Hindawi Publishing Corporation
Advances in Materials Science and Engineering
Volume 2014, Article ID 706986, 7 pages
http://dx.doi.org/10.1155/2014/706986

Research Article

Study on Strength and Ultrasonic Velocity of Air-Entrained Concrete and Plain Concrete in Cold Environment

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Received 11 November 2013; Accepted 2 January 2014; Published 10 February 2014

Academic Editor: Konstantinos I. Tserpes

Nondestructive testing technology is essential in the quality inspection of repair, alteration, and renovation of the existing engineering, especially for concrete structure in severe environment. The objective of this work is to deal with the behavior of ultrasonic velocity and mechanical properties of plain concrete and air-entrained concrete subjected to freeze-thaw cycles (F-T-C). The ultrasonic velocity and mechanical properties (tensile strength, compressive strength, cubic compressive strength, and splitting strength) of C30 air-entrained concrete and plain concrete with different water-cement ratio (water-cement ratio was 0.55, 0.45, and 0.50, resp.) after F-T cycles were measured. The influences of F-T cycles on ultrasonic velocity and mechanical properties of C30 air-entrained concrete and plain concrete were analyzed. And the relationship between mechanical properties and ultrasonic velocity was established. The experimental results can be useful for the design of new concrete structure, maintenance and life prediction of existing concrete structure such as offshore platform and concrete dock wall.

1. Introduction

For concrete structures during their service life, rapid decay may be caused by chemical, physical, and biological agents; then the service life will be shortened and more maintenance and repair costs will be used [1]. Such as concrete dams and hydraulic structures and so forth in cold environments. As one of the most important behavior of concrete materials, the durability [2–7] of concrete involves resistance to frost, carbonation, permeation, chemical attack, stress corrosion, and so forth. The durability is defined as follows: "as a durable structure, serviceability, strength, and stability should meet the requirements throughout its working life." For preventing the deterioration of concrete [8] in cold climates, freeze-thaw action should be taken into consideration in the design of concrete structures.

As the most important technical measure to improve the frost resistance of concrete, air-entraining agents [9–11] have been widely used in concrete engineering, especially in cold zone (such as the northern of China and Europe, arctic zone, etc.). Gokce et al. [12] discussed the freeze-thaw resistance when recycled coarse aggregate (the aggregate was produced from air-entrained concrete (A-E-C) and non-air-entrained concrete (N-A-E-C), resp.) was added into A-E-C. The conclusion that freeze-thaw resistance was poor when recycled coarse aggregate made with N-A-E-C was used even when air entrainment proper in the new system was got. The freeze-thaw resistance of high performance self-compacting concrete made with non-air-entrained admixtures was investigated in [13].

For concrete structures in service life, the deterioration was caused due to the chemical attack, environmental action (such as freeze-thaw action), and service loads. So it is important to accurately assess the service condition of concrete structures. The deterioration of concrete structures can be assessed by destructive testing technology and nondestructive testing technology (such as measurement of ultrasonic velocity and resonance frequency) [14–16], but reduction in load bearing area will be caused when destructive testing methods were used. So the nondestructive testing methods were recommended to use when the service condition of concrete structure needs to be evaluated. Experimental study on the concrete samples containing artificial cracks with different depths and lengths was carried out the analytical studies based on the experimental results were compared by Shah and Ribakov [17]. The nonlinear ultrasonic testing of concrete in undamaged and damaged states was carried out by Shah and Ribakov [18]. The conclusion that nonlinear ultrasound was found to be very helpful in assessing degree of deterioration in concrete was got in [19].

Mechanical behavior, microstructure, ultrasonic velocity of A-E-C, and plain concrete after F-T cycles according to GB/TJ50082-2009 [20] were investigated in this paper. Based on the experimental results of F-T cycle tests, F-T damage mechanics models of A-E-C and plain concrete were established through the methods of mathematic simulation and damage mechanics.

2. Experimental Procedures

2.1. Materials and Mix Proportions. In this investigation, (1) the cementitious materials $32.5^{\#}$ and $42.5^{\#}$ ordinary Portland Cement [21] were used; (2) the coarse aggregate used was a crushed granite (specific gravity: 2.62 g/cm^3, diameter: 5 mm to 10 mm); (3) the fine aggregate was natural river sand (fineness modulus: 2.6).

The mix proportions of A-E-C in per cubic meter is are follows: cement (412.68 kg/m^3), sand (586.83 kg/m^3), coarse aggregate (1186.00 kg/m^3), water (164.30 kg/m^3), and air-entraining agent (1.03 kg/m^3). The major parameters and mix proportions of plain concrete with water-to-cementitious materials ratio of 0.45, 0.50, and 0.55 are given in Table 1.

The concrete mixtures were prepared in a mixer. After putting cementitious materials, fine aggregate and coarse aggregate, into the mixture, mixed the ingredients for about 1 min, and then added the water in 1minute. After all water was added, the mixing continued for about 2 min.

2.2. Test Specimens and Testing Programs. The size of concrete cube is 100 mm × 100 mm × 100 mm (study for tensile strength, splitting strength, and compressive strength). The size of concrete prism is 100 mm × 100 mm × 400 mm (study for ultrasonic velocity and cubic compressive strength (cutting the specimen from the middle)). The samples were all casted in steel molds and removed from steel molds after 24 h. The samples were cured in a condition of 95 percent RH (relative humidity) and 20 ± 3°C until the age of 24 days. And then some of the samples were immersed into water for 4 days for experiment of F-T cycles, while others were cured until the age of 28 days.

In this experimental study, the F-T test apparatus [22] meeting the GB/T 50082-2009 requirement was used. The F-T cycle consisted of alternately lowering temperature of concrete samples from 6°C to −15°C and raising temperature of concrete samples from −15°C to 6°C, while lowering the temperature of antifreeze from 8 ± 2°C to −17 ± 2°C and warming from −17 ± 2°C to 8 ± 2°C all within 2.5~3 hours. Specimens were removed for experiment study at 25-, 50-, 75-cycle intervals for plain concrete and at 50-, 100-, 150-, 200-, 300-, 350-, and 400-cycle intervals for A-E-C.

Stringent requirements on the stiffness of the servo hydraulic testing system or the control of the specimen deformation rate was required in the direct tension experiment because of the intrinsic brittleness of concrete. So the tensile tests were carried out in a triaxial testing machine [23]. The loading mode of direct tensile test in reference [23] was used. The loading mode of splitting test meeting JTJ 270-98 [24] was used. The compressive strength, cubic compressive strength, tensile strength and splitting strength of the specimens were monitored and recorded. At least, three samples for each batch should be tested.

3. Results and Discussions

3.1. Microstructure. The scanning electron SEM microphoto graphs of plain concrete and A-E-C prior to F-T cycles and subjected to different cycles of F-T were given in Figures 1 and 2, respectively. As shown in Figures 1(a) and 2(a), no crack between cement slurry and coarse aggregates as well as in cement slurry was found; the coarse aggregates did not split and the cement slurry is intact both for plain concrete and A-E-C (just as shown in rectangle in Figures 1(a) and 2(a)), and for A-E-C, the air bubble in the cement slurry is well proportioned and intact (just as shown in polygon in Figure 2(a)). For A-E-C after 400 cycles of F-T, the cement slurry becomes loosen, the crack in the cement slurry is caused, the crack between cement slurry and coarse aggregates expands greatly (just as shown in ellipse in Figure 2(b)), and the coarse aggregates and cement slurry are separated. While for plain concrete, only after 50 cycles, the crack in the cement slurry and between cement slurry and coarse aggregates is caused and even expands greatly (just as shown in ellipse in Figure 1(b)).

3.2. The Compressive Strength and Cubic Compressive Strength. The compressive stresses can be got by sharing the uniaxial compression load by the loading section area (0.01 m^2).

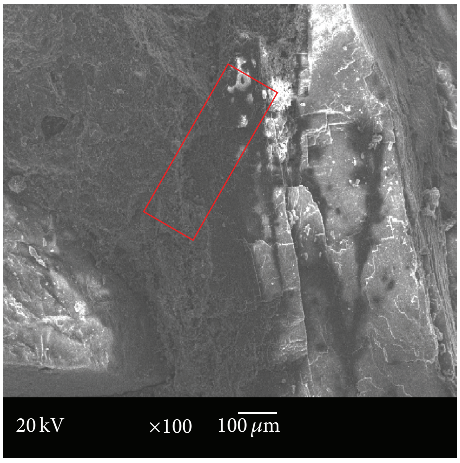
Table 2 listed the data of the compression tests for C30 A-E-C after different cycles of F-T, respectively. Table 3 listed the data of the compression tests for plain concrete (W/C was 0.55, 0.50, and 0.45) after different cycles of F-T, respectively.

As seen from Table 2, the cubic compressive strength and compressive strength decreased as F-T cycles increased. After the same cycles of F-T, the decreased percentage of the cubic compressive strength is larger than that of compressive strength for C30 A-E-C samples. After the action of 350 cycles of F-T, the cubic compressive strength of C30 A-E-C decreased to 55.9 percent of the initial cubic compressive strength, while the compressive strength decreased to 66.5 percent of the initial value prior to F-T cycles.

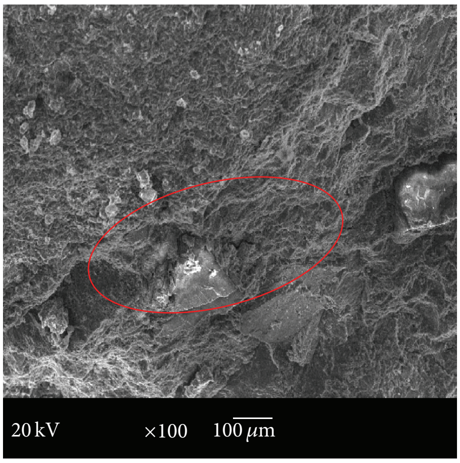
Besides, as shown in Table 3, the cubic compressive strength and the compressive strength of plain concrete decreased with the number of F-T cycles increasing. Unlike A-E-C, the decreased percentage of the cubic compressive

Table 1: The mix proportion of plain concrete per cubic metre.

W/C	Strength of cement (MPa)	Cement (kg/m^3)	Sand (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)	Air content (%)
0.45	42.5	427	499	1284	192	0.9
0.50	42.5	383	663	1154	193	1.7
0.55	32.5	360	611	1241	198	1.9

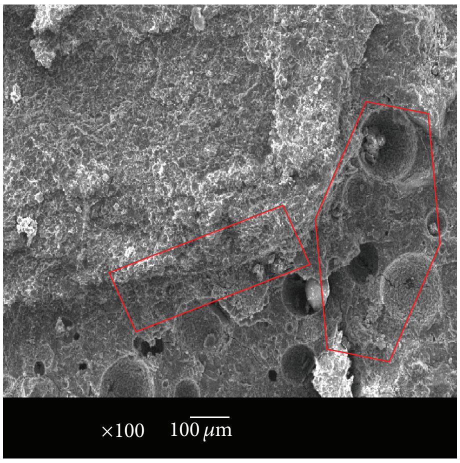


(a) Prior to F-T cycle

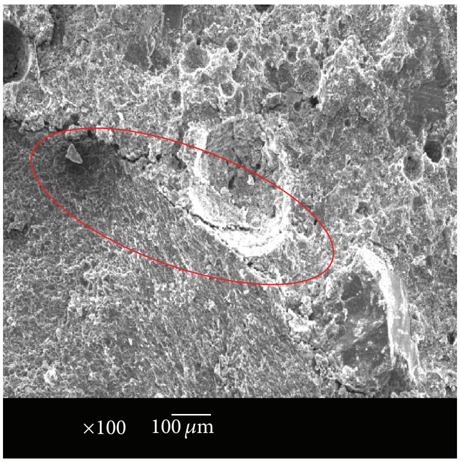


(b) 50 cycles of F-T

Figure 1: Scanning electron SEM microphoto graphs of plain concrete after F-T cycles.



(a) Prior to F-T cycle



(b) 400 cycles of F-T

Figure 2: Scanning electron SEM microphoto graphs of A-E-C after F-T cycles.

strength is smaller than that of compressive strength for plain concrete after the same cycles of F-T. For plain concrete of water-cement ratio 0.55, the cubic compressive strength after 50 F-T cycles decreased to 66.0 percent of the initial cubic compressive strength, while the compressive strength after 50 F-T cycles decreased to 50.6 percent of the initial compressive strength.

The effect of F-T cycles on the C30 plain concrete was studied in [25]. According to the experimental results in [25], after 100 cycles of F-T, the compressive strength reduced to 63.7% of the initial compressive strength.

3.3. The Tensile Strength, Splitting Strength of A-E-C, and Plain Concrete.

The cracking behavior of concrete is controlled by its tensile properties, while this property was always ignored or treated only in the design and analysis of concrete structure. An accurate analysis for concrete of the crack width and load-deflection characteristics depended on the performance of postcracking response. Therefore, the experiment study of concrete in the area of tensile property was carried out.

Table 4 gives the experimental results of splitting and tensile strength of C30 A-E-C after F-T cycles on basis of the experimental results. As shown in Table 4, the present test results indicated that for A-E-C after 400 cycles of F-T, the direct tensile strength was only 36.7 percent of the initial value, and the splitting strength decreased to only 55.16% of the splitting strength prior to F-T cycles. The loss rate of splitting strength is notably lower than the loss rate of tensile strength for A-E-C with the F-T cycles increasing.

The direct tensile strength of A-E-C was 10.1% and 6.9% of the compressive strength prior to F-T cycles and after 400 cycles of F-T, respectively. It means that, comparing to the compressive strength, the direct tensile strength dropped sharply as the F-T cycles increased. Reference [26] investigated the influence of F-T cycles on the mechanical behavior of high-strength concrete with air-entrainied agent. The experiment results of the tensile strength were only 4.2 percent and 3.4 percent of the compressive strength prior to F-T cycles and after 700 cycles of F-T, respectively.

Table 5 gives the splitting strength and tensile strength of plain concrete samples with water-cement ratio 0.55, 0.50, and 0.45 after F-T cycles on basis of the experimental results. According to the experimental data in Table 5, after 75 cycles of F-T, the splitting and direct tensile strength of plain concrete with water-cement ratio 0.55 were only 59.2% and 29.0% of the initial value, while, for plain concrete with water-cement ratio being 0.45, the splitting and direct tensile strength were only 61.3% and 32.7% of the initial value.

According to the experimental results of plain concrete in [27], during the initial 25 F-T cycles, the tensile strength dropped sharply and the tensile strength after 25 F-T cycles decreased to about 58% of the initial value prior to F-T cycles. However, in subsequent F-T cycles, the phenomenon of continuing deterioration was observed, but the decreasing rate becomes smaller from 25 to 100 F-T cycles. And after 100 cycles of F-T, the tensile strength decreased to about 25% of the initial strength prior to F-T cycles. Namely, after the action of the first 25 cycles, the rate of reduction is lower with freeze-thaw cycles increasing. Reference [25] investigated the effect of F-T cycles on the splitting strength of C30 plain concrete. The experimental conclusion showed that splitting strength after 100 cycles of F-T decreased to 67.2% of the initial strength value prior to F-T cycles.

3.4. The Ultrasonic Velocity. Table 6 provides the reduced percentage of ultrasonic velocity measured on 100 mm cubic plain concrete samples with water-cement ratio being 0.55, 0.50, and 0.45 after F-T cycles.

As seen in Table 6, the ultrasonic velocity reduced with F-T cycles being increased. For plain concrete with water-cement ratio 0.45 and 0.55 after the action of 100 cycles of F-T, the ultrasonic velocity decreased to 30.8% and 61.65% of the initial value. There is a sudden descent stage for the plain concrete of water-cement ratio 0.45. After 100 cycles of F-T, the ultrasonic velocity decreased to 30.8% of the original value prior to F-T cycles. The diagram of the ultrasonic velocity loss versus number of F-T cycles was given in Figure 3.

Table 7 provides the reduced percentage of ultrasonic velocity measured on 100 mm cubic A-E-C samples after different cycles of F-T. According to the experimental results in Table 7, the ultrasonic velocity of A-E-C after 100 cycles of F-T decreased to 97.68% of the initial value. It can be observed through comparing the results in Table 6 with those in Table 7 that, after the action of the same cycles of F-T, the reduced percentage of ultrasonic velocity of A-E-C was less than that of plain concrete. So it can be said that the F-T durability of plain concrete is poor than that of A-E-C.

3.5. Strength Loss. The strength (tensile strength, cubic compressive strength, compressive strength, and splitting strength) loss and ultrasonic velocity loss of plain concrete with water-cement ratio 0.55 after different F-T cycles were shown in Figure 3. The loss of tensile strength, splitting strength and cubic compressive strength compressive strength were 29.5%, 13.1%, 18.4% after 25 F-T cycles (the loss of compressive strength was 22.9% after 25 F-T cycles) and 71.0%, 40.8%, 40.0% after 75 F-T cycles, respectively. The loss of tensile strength was the largest compared to loss of other strength after the same cycles of F-T and the loss of splitting strength was the smallest. What is more, it can be realized from Figure 3 that the strength loss of plain concrete is synchronous with the loss of ultrasonic velocity after the action of freeze-thaw cycles. The strength loss and ultrasonic velocity loss of C30 A-E-C subjected to F-T cycles were given in Figure 4.

The loss of tensile strength, splitting strength, cubic compressive strength, and compressive strength for A-E-C was 14.5%, 9.6%, 7.4%, and 1.5% after 100 F-T cycles and 42.4%, 23.5%, 38.3%, and 14.0% after 300 F-T cycles, respectively. Compared to the loss of tensile strength and cubic compressive strength, the loss of compressive strength was smaller, especially after the action of first 300 cycles of F-T. What is more, the conclusion that the loss of ultrasonic velocity for plain concrete is much more than that of A-E-C after the same cycles of F-T can be drawn according to Figures 3 and 4.

It can be drawn that the effect of F-T cycles on tension behavior and compression behavior of A-E-C is different. But the reduction of compressive strength of concrete can be associated with the cycles of F-T, while the reduction of tensile strength of concrete should be associated with the occurrence of crack caused by F-T cycles.

For concrete material under the action of tensile loading, the initiation of new microcracks and growth of inherent micro-cracks will be caused. And this will result in the reduction of the load-carrying area and the increment of stress concentration at critical crack tips. The final result is the cracks to propagate further. If these cracks are not effectively prevented, failure of the concrete will occur.

As the basic representative value of mechanical behavior of concrete, the compressive strength is of vital importance to the application. Based on this, the relationship between the cubic compressive and ultrasonic velocity of plain concrete and C30 A-E-C can be established as follows:

$$\frac{f_c^D}{f_c} = a * P^2 + b * P + c, \tag{1}$$

TABLE 2: Compressive strength of A-E-C after different cycles of F-T (MPa).

Number of F-T cycles	0	50	100	150	200	300	350	400
Cubic compressive strength	34.20	33.40	31.67	27.60	26.38	21.10	19.13	16.22
Compressive strength	26.30	25.90	25.90	24.80	23.33	22.63	17.50	14.25

TABLE 3: Compressive strength of plain concrete after different cycles of F-T (MPa).

W/C	Number of F-T cycles	0	25	50	75
0.55	Cubic compressive strength	27.41	22.36	18.09	16.45
	Compressive strength	19.66	15.15	9.95	/
0.50	Cubic compressive strength	45.85	38.00	35.71	28.92
	Compressive strength	34.20	30.01	24.10	21.67
0.45	Cubic compressive strength	50.65	45.23	37.45	32.23
	Compressive strength	38.90	34.4	29.43	25.67

TABLE 4: The splitting and tensile strength of A-E-C after F-T cycles (MPa).

Number of F-T cycles	0	100	200	300	400
Tensile strength	2.67	2.28	2.06	1.54	0.98
Splitting strength	2.81	2.54	2.35	2.15	1.55

TABLE 5: The splitting and tensile strength of plain concrete after F-T cycles (MPa).

W/C	Number of F-T cycles	0	25	50	75	100
0.55	Tensile strength	1.93	1.36	0.84	0.56	/
	Splitting strength	2.13	1.85	1.62	1.26	1.18
0.5	Tensile strength	3.14	1.32	1.15	0.98	/
	Splitting strength	2.73	2.04	1.64	1.49	1.33
0.45	Tensile strength	3.61	1.99	1.36	1.18	/
	Splitting strength	3.31	2.93	2.62	2.03	1.53

TABLE 6: Reduced percentage of ultrasonic velocity of plain concrete subjected to F-T cycles.

W/C	Number of F-T cycles				
	0	25	50	75	100
0.45	100	92.86	86.19	69.64	30.80
0.50	100	85.23	67.53	59.43	—
0.55	100	92.08	85.45	72.69	61.65

TABLE 7: Reduced percentage of ultrasonic velocity of A-E-C subjected to F-T cycles.

Number of F-T cycles	0	100	200	300	400
Reduced percentage of ultrasonic velocity	100.00	97.68	97.63	91.02	84.70

where f_c^D is the cubic compressive strength of A-E-C and plain concrete after different cycles of F-T. P is the decreasing percentage of ultrasonic velocity for A-E-C and plain concrete after different F-T cycles. a, b, and c are the regress parameters.

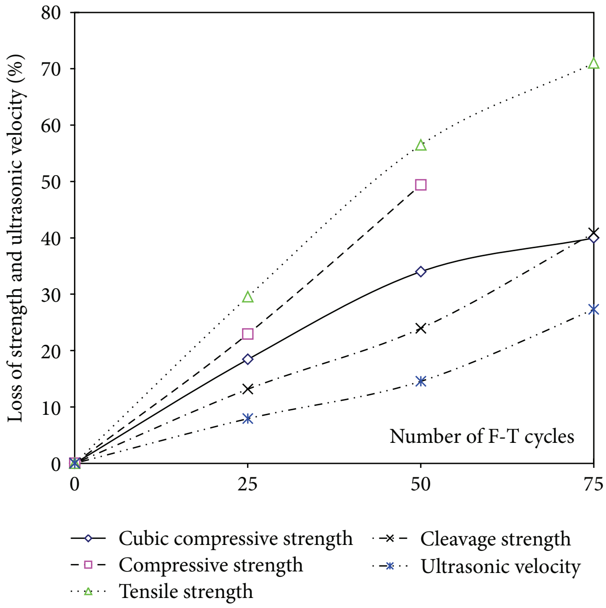


FIGURE 3: The loss of strength and ultrasonic velocity of plain concrete versus number of F-T cycles.

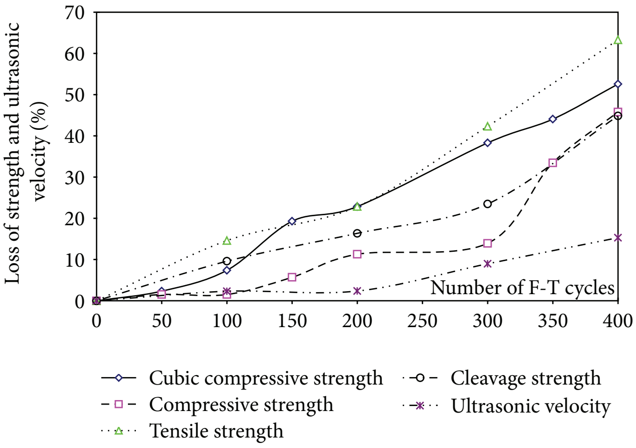


FIGURE 4: The loss of strength and ultrasonic velocity of A-E-C versus number of F-T cycles.

The regression coefficient such as R^2, SSE, RM, and M used to judge the measure of accuracy was given in this study:

$$R^2 = 1 - \left\{ \frac{\left[\sum_{i=1}^{n}\left(f^D_{ci(\text{tested})} - f^D_{ci(\text{computed})}\right)^2\right]}{\left[\sum_{i=1}^{n}\left(f^D_{ci(\text{tested})} - f^D_{ci(\text{mean})}\right)^2\right]} \right\},$$

$$\text{RM} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(f^D_{ci(\text{tested})} - f^D_{ci(\text{computed})}\right)^2},$$

Table 8: Value of a, b, c, R^2, SSE, RM, and M.

	a	b	c	R^2	RMSE	SSE	MAPE
A-E-C	14.979	−24.359	10.365	0.934	2.896	14.480	1.885%
Plain concrete with 0.55	6.013	−8.885	3.878	0.992	0.014	0.0007	−0.002%
Plain concrete with 0.50	0.049	0.727	0.212	0.922	0.037	0.005	−0.256%
Plain concrete with 0.45	3.459	−4.626	2.178	0.983	0.018	0.001	−0.046%

$$\text{SSE} = \sum_{i=1}^{n} \left(f^{D}_{ci(\text{tested})} - f^{D}_{ci(\text{computed})} \right)^2,$$

$$M = \frac{\sum_{i=1}^{n} \left(f^{D}_{ci(\text{tested})} - f^{D}_{ci(\text{computed})} \right) / \left(f^{D}_{ci(\text{tested})} \right)}{n} \times 100\%, \qquad (2)$$

where R^2 was the determination coefficient, SSE was the sum value of squared error RM was the root mean value of square error, and M was the mean absolute percentage error.

By computation, the results of R^2, SSE, RM, and M are given in Table 8.

3.6. Discussion. From the microscale, concrete is a three-phase composite structure (aggregate, a cement matrix, and the interface or transition zone between above two materials). The distribution and direction of microcracks caused by F-T cycles are stochastic. Under the action of continuing F-T cycles, more serious damage will be caused by microcrack accumulation (mainly manifested as: the number of microcosmic cracks increase and the width of microcosmic cracks become broad) due to water pressure caused by F-T cycles. In another way, the initiation of new crack and growth of existing cracks under the action of tensile load, compressive load, and splitting load will reduce the load-carrying area. And the reduction of load-carrying area will lead the stress concentration at crack tips. At last, the deterioration of concrete (such as strength reduction, spalling) will be caused as F-T cycles were repeated.

On the other hand, billions of microscopic air cells were contained in A-E-C. The existence of microscopic air cells can relieve internal compressive pressure caused by F-T cycles through providing tiny chambers. So after the same cycles of F-T, the deceased percentage of strength of A-E-C is lower than that of plain concrete.

According to the experimental results in this paper and the experimental results obtained from other authors, the conclusion that the deterioration rate of durability of A-E-C is slower than deterioration rate of plain concrete can be got.

4. Conclusions

In the range of experimental works of plain concrete and A-E-C and discussion of the experimental results, the conclusion was stated as follows.

(1) The mechanical behavior of A-E-C and plain concrete decreased as the F-T cycles increased. After the action of the same cycles of F-T, the decreased percentage of the strength for C30 A-E-C specimens is larger than plain concrete specimens.

(2) For F-T durability deterioration, the first reason is the cracks caused by freezing of water, and the second reason is the action of thermal stress caused by repeated F-T cycles. The failure of A-E-C specimens should be attributed to the cracking of the paste.

(3) The F-T durability of plain concrete sample was poor (after 75 cycles of F-T cycles, the compressive strength loss of plain concrete (W/C = 0.45) exceeded 30 percent) according to experimental results, but the F-T durability of plain concrete can be improved greatly through adding air-entraining agent. It means that plain concrete can have higher F-T durability.

(4) According to the results, the F-T durability of concrete should be taken into consideration in design and maintenance of concrete structure.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

This work was supported by the "National Natural Science Foundation of China" (Grant nos. 51208273, 51121005, and 51222806), "Project of Shandong Province Higher Educational Science and Technology Program" (Grant no. J12LG07). "the Open Research Fund of State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin (China Institute of Water Resources and Hydropower Research)" (Grant no. IWHR-SKL-201305), and "Open Research Fund Program of State Key Laboratory of Water Resources and Hydropower Engineering Science" (Grant no. 2013B113). The authors gratefully acknowledge the financial support.

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