

Influence of high-volume mineral mixtures and the steam-curing temperatures on the properties of precast concrete

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The compressive strengths of concrete and hardened paste, the resistance to chloride ion of concrete, the pore structure of hardened paste are tested to investigate the influence of high volume mineral admixture on the properties of concrete and hardened paste under steam-curing condition. Three binders used are the pure cement, the binder containing high content of GGBS, and the binder containing high content of fly ash. Two steam-curing temperatures used are 60°C and 80°C. The results show that the addition of high volume GGBS tends to decrease the early strength of concrete slightly, but it refines the pore structure of hardened paste and improves the compressive strength and resistance to chloride ion penetration of concrete at late ages. The addition of high volume fly ash tends to decrease the early strength of concrete sharply, but its negative effect on the strength of concrete decreases obviously with the prolonging of age and it can refine the pore structure of hardened paste and improve the resistance to chloride ion penetration of concrete in some cases. Increasing the steam-curing temperature has negative effect on the pore structure of hardened pure cement paste and the resistance to chloride ion penetration of the pure cement concrete at late ages, but the addition of high volume GGBS or fly ash can eliminate this negative effect.

Key words: Steam-curing, Fly ash, GGBS, Concrete, Hardened paste

Concrete is one of the most important building materials in modern society. In the construction of concrete engineering, concrete is ready mixed in the factory and transported to the site for casting in most cases. However, precast concrete industry is booming and precast concrete elements are used increasingly in construction due to its advantages¹⁻⁵: reduction in building time, the multiplicity of available products, assured quality with certified performance levels, optimized costs, increased production by a more rapid turnover of molds, formwork shorter curing periods before shipment or pre-stressing, less damage to the product during handling simple fabrication process, low noise and little pollution on the construction site, and so on.

According to economy, availability, and long-term performance of the precast concrete elements, the most common method is accelerated curing by means of increased temperature and humidity (steam-curing). The hydration rate of binder increases with an increase in temperature, and the gain of strength of concrete can be speeded up under steam-curing condition⁶⁻⁸. Some experimental results^{9,10} indicated that the compressive strength of steam cured concrete increased compared with control sample without steam-curing at 90 days.

This could be explained by the initial steam-curing, which promoted the hydration reaction of cement and pozzolanic reaction of mineral admixture. Zhao *et al.*¹¹ has proved that the concretes containing fly ash cured at 50°C and 90°C produce more hydration products, with a slight decrease of $\text{Ca}(\text{OH})_2$, and the specific creep of which is smaller than that of the reference concrete cured with standard conditions. Selcuk *et al.*¹² has reported the effect of steam-curing with five different curing periods (4, 8, 16, 24 and 32 h) and two curing temperatures (65°C and 85°C). However, some researches¹³⁻¹⁵ proved that the concrete under elevated temperature curing usually exhibited lower strength and higher permeability at the later ages since elevated temperature curing tended to hinder the late hydration of binder and makes the hydration products distribute non-uniformly. Bingöl *et al.*¹⁶ reported the influence of curing regimes on the mechanical properties of concrete containing fly ash or silica fume. Same results were concluded that the concretes cured at 60°C, 70°C and 80°C have relatively lower compressive strength than that of the reference concrete which can be explained with the fact that high temperature produces a non-uniform distribution of hydration products, leaving weak zones in the cement paste that govern the strength¹⁷. The autogenous shrinkage of concrete is mainly due to the reduction in interior humidity during

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the hydration process of binder, but the interior humidity of steam cured concrete declines very little due to the penetration of steam, thus the autogenous shrinkage of the steam cured concrete is much smaller than that of the concrete without steam-curing. What's more, the drying shrinkage of concrete is very small under steam-curing condition¹⁰.

Ground granulated blast furnace slag (GGBS) from metal industries and fly ash from the combustion of coal are both industrial by-products that have been widely used as mineral admixtures to improve durability and produce high performance concrete for over half a century. GGBS is a kind of beneficial mineral admixture for concrete due to its high pozzolanic activity, which reduces the porosity and makes the pores finer as well as changes the mineralogy of cement hydrates that leads to a reduction in mobility of chloride ions¹⁸⁻²⁰. The benefits of using fly ash include lowering the heat of hydration, improving the workability, enhancing the durability and decreasing the cracking risk of concrete²¹⁻²³. However, the rate of the reaction between fly ash or GGBS and calcium hydroxide depends on the hydration of Portland cement, and the gain of the initial strength may be reduced since the reduction in cement dosage, especially for concrete containing high volume of mineral admixtures^{24,25}.

The early activity of GGBS and fly ash is very sensitive to curing temperature. Many researches indicated that elevated curing temperature promoted the early reaction of GGBS and fly ash significantly^{7,8,26}. In view of sustainable development, it is imperative that mineral admixtures should be used to replace part of cement in the precast concrete industry. Zhimin *et al.*²⁷ reported that under the steam-curing condition, the high temperature greatly enhanced the reactivity of fly ash and GGBS in concrete, and thus the addition of mineral admixture significantly improved the microstructure of steam cured concrete. Although steam-curing might cause the reduction of strength of plain cement concrete at later age due to the initial rapid hydration rate of cement at elevated temperature which hinders the subsequent hydration and produces a non-uniform distribution of the hydration products, the pozzolanic reaction of fly ash or GGBS could make considerable contributions to the long-term strength of concrete due to the extra production of C-S-H gel and the improvement of transition zone. So the application of mineral admixtures to steam cured concrete is a potential way to improve its durability.

At present, the ready-mixed concrete with high volume mineral admixture has been widely used. But the researches about steam cured concrete with high volume mineral admixture are scarce. In this paper, the influence of high volume fly ash and GGBS on the properties of steam cured concrete was investigated.

Experimental Procedure

Materials

The ordinary Portland cement with the strength grade of 42.5 conforming to the Chinese National Standard GB175-2007 was utilized as the main binder in this research. Ground granulated blast-furnace slag and low calcium fly ash conforming to the Chinese National Standard GB/T 18046-2000 and Chinese National Standard GB/T 1596-2005, respectively, were used as mineral admixtures. The specific surface areas of the cement, GGBS, and fly ash were 376, 430, and 358 m²/kg, respectively. The chemical compositions of cement, GGBS, and fly ash are summarized in Table 1. Natural river sand smaller than 5 mm and crushed limestone between 5 and 25 mm were used as fine and coarse aggregates, respectively.

The mix proportions of the pastes and concretes are shown in Tables 2 and 3, respectively. Three mix proportions of pastes were prepared. Sample PC was cement paste without mineral admixtures while PB and PF were composited pastes with 50% cement replacement by GGBS and fly ash, respectively. Six

Table 1 — Chemical compositions of the raw materials (%)

Sample	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	Na ₂ O _{eq}	LOI
Cement	21.10	6.33	4.22	54.86	2.60	2.66	0.53	2.42
GGBS	31.76	14.84	0.6	36.44	9.08	1.94	0.56	0.86
Fly ash	53.33	27.65	6.04	2.86	1.35	0.45	0.64	4.71

Note: Na₂O_{eq} = Na₂O + 0.658K₂O; LOI: loss on ignition

Table 2 — Mix proportions of pastes (%)

Sample	cement	GGBS	Fly ash	Water
PC	100	0	0	30
PB	50	50	0	30
PF	50	0	50	30

Table 3 — Mix proportions of concretes (kg/m³)

Sample	Cement	Slag	Fly ash	Sand	Stone	water
C	350	0	0	812	1077	161
B	210	140	0	812	1077	161
F	210	0	140	812	1077	161
CC	450	0	0	802	1063	135
BB	270	180	0	802	1063	135
FF	270	0	180	802	1063	135

mix proportions of concrete were prepared. The concretes with water to binder ratio (W/B) of 0.3 were high strength concretes, and those with W/B of 0.46 were normal strength concrete. In concretes B and BB, 40% of cement was replaced by GGBS. In concretes F and FF, 40% of cement was replaced by fly ash.

Test methods

Pastes of 40×40×40 mm and concretes of 100×100×100 mm were prepared. Two temperatures for the steam-curing period were adopted: 60°C and 80°C. The pre-curing time before steam-curing period was 6 h and all the samples were cured under the conditions of 20°C and relative humidity higher than 95% during the pre-curing period and after steam-curing. The samples cured at the steam-curing temperature of 60°C and 80°C are denoted with a suffix “-60” and “-80”, respectively. For example, sample PB-60 is the paste PB at the steam-curing temperature of 60°C, and sample BB-80 is the concrete BB at the steam-curing temperature of 80°C. The curing regime is given in Table 4.

The compressive strength of concrete was tested at the ages of 3, 28, and 90 days. Chloride ion permeability test was conducted at 28 and 90 days in order to determine the resistance of the concretes to penetration of chloride ions according to ASTM C 1202 “Standard Test Method for Electrical Indication of Concretes Ability to Resist Chloride Ion Penetration.” The pore characteristics of pastes were tested by means of mercury intrusion porosimetry (MIP).

Results and Discussion

The properties of concretes and pastes at steam-curing temperature of 60°C

Compressive strength of concrete

Figure 1 shows the compressive strengths of the normal and high strength concretes at 3, 28, and 90 days. Figure 1 shows that the compressive strength of sample C-60 is a little higher than that of sample B-60, and it is much higher than that of Sample F-60 at the age of 3 days. It should be noted that the early strength of the concrete with high volume GGBS is obviously lower than that of pure cement concrete at room

temperature^{13,14,19}. So it is clear that GGBS exhibits high activity at early ages at 60°C. However, the early strength of the concrete with high volume fly ash is 56.4% lower than that of the pure cement concrete, indicating that fly ash does not exhibit high activity at early ages at 60°C. At the ages of 28 and 90 days, the compressive strength of sample B-60 exceeds that of sample C-60, but the compressive strength of sample F-60 is still much lower than that of sample C-60. It should be noted that from 3 to 90 days, the compressive strengths of samples C-60, B-60, and F-60 increase 19.9, 26.8, and 28.4 MPa, respectively. It is obvious that the increase amplitude of strength of the concrete with high volume mineral admixture is more than that of the pure cement concrete at later ages. As for the concrete with high volume fly ash, its 90 d compressive strength is 20.2% lower than that of the pure cement concrete. So it can be seen that the gap of compressive strengths between the concrete with high volume fly ash and the pure cement concrete is mainly formed at early ages, and it becomes smaller at later ages.

The 3d compressive strength of sample BB-60 is a little lower than that of sample CC-60, but the 3 d compressive strength of sample FF-60 is much lower than that of sample CC-60. Though the early activity of the binder with high volume fly ash is much lower than that of pure cement at 60°C whether at W/B of 0.46 or 0.30, the gap of early strengths between the concrete with high volume fly ash and the pure cement concrete is smaller at lower W/B. The 3 d compressive strength of sample FF-60 is 37.3% lower than that of sample CC-60. It is believed that the early activity of

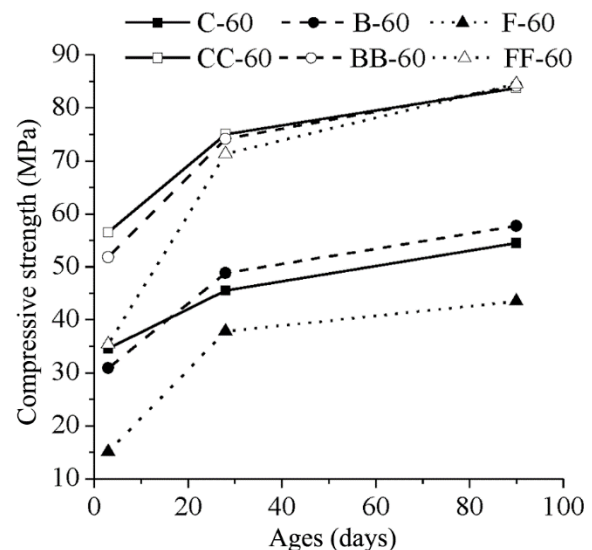


Fig. 1 — Compressive strengths of the concretes at steam-curing temperature of 60°C

Table 4 — The curing regimes of the paste and concrete

Sample	Presetting/ h	Rate of temp. (°C/h)	Maximum temp./ °C	Curing at maximum temp/d
“-60”	6	20	60	7
“-80”	6	20	80	7

the binder with high volume fly ash is not higher at lower W/B. However, the dilution effect of fly ash on the early hydration of cement cannot be neglected: in the case of the same W/B, the actual water to cement ratio in the binder with high volume fly ash is higher than that in pure cement. At lower W/B, the dilution effect of fly ash is more obvious, which promotes the hydration of cement more significantly. It is commonly accepted that the activity of GGBS is higher than that of fly ash. However, as shown in Fig.1, both the long term compressive strengths of samples BB-60 and FF-60 are very close to that of sample CC-60. As for the sample FF-60, there are two possible reasons for the large increment of strength at late ages: the dilution effect of fly ash on the late hydration of cement is significant at low W/B; the improvement of transition zone of concrete due to the reaction of fly ash is significant at low W/B.

Permeability of concrete

Figure 2 shows the chloride ion permeability of the normal and high strength concretes at 90 days. According to ASTM C1202, the permeability of concrete falls in the “Very Low” level when the charge passed is between 100 and 1,000 coulombs, while it falls in the “Low” level when the charge passed is between 1,000 and 2,000 coulombs. As shown in Fig. 2, the permeability of normal strength concrete with either GGBS or fly ash decreases a level compared with that of the pure cement concrete, indicating that the resistance to chloride ion penetration of concrete is significantly enhanced by adding GGBS or fly ash. Figure 2 shows that though the charge passed of the high strength concrete with either GGBS

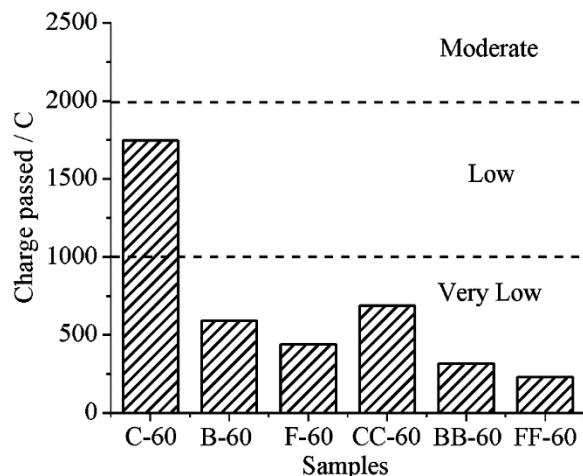


Fig. 2 — Chloride ion permeability of the concretes at steam-curing temperature of 60°C

or fly ash is obviously smaller than that of the pure cement concrete, the permeability of all the high strength concretes falls in “Very Low” level. Based on the evaluation standard for permeability, different test samples that fall in the same level are considered to be equivalent. Therefore, for the high strength concrete, though the addition of mineral admixture tends to reduce its charge passed, its resistance to chloride ion penetration is not improved much. Both GGBS and fly ash have the capacity of filling the voids between the larger cement particles, and increasing production of secondary hydrates by pozzolanic reactions with the lime resulting from the primary hydration to improve the interface transition zone^{14,18,21,22}. In the steam cured concrete, the high temperature curing at early age can promote the pozzolanic reaction of GGBS and fly ash, which enhances their positive effect on the compactness of concrete. Figure 2 indicates that the promoting effect of GGBS and fly ash on the resistance to ion penetration is less significant at lower W/B, which might be due to the fact that the resistance to ion penetration of the pure cement concrete with lower W/B is higher and thus the further improvement is difficult.

Properties of pastes

The compressive strengths of pastes at steam-curing temperature of 60°C at 28 and 90 days are shown in Fig. 3. It is obvious that the compressive strengths of the paste with high volume GGBS and the paste with high volume fly ash are much lower than that of the pure cement paste. Note that the compressive strengths of the concretes are very close to each other at 28 and 90 days (Fig. 1). It can be deduced that the difference of the strength's trends between the concretes and

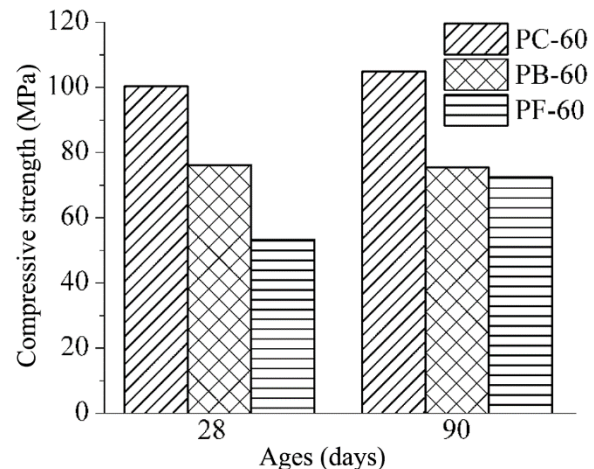


Fig. 3 — Compressive strengths of pastes at steam-curing temperature of 60°C

pastes lies in the transition zone. In the pastes, the effect of GGBS and fly ash on the improvement of the transition zone cannot be reflected.

Figure 4 shows the pore size distributions of the pastes PC, PF, and PB at the age of 28 days. Pores can be classified based on the pore diameter in accordance with the International Union of Pure and Applied Chemistry (IUPAC)²⁸. The micropores, macropores and mesopores are classified as the pore diameter less than 2 nm, between 2 nm and 50 nm, and larger than 50 nm, respectively. The peak of the differential pore volume curve is the main index for the pore size distribution because it illustrates the pores of the most widely distributed. For sample PC-60 and PF-60, the pore sizes corresponding to the dominant peak are very close to each other, indicating that the pastes have similar pore size distributions no matter whether cement was replaced with fly ash or not. The differential pore volume curve of sample PB-60 with no significant peak on it, however, is quite different from that of sample PC-60. It is clear that the addition of GGBS can refine the pore structure of hardened paste by the secondary pozzolanic reaction at late age. The main peak of the differential pore volume curve of sample PF-60 is very close to that of sample PC-60, though sample PF-60 has a larger volume of fine pores (smaller than 30 nm). It is an indication that the addition of high volume fly ash does not have negative effect on the late pore structure of hardened paste.

Properties of concretes and pastes at steam-curing temperature of 80°C

Compressive strength of concrete

Figure 5 shows the compressive strengths of the normal and high strength concretes at 3, 28, and

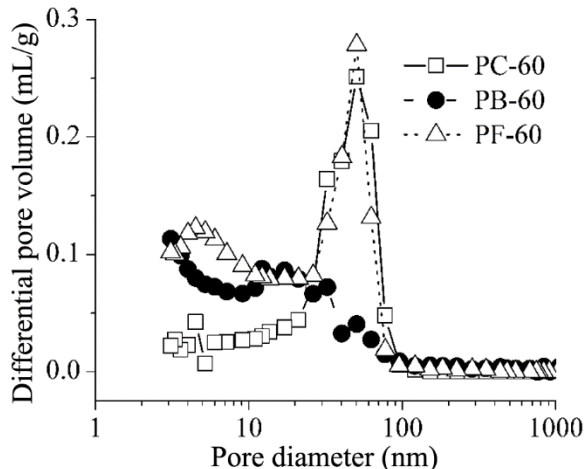


Fig. 4 — Pore size distribution of pastes at steam-curing temperature of 60°C

90 days. The trends are similar to those at steam-curing temperature of 60°C: the early strength of the concrete with GGBS is close to that of the pure cement concrete while that of the concrete with fly ash is much lower; the late strength of the concrete with GGBS is close to or even a little higher than that of the pure cement concrete; the late strength of the concrete with fly ash is still obviously lower than that of the pure cement concrete at the W/B of 0.46 but it is very close to that of the pure cement concrete at the W/B of 0.30. The results of Fig. 5 further prove that GGBS exhibits high early activity at high temperature and it makes much more contributions to the early strength of concrete than fly ash under steam-curing condition. Fly ash tends to make more contributions to the late strength of concrete at lower W/B.

Permeability of concrete

Figure 6 shows the chloride ion permeability of the normal and high strength concretes at steam-curing temperature of 80°C at 90 days. The permeability of both normal and high strength concretes containing mineral mixtures falls in “very low” level while that of the normal and high strength concretes without mineral mixtures falls in “moderate” and “low” levels, respectively. It is an indication that for the steam cured normal strength concrete, the addition of either high volume GGBS or fly ash can enhance its resistance to chloride ion significantly by decreasing its permeability by two levels. For the steam cured high strength concrete, the addition of either high volume GGBS or fly ash can also enhance its resistance to

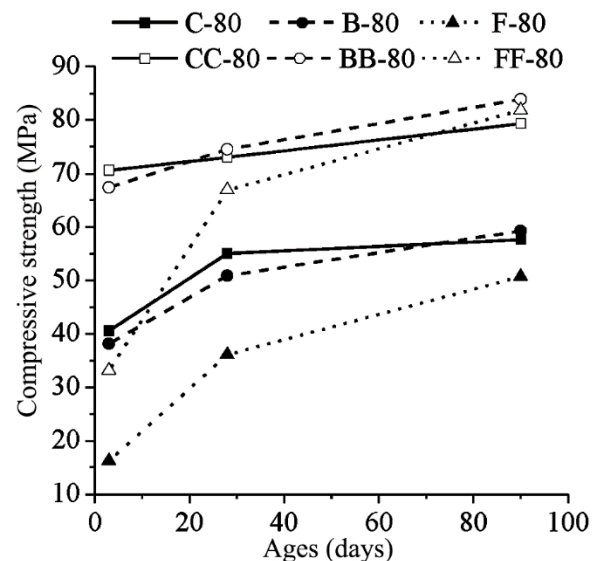


Fig. 5 — Compressive strengths of the concretes at steam-curing temperature of 80°C

chloride ion by decreasing its permeability by one level.

Properties of pastes

The compressive strengths of the pastes at steam-curing temperature of 80°C is shown in Fig. 7. The compressive strength of the paste with high volume GGBS is a little lower than that of the pure cement paste at 28 days, and their gap becomes smaller from 28 to 90 days. It is an indication that the high temperature of 80°C enhances the reaction degree of GGBS significantly and a lot of reaction products are produced which makes significant contributions to the strength of hardened paste. However, the high temperature of 80°C still seems to have an insufficient promoting effect on the reaction of fly ash compared with GGBS, and the compressive strength of the paste with high volume fly ash is much lower than that of the pure cement paste.

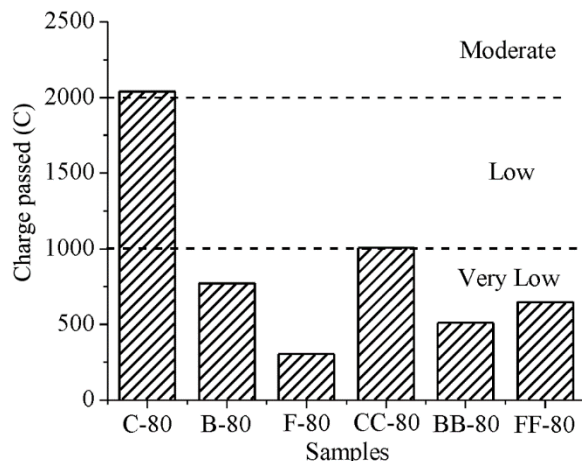


Fig. 6 — Chloride ion permeability of the concretes at steam-curing temperature of 80°C

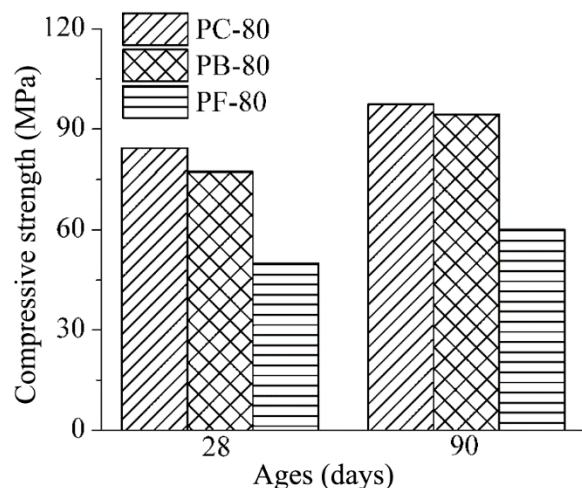


Fig. 7 — Compressive strengths of pastes at steam-curing temperature of 80°C

Figure 8 shows the pore size distribution of pastes at steam-curing temperature of 80°C at the age of 28 days. It is shown in Fig. 8 that the pore size corresponding to the dominant peak of sample PB-80 is apparently smaller than that of sample PC-80 due to the reaction of GGBS which is highly effective for the improvement of pore structure. The pore size corresponding to the dominant peak of sample PF-80 is a little smaller than that of sample PC-80, but it should be noted that the peak value of sample PF-80 is much higher, indicating that paste PF has less pores of about 80 nm but much more pores of about 40 nm. On the whole, the improvement effect of fly ash on the pore structure is much poorer than that of GGBS.

Influence of steam-curing temperature on the properties of concretes and pastes

Compressive strength of concrete

Figure 9 shows the influence of steam-curing temperature on the compressive strength of concrete. It is noted that the early strengths of the pure cement concrete and the concrete with GGBS increase with the increase of steam-curing temperature, however, the early strength of the concrete with fly ash changes little with steam-curing temperature. For all the concretes except the concrete with fly ash at W/B of 0.46, the influence of steam-curing temperature on the late compressive strength especially the 90 d strength is very little. The obvious increase of strength from 28 to 90 days for the concrete F-80 might due to the pozzolanic reaction of fly ash which is excited by the high temperature (80°C) at early ages.

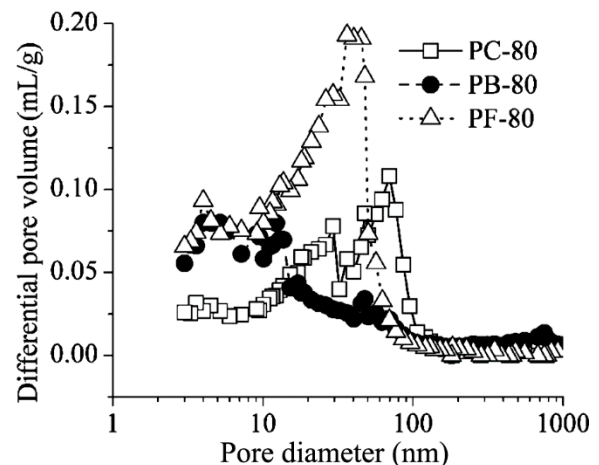


Fig. 8 — Pore size distribution of pastes at steam-curing temperature of 80°C

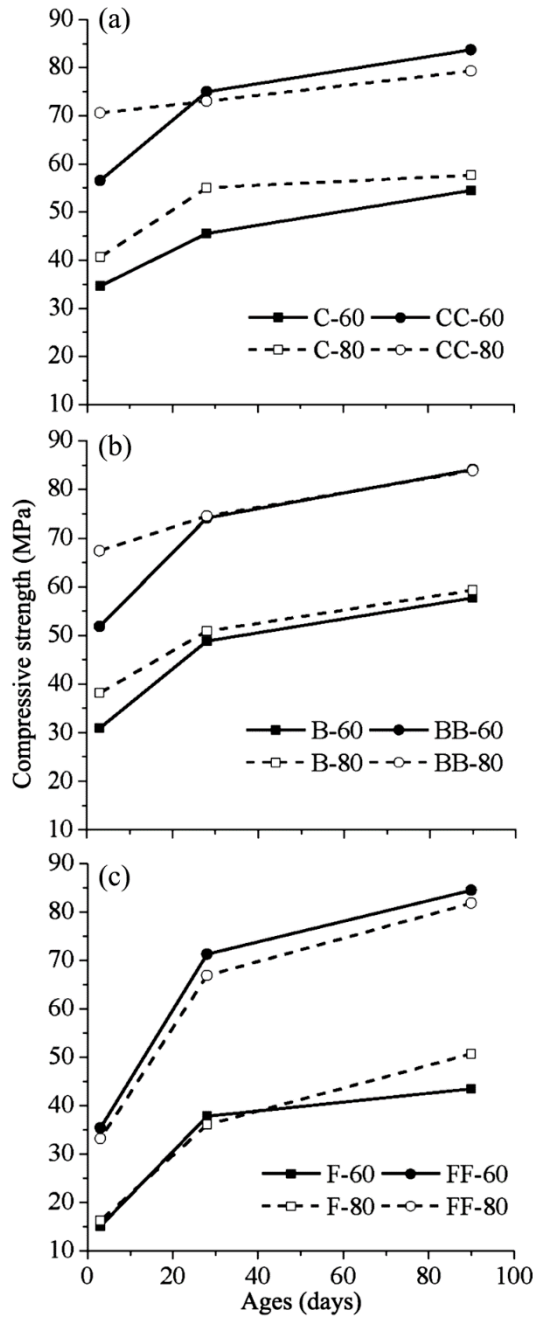


Fig. 9 — Compressive strengths of concretes at steam-curing temperatures of 60°C and 80°C (a) pure cement concrete, (b) concrete containing GGBS and (c) concrete containing fly ash

Permeability of concrete

Figure 10 shows the difference of chloride ion permeability of concretes at steam-curing temperature of 60°C and 80°C at the age of 28 days. For the pure cement concrete, its permeability increases by one level as the steam-curing temperature increases from 60°C to 80°C whether at W/B of 0.46 or 0.3. This is

because higher temperature tends to make the hydration products of cement distribute more non-uniformly and introduce more large pores to the hardened cement paste. However, for the concrete with high volume GGBS or fly ash, its permeability level keeps unchanged by raising the steam-curing temperature from 60°C to 80°C. Though higher temperature also has negative effects on the hydration of the binder with high volume GGBS or fly ash, it can promote the pozzolanic reaction of mineral admixture more significantly which is beneficial to the improvement of pore structure. On the whole, Figure 10 indicates that increasing the steam-curing temperature from 60°C to 80°C has no positive effect on improving the resistance of concrete to chloride ion penetration.

Properties of pastes

Figure 11 shows the difference of the compressive strengths of pastes at steam-curing temperatures of 60°C and 80°C. As expected, the compressive strength of PC-80 is lower than that of PC-60 due to the negative effect of elevated temperature on the hydration of cement. However, the compressive strength of PB-80 is higher than that of PB-60, indicating that elevated temperature has an obvious positive effect on the reaction of GGBS which is sufficient to offset its negative effect on the cement. The positive effect of elevated temperature on the reaction of fly ash is not obvious compared with that of GGBS, and thus it cannot offset the negative effect of elevated temperature on the cement hydration, resulting in the decrease in compressive strength of paste PF.

Figure 12 shows the difference of the pore size distributions of pastes at steam-curing temperatures of 60°C and 80°C at the age of 28 days. As expected, the pore size corresponding to the dominant peak of sample PC-80 is larger than that of sample PC-60, which further proves that elevated temperature tends to introduce larger pores to the pore structure. However, the pore size corresponding to the dominant peak of sample PB-80 is much smaller than that of sample PB-60, which is believed to be due to the higher reaction degree of GGBS at higher steam-curing temperature. Though the promoting effect of elevated temperature on the reaction of fly ash is not so obvious as that of GGBS, the pore size corresponding to the dominant peak of sample PF-80 is a little smaller than that of sample PF-60, which further proves that the reaction of fly ash is beneficial to the improvement of pore structure.

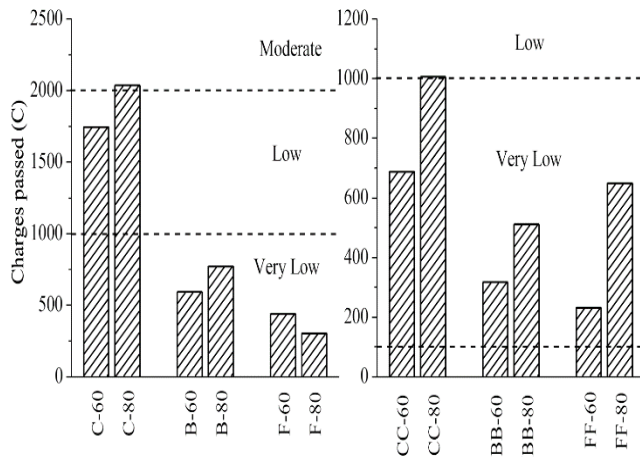


Fig. 10 — Chloride ion permeability of concretes at steam-curing temperatures of 60°C and 80°C

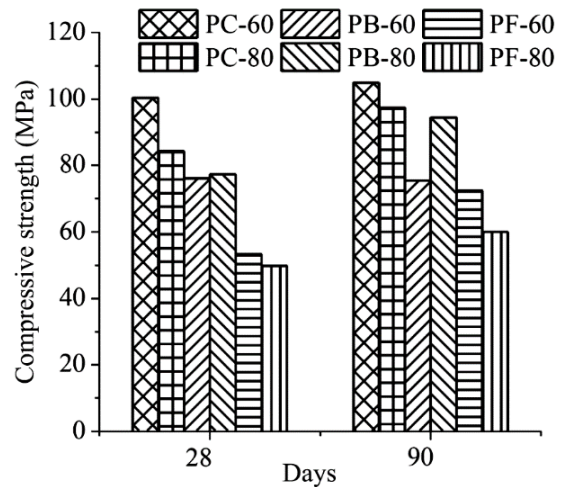


Fig. 11 — Compressive strengths of pastes at steam-curing temperatures of 60°C and 80°C

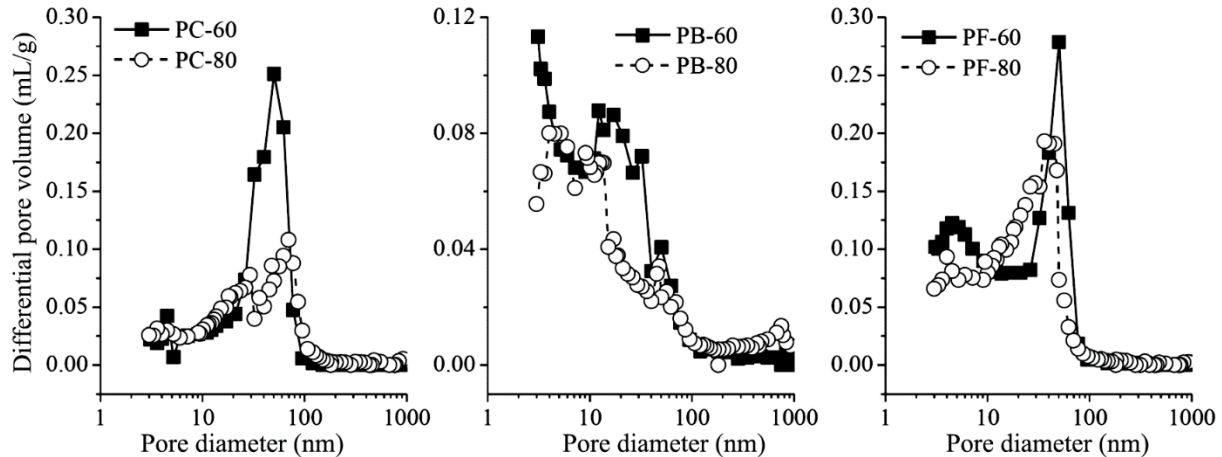


Fig. 12 — Pore size distribution of pastes at steam-curing temperature of 60°C and 80°C

Conclusions

The following conclusions can be drawn from this study:

- (i) Whether under steam-curing condition of 60°C or 80°C, the addition of high volume fly ash tends to decrease the early strength of concrete sharply, but the addition of high volume GGBS has only a small negative effect on the early strength of concrete. The late strength of the concrete with GGBS is close to or even a little higher than that of the pure cement concrete. The negative effect of fly ash on the late strength of concrete is much smaller than that on the early strength especially at lower W/B.
- (ii) Under steam-curing condition of 60°C, the resistance to chloride ion penetration of concrete is significantly enhanced by adding high volume GGBS or fly ash in the case of high W/B, but it is less significant in the case of low W/B. Under

steam-curing condition of 80°C, the addition of GGBS or fly ash can significantly improve the resistance to chloride ion penetration of concrete in the cases of whether high W/B or low W/B.

- (iii) The contribution of fly ash and GGBS to the strength of concrete is more than that to the strength of hardened paste due to their positive effect on the transition zone of concrete. The addition of GGBS tends to refine the pore structure of hardened paste at late ages, and its effect on the pore structure is greater than that of fly ash. Increasing steam-curing temperature tends to enhance the positive effect of fly ash on the pore structure of hardened paste at late ages.
- (iv) Increasing the steam-curing temperature has negative effect on the pore structure of hardened pure cement paste and the resistance to chloride

ion penetration of the pure cement concrete at late ages, but it tends to enhance the positive effect of GGBS and fly ash on the pore structure of hardened paste and has little influence on the resistance to chloride ion penetration of the concrete with GGBS and the concrete with fly ash at late ages.

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References

- 1 Choi H K, Choi Y C & Choi C S, *Eng Struct*, 56 (2013) 1820-1835.
- 2 Won I, Na Y, Kim J T & Kim S, *Energy Build*, 64 (2013) 275-284.
- 3 De Albuquerque A T, El Debs M K & Melo A, *Automat Constr*, 22 (2012) 348-356.
- 4 Maya L F, Zanuy C, Albajar L, Lopez C & Portabella J, *Constr Build Mater*, 48 (2013) 173-186.
- 5 Cassagnabère F, Mouret M & Escadeillas G, *Cem Concr Res*, 39(12) (2009) 1164-1173.
- 6 Ramezani pour A M, Esmaeili K, Ghahari S A & Ramezani pour A A, *Constr Build Mater*, 73 (2014) 187-194.
- 7 Benammar B, Mezghiche B & Guettala S, *Constr Build Mater*, 49(6) (2013) 511-518.
- 8 Ramezani pour A A, Khazali M H & Vosoughi P, *Constr Build Mater*, 49(6) (2013) 807-813.
- 9 Ba M, Qian C, Guo X & Han X, *Constr Build Mater*, 25(1) (2011) 123-128.
- 10 Wu D S & Peng Y N, *Cem Concr Res*, 33(9) (2003) 1331-1345.
- 11 Zhao Q, Liu X & Jiang J, *Constr Build Mater*, 96 (2015) 326-333.
- 12 Türkel S & Alabas V, *Cem Concr Res*, 35(2) (2005) 405-411.
- 13 Barnett S J, Soutsos M N, Millard S G & Bungey J H, *Cem Concr Res*, 36(3) (2006) 434-440.
- 14 Escalante-García J I & Sharp J H, *Cem Concr Res*, 31(5) (2001) 695-702.
- 15 Paul M & Glasser F P, *Cem Concr Res*, 30(12) (2000) 1869-1877.
- 16 Bingöl A F & İlhan Tohumcu, *Mater Des*, 51(5) (2013) 12-18.
- 17 Mindess S & Young J F, *Concrete*, (Prentice Hall), 1981.
- 18 Osborne G J, *Cem Concr Res*, 21 (1999) 11-21.
- 19 Richardson I G, Wilding C R & Dickson M J, *Adv Cem Res*, 2 (1989) 147-157.
- 20 Song H W & Saraswathy V, *J Hazard Mater*, 138(2) (2006) 226-233.
- 21 Rafat S, *Cem Concr Res*, 34 (2004) 487-493.
- 22 Berry E E & Malhotra V M, *ACI J*, 2(3) (1982) 59-73.
- 23 Malhotra V M, *Cem Concr Compos*, 12(4) (1990) 271-277.
- 24 Fonseca F S, Godfrey R C & Siggard K, *Constr Build Mater*, 94(9) (2015) 719-727.
- 25 Shaikh F U A & Supit S W M, *Constr Build Mater*, 82 (2015) 192-205.
- 26 Termkhajornkit P, Nawa O & Kurumisawa K, *Cem Concr Res*, 28 (2006) 781-789.
- 27 Zhimin H, Junzhe L & Kangwu Z, *Energy Procedia*, 16 (2012) 836-841.
- 28 International Union of Pure and Applied Chemistry, (IUAPC) 4, Reporting physisorption data for gas/solid systems with special reference to the determination of surface area and porosity, *Pure Appl Chem*, 1985, 603-619.