples prepared with rFA-FGD-cement, which are higher than the control at 90 days. The strength of the sample with 10% FGD by mass of rFA is also higher than the control at 90 days.

The hydration degree of the rFA increases with the increase in FGD content at all ages except for mixes G1 and G2 at 90 days (gypsum in these two samples almost disappeared at 28 days; Fig. 11), which is contrary to the results of Ma and Brown [12], which showed from a calorimetric study that addition of gypsum did not accelerate the reaction of low lime fly ash at temperature of 60 °C and below.

In the rFA-FGD-cement system, although AFt is formed at about 28 days, the rate of strength increase is similar to the control sample. This may be related to the increase in porosity after gypsum has entered into chemical reaction in the rFA-FGD-cement system.

4.2. Effect on the rFA-Ca(OH)$_2$-cement system

The addition of Ca(OH)$_2$ has no obvious effect on the rFA-Ca(OH)$_2$-cement system, except for a small increase in strength at 90 days. The optimal addition of Ca(OH)$_2$ in the rFA-Ca(OH)$_2$-cement system is about 20% by mass of rFA.

The hydration degree of rFA increases with increase in FGD content at all curing ages (until 25% FGD by mass of rFA). The optimal addition of FGD in the rFA-Ca(OH)$_2$-cement system is 25% by mass of rFA. This can be supported by the results of the XRD study, which shows that the formation of AFt increases with the increase of FGD at 28 days but the AFt phase disappears when the addition of FGD exceeds 25% by mass of rFA. In addition, the hydration degrees in the rFA-Ca(OH)$_2$-cement system are all higher than that in the rFA-cement system at all curing ages. This means that the presence of Ca(OH)$_2$ together with FGD is necessary to activate the hydration of rFA. It may be due to the addition of Ca(OH)$_2$, which accelerates the buildup of its concentration in the pore solution to reach saturation. This can bring forward the dissolution of FGD as an activator [8].

Although the addition of FGD increases the hydration degree of rFA, the compressive strength data show that the addition of FGD decreases the compressive strength except for mix H3 at 90 days. This may be because it is impossible for all the added FGD to participate in the reaction. The surplus FGD will reduce the strength because the overall cement content of the pastes in the rFA/Ca(OH)$_2$/FGD/cement system is reduced.

4.3. Influence on the rFA-Ca(OH)$_2$-cement-chemical system

Shi et al. [3,5] showed that Na_2SO_4 has a predominant influence on the early hydration of fly ash pastes and the addition of $CaCl_2$ improved the strength significantly at later curing ages. Shi et al. [4] also reported that Na_2SO_4 accelerated the reaction of fly ash by the following reaction:

$$Na_2SO_4 + Ca(OH)_2 + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O + 2NaOH \quad (1)$$

The generated NaOH increased the pH of the solution and speeded up the pozzolanic reaction between Ca(OH)$_2$ and fly ash.

The addition of a small quantity of chemical activator to the rFA-Ca(OH)$_2$-cement system plays a significant role in improving the strength at all curing ages. This is consistent with the porosity results and hydration degree tests. K_2SO_4 is the most effective chemical activator for strength at 7 days, followed by Na_2SO_4 and $CaCl_2$. This may be related to the formation of AFt, which is present only in the mix with K_2SO_4 at 7 days. After 7 days, Na_2SO_4 is the most effective in enhancing the strength, which is consistent with the hydration degree results.

Compared with the mixes in the rFA-Ca(OH)$_2$-cement-chemical system, the addition of FGD can improve the hydration degree of rFA considerably and can accelerate the formation of AFt or $C_3A\cdot CaCl_2\cdot 10H_2O$ [3]. However, the compressive strength decreases with increase in FGD, which is consistent with the results of the porosity study.

The effects of chemical activators in the rFA-Ca(OH)$_2$-cement-chemical system change conspicuously after the addition of FGD. $CaCl_2$ seemed to be most useful to the strength development and the hydration of rFA possibly because $CaCl_2$ can reduce the setting time and induce the formation of $C_3A\cdot CaCl_2\cdot 10H_2O$ [3].

When NaOH and KOH are used to replace Na_2SO_4 and K_2SO_4, respectively, in the rFA-Ca(OH)$_2$-FGD-cement system, both the strength and hydration degree decrease. The accelerating effect of Na_2SO_4 or K_2SO_4 on the reaction of rFA does not follow Eq. (1) when FGD is present. Or else, the compressive strength and the hydration degree of the mix with NaOH or KOH should be higher than that of the mix with Na_2SO_4 or K_2SO_4. It is because the presence of gypsum in the FGD may have retarded the reaction described in Eq. (1). The chemical activators may accelerate the hydration of rFA by directly reacting with the rFA.

5. Conclusions

1. FGD begins to take effect as an activator only after 28 days of curing in the rFA-FGD-cement system.
2. The presence of Ca(OH)2 benefits the reaction between FGD and rFA by supplying the Ca^{2+}.

3. Despite the increase in the degree of hydration of the rFA, a minimum cement content is necessary to guarantee strength development when FGD is used.
4. Alkali sulphates are more effective in enhancing strength and degree of hydration rFA than $CaCl_2$ at all curing ages in the rFA-$Ca(OH)_2$-cement system.
5. $CaCl_2$ is more effective in enhancing strength development and hydration degree of rFA than alkali sulphate at all curing ages in the rFA-$Ca(OH)_2$-FGD-cement system.
6. The chemical activators speed up the reaction of the rFA through the formation hydration products.

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References

[1] W.S. Langley, G.G. Carette, V.M. Malhotra, Structural concrete incorporating high volumes of ASTM class F fly ash, ACI Mater J 86 (1989) 507–514.

[2] S. Horiuchi, M. Kawaguchi, K. Yasuhara, Effective use of fly ash slurry as fill material, J Hazard Mater 76 (2000) 301–337.

[3] C. Shi, Pozzolanic reaction and microstructure of chemical activated lime-fly ash pastes, ACI Mater J 95 (1998) 537–545.

[4] J. Qian, C. Shi, Z. Wang, Activation of blended cements containing fly ash, Cem Concr Res 31 (2001) 1121–1127.

[5] C. Shi, R.L. Day, Acceleration of the reactivity of fly ash by chemical activation, Cem Concr Res 25 (1995) 15–21.

[6] A. Katz, Microscopic study of alkali-activated fly ash, Cem Concr Res 28 (1998) 197–208.

[7] A.L.A. Fraay, J.M. Bijen, Y.M. de Haan, The reaction of fly-ash in concrete—a critical-examination, Cem Concr Res 19 (1989) 235–246.

[8] A. Xu, S.L. Sarkar, Microstructural study of gypsum activated fly ash hydration in cement paste, Cem Concr Res 21 (1991) 1137–1147.

[9] C.S. Poon, S.C. Kou, L. Lam, Z.S. Lin, Activation of fly ash/cement using calcium sulfate anhydrate ($CaSO_4$), Cem Concr Res 31 (2001) 873–881.

[10] W. Ma, C. Liu, P.W. Brown, S. Komarneni, Pore structures of fly ashes activated by $Ca(OH)_2$ and $CaSO_4 \cdot 2H_2O$, Cem Concr Res 25 (1995) 417–425.

[11] A.F.L. Hyde, Some preliminary test data on cement-PFA-anhydrite mixes, Mag Concr Res 36 (1984) 174–180.

[12] W. Ma, P.W. Brown, Hydration reactions of fly ash with $Ca(OH)_2$ and $CaSO_4 \cdot 2H_2O$, Cem Concr Res 27 (1997) 1237–1248.

[13] C.S. Poon, X.C. Qiao, Z.S. Lin, Pozzolanic properties of reject fly ash in blended cement pastes, Cem Concr Res, 33 (2003) 1857–1865.