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Communication

Durability of concrete incorporating large volumes of low-quality fly ash

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Abstract

The carbonation, corrosion of steel reinforcement in concrete and corrosion resistance of concrete, incorporating large volumes of low-quality fly ash (LVLQFA), were studied. The effect of concentration of carbon dioxide used in the experiment on estimating the carbonation resistance of LVLQFA concrete were also investigated. Test results show that the LVLQFA concrete with an activator has good carbonation and corrosion resistances of steel reinforcement. The corrosion resistance of LVLQFA concrete is better than that of the control concrete. The concentration of carbon dioxide used in the experiment has considerable effect on estimating the carbonation resistance of LVLQFA concrete.

Keywords: Low-quality fly ash; Concrete; Durability

1. Introduction

In China, the total coal-ash production was more than 160 million tons in 2000. To increase the use of fly ash, and to improve the properties of concrete, many investigations on high-volume fly-ash concrete have been made at Hohai University and others [1–7]. In general, some classified high-quality fly ash has been used in concrete. Many other kinds of fly ash, due to their low quality, are still unused. The total usage rate of fly ash in concrete is very low. It is, therefore, necessary to investigate and develop a concrete incorporating large volumes of low-quality fly ash (LVLQFA) to increase considerably the utilization of fly ash. This paper reports the results of tests of durability of LVLQFA concrete. The work is part of a research project on LVLQFA concrete.

2. Experimental

2.1. Materials

The cement used was Portland Cement. The fly ash was obtained from Hua Neng Power Plant, Nanjing, China. The chemical analyses of fly ash are presented in Table 1 and the fineness of the fly ash (retained on a 45-μm sieve) was 28.8%. The fine aggregate was natural sand from Nanjing and the coarse aggregate was a crushed limestone, with a maximum size of 31.5 mm. The admixtures used in this study were water-reducing admixture (JM-II) and an activator (HHA).

2.2. Concrete mixtures and specimens

The mixture proportions for the concrete are given in Table 2. The $100 \times 100 \times 400$ mm^3 concrete specimens were cast for carbonation, corrosion of steel reinforcement in concrete and corrosion resistance (flexural strength) testing, while the $100 \times 100 \times 100$ mm^3 concrete specimens were cast for corrosion resistance (compressive strength) testing. For the corrosion of steel reinforcement in concrete testing, the diameter of the reinforcing steel bar was 6.5 mm and the concrete cover was 25 mm. All specimens were cured at 20 ± 3 °C and 100% relative humidity for 28 days prior to exposure to a particular test or test environment.

Table 1
Chemical analyses of fly ash

CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	TiO_2	Na_2O	K_2O	SO_3
3.60	53.52	34.26	3.10	0.92	0.97	0.71	0.97	0.45

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Table 2
Proportions of concrete mixtures

Mix number	F/ (F + C)	W/ (F + C)	Quantities (kg/m^3)					JM-II (%)	HHA (%)
			Water	Cement	Fly ash	Fine aggregate	Coarse aggregate		
C1	0	0.45	153	340	–	646	1251	1.0	0
C2	40	0.45	153	204	136	649	1258	1.0	0
C3	40	0.45	153	204	136	636	1272	1.0	11.6
C00	0	0.50	165	330	–	640	1188	0.5	0
A40	40	0.40	152	228	152	642	1189	0.8	0
A60	60	0.40	152	152	228	631	1170	1.0	0

2.3. Tests

The carbonation test was conducted in a test chamber kept at a temperature of 20 °C and a 70% relative humidity. The concentrations of CO_2 were 3% and 20%. The depth of carbonation was determined by removing a slice of about 50-mm thick from the specimen, spraying the freshly broken samples with a phenolphthalein indicator, and measuring the depth to the colour change. The depth of carbonation was measured at eight points, each side, using a scale that enabled a single measurement of depth of carbonation to be made to within ± 1 mm.

The corrosion test of steel reinforcement in concrete was conducted in two ways. One way was the dry–wet cycle. After curing, the specimens were oven dried at 80 °C for 4 days, soaked in 5% NaCl for 2 days and oven dried at 60 °C for 12 days. Then, the conditioning cycle was repeated. The other was carbonation and dry–wet cycle. The specimens were carbonated at 20% CO_2 first, then the dry–wet cycle was repeated. The corrosion of steel reinforcement in concrete was assessed using linear polarization methods.

The corrosion resistance test was performed with 5% Na_2SO_4 solution and 5% HCl solution.

3. Results and discussion

3.1. Carbonation

The carbonation test results are given in Table 3. Table 3 shows that at the concentration of 20% CO_2, the depth of carbonation of the LVLQFA concrete is greater than the control concrete, especially at the early-age carbonation. The activator can improve the carbonation resistance of LVLQFA concrete. At the exposure duration of 28 days, the carbonation depth of the LVLQFA concrete is close to the control concrete. At the concentration of 3% CO_2, the depth of carbonation of the LVLQFA concrete without an activator is greater than others. The carbonation depth of LVLQFA concrete with an activator is close to the control concrete. It is seen, therefore, that the concentration of CO_2 used in the experiment has considerable effect on estimating the carbonation resistance of LVLQFA concrete.

Table 3
Experiments' results of carbonation of concrete

Mix number	Depth of carbonation (mm)							
	Concentration of CO_2 of 20%				Concentration of CO_2 of 3%			
	3d	7d	14d	28d	3d	7d	14d	28d
C1	7.7	10.4	12.7	14.8	7.8	11.2	12.3	13.8
C2	12.2	15.7	19.4	22.4	11.3	14.1	15.8	17.7
C3	10.3	12.4	14.1	15.9	8.1	11.4	12.4	13.7

3.2. Corrosion of steel reinforcement in concrete

Table 4 presents the results obtained by the linear polarization technique. It is seen that the corrosion resistance of steel reinforcement in the LVLQFA concrete without an activator is lower than the control concrete. The activator can increase the corrosion resistance of steel reinforcement in LVLQFA concrete. The corrosion resistance of steel reinforcement in LVLQFA concrete with an activator can approach that of the control concrete.

3.3. Corrosion resistance

The changes of concrete strength with the exposure time are presented in Table 5. It can be seen that, for normal curing, the strengths of all mixtures increase with the increase of curing period. The later-strength of LVLQFA concrete increases greatly. For the concrete immersed in 5% Na_2SO_4 solution, the compressive strengths of all mixtures also increase with the increase of age. The compressive strengths of concrete immersed in 5% HCl solution decreases significantly. The flexural strengths of LVLQFA concrete immersed in 5% Na_2SO_4 and 5% HCl solution are higher than that of the corresponding concrete normally cured. The flexural strength of the control concrete immersed in 5% HCl solution is lower than that of the corresponding concrete normally cured.

To compare the corrosion resistance effectively, the corrosion resistance coefficient K is used.

$$K = f_{ci}/f_{cs} \quad (1)$$

Table 4
Experiments' results of corrosion of steel reinforcement in concrete

Mix number	Dry–wet cycles				Carbonation and dry–wet cycles			
	Before		After		Before		After	
	I_{corr} (μA/cm^2)	R (kΩ cm)	I_{corr} (μA/cm^2)	R (kΩ cm)	I_{corr} (μA/cm^2)	R (kΩ cm)	I_{corr} (μA/cm^2)	R (kΩ cm)
C1	0.018	–	1.105	15.60	0.045	–	0.131	12.46
C2	0.015	–	1.327	20.86	0.076	–	0.356	21.61
C3	0.013	–	1.019	13.80	0.053	–	0.158	14.85

I_{corr}: Corrosion current density; R: Resistivity.

Table 5
Strength of the concrete

Mix number	Compressive strength (MPa)						Flexural strength (MPa)					
	A		B		C		A		B		C	
	56d	118d	56d	118d	56d	118d	56d	118d	56d	118d	56d	118d
C00	56.0	61.6	55.9	59.0	34.7	32.7	4.58	5.32	5.74	5.36	3.94	3.45
A40	49.3	66.6	53.8	63.2	48.5	40.2	4.96	5.26	5.47	6.11	5.06	6.03
A60	37.0	49.1	42.8	51.3	40.3	42.4	3.80	4.07	4.01	5.15	4.05	4.26

A: Cured by standard (20 ± 3 °C and more than 95% relative humidity); B: Immersed in 5% Na_2SO_4; C: Immersed in 5% HCl.

Where f_{ci} is the compressive strength of concrete immersed in corrosive solution, f_{cs} is the compressive strength of the normally cured concrete. The corrosion resistance coefficients of concrete are given in Table 6.

It can be seen that, for the concrete immersed in corrosive solution, the corrosion resistance coefficients decrease with the increase of the exposure time. The corrosion resistance of LVLQFA concrete is better than that of the control concrete.

4. Conclusions

The following conclusions can be drawn from this study:

1. The use of an activator can improve the carbonation resistance of LVLQFA concrete. The carbonation resistance of LVLQFA concrete with an activator is close to the control concrete.
2. The activator can improve the corrosion resistance of steel reinforcement in LVLQFA concrete caused by carbonation and seawater. The corrosion resistance of steel reinforcement in LVLQFA concrete with an activator is close to the control concrete.
3. The corrosion resistance of LVLQFA concrete in 5% Na_2SO_4 and 5% HCl solution is better than that of the control concrete.
4. The concentration of carbon dioxide has a considerable effect on estimating the carbonation resistance of LVLQFA concrete. Further investigation is needed to obtain a suitable concentration of carbon dioxide for LVLQFA concrete carbonation test.

Table 6
Coefficients of corrosion resistance of concrete

Mix number	B		C	
	56d	118d	56d	118d
C00	0.998	0.958	0.620	0.531
A40	1.091	0.949	0.984	0.604
A60	1.157	1.045	1.089	0.864

B: Immersed in 5% Na_2SO_4; C: Immersed in 5% HCl.

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