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THE EFFECT OF AAR ON CONCRETE MECHANICAL PROPERTIES

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Abstract

A kind of active aggregate from practical project was used in the study. Based on practical mix proportion of hydraulic project, concrete was prepared to investigate the effect of AAR on concrete mechanical properties. After cured in standard curing room for 28 days, all the concrete samples were moved to the curing room with a curing temperature of 60±1□ and a relative humidity of 90% - 95%. At several certain AAR expansion values, mechanical properties were tested. The results showed that concrete mechanical properties decreased with the increase of damage amount resulting from AAR. The damage of concrete was characterized by relative dynamic modulus of elasticity; according to the relationship between concrete mechanical properties and damage amount, the prediction model about the damage degree of mechanical properties was established.

Keywords：AAR；prediction model；damage amount.

1. INTRODUCTION

Alkali aggregate reaction (AAR) is a kind of chemical reaction between alkali in hardened concrete and active minerals in aggregates, which can cause concrete expansion and cracks, etc. From the first time that AAR was discovered in America in 1940s, AAR-induced cracks and damage were successively found in Canada, France, South Africa and Britain. [1]

From the time that AAR was firstly discovered by Stanton [2], scholars all over the world learned about AAR and carried out extensive research on it. However, the research were mainly focused on the mechanism of AAR and the suppression measures against AAR expansion, while the research on the effect of AAR-induced damage on concrete mechanical properties was scarce. Moreover, most of the published research data were related to mortar, but not concrete. Based on practical mix proportion, concrete specimens were prepared to investigate the effect of AAR on concrete mechanical properties, including compression strength (cube 150mm by 150mm by 150mm), splitting tensile strength(cube 150mm by 150mm by 150mm), bending strength (prism 100mm by 100mm by 400mm), axial tensile strength (specimens in the shape of "8": 100mm by 100→130mm by 550mm). At several AAR expansion values, mechanical properties were tested to study the relation between AAR expansion and mechanical properties, in order to provide basic data for the aging degree and safety evaluation of AAR-damaged concrete.

2. CONCRETE RAW MATERIALS AND MIXING PROPORTIONS

2.1 Raw materials

Chemical composition of portland medium-heat cement 42.5 (P.MH42.5) used in the experiments was shown in table 1.

Table 1：Chemical composition of Portland Medium-heat Cement 42.5（%）

Chemical composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	Na_2O_{eq}
Results	21.28	3.94	5.66	62.87	1.98	2.3	0.21	0.09	0.23

According to GB/T750-92 <Autoclave method for soundness of Portland cement>, the autoclave expansion ratio of P.MH42.5 was 0.023%, less than the value of 0.2% specified in Section 2.37 of <Test code for hydraulic concrete> (SL352-2006).

Crushed aggregates of quartz sandstone, named JP aggregate, were used in the study. Petrographic analysis revealed that there was 5-12% microcrystalline silica in the aggregates. According to the method of ultra-accelerated mortar bar test in Section 2.37 "aggregate alkaline activity test" of <Test code for hydraulic concrete> (SL352-2006), the alkaline activity of aggregate was tested, and the expansion ratio of mortar bar was 0.365%. Therefore, it can be judged that the aggregates were of potential alkali-silica reaction activity. The maximum particle size of coarse aggregate in the concrete was 40mm, and the fineness modulus and fine powder of fine aggregate was 3.04 and 19.7%, respectively.

Naphthalene superplasticizer and rosin-based air-entraining agent were used in the study.

2.2 Mixing proportion

Concrete specimens were prepared according to mixing proportions of practical projects. The mixing proportion was presented in table 2.

Table 2：Mix proportion of test

maximum particle diameter（mm）	Test code	W/C	Sand ratio（%）	Dosage of admixture（%）		Quantity of Material for unit volume （kg/m^3）			
				water-reducing admixture	Air-entraining admixture	water	cement	sand	stone
40	Sg-45	0.45	38	0.6	0.03	125	278	800	1305

3. TEST METHODS

After demolded, concrete specimens were moved to standard curing room until the age of 28d, and then transferred to a curing cabinet at 60±1℃ and 90-95% relative humidity to accelerate the progress of alkali-aggregate reaction. Cylinder specimens (Φ150mm×450mm) with a strain meter buried in the center were used to test the AAR expansive deformation. The deformation observation and data collection was automatically executed. When the expansive deformation of concrete reached 0.01%、0.03%、0.06%、0.09% and 0.12%, concrete specimens were taken from the curing cabinet for mechanical property tests. The tests were carried out following the test method in Test Code for Hydraulic Concrete (SL352-2006).

4. RESULTS AND DISCUSSION

Expansion ratios of reference concrete without active aggregates and AAR concrete were shown in table 3, and the expansion curve of AAR concrete cured under 60℃ in fig.1. Specimen J-0.23 was reference concrete with an alkali content of 0.23% in cement, and specimen JJ-2.0 was concrete with an alkali content of 2.0% in cement. A solution containing 10 wt.% NaOH was added to the latter one to increase the equivalent alkali content to 2.0%.

Table 3：Expansion ratio of concrete under 60℃（%）

Curing age under 60℃（d）	0	4	10	15	20	25	30	35	40
J-0.23	0	0.0001	-0.0005	-0.0004	-0.0005	-0.0003	-0.0003	-0.0001	-0.0005
JJ-2.0	0	0.0037	0.0135	0.0296	0.0501	0.0741	0.0956	0.1146	0.1223

It can be seen from table 3 that concrete JJ-2.0 showed an expansion ratio of 0.1223% after 40 days cured under 60□, equivalent to a deformation of 1223×10^{-6} of concrete. Such an expansion ratio was not acceptable to concrete.

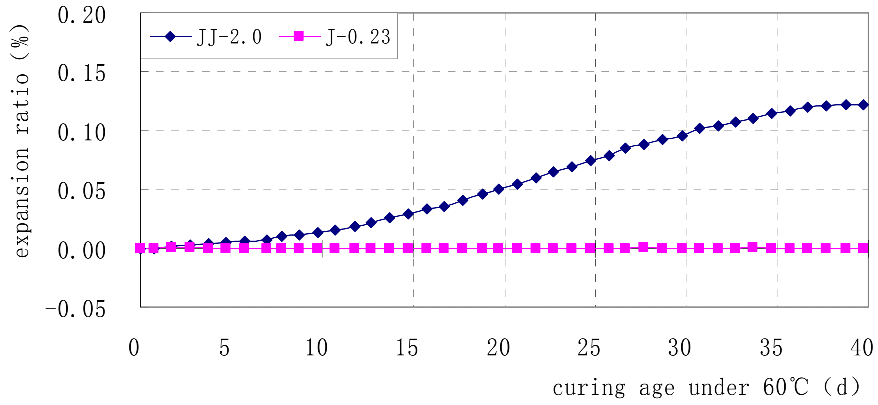

Fig.1：Expansion curve of concrete under 60□

From table 3 and fig.1, it can be concluded that the expansion of specimen JJ-2.0 mainly developed at a curing age of 5 to 35 days in the curing cabinet at 60□, and then the AAR expansion rate obviously slowed down. Specimen J-0.23 was always in a micro-shrinkage state, indicating no occurrence of AAR in specimen J-0.23 under 60□.

The test results of mechanical properties of concrete cured under 60□ were listed table 4, and the relative mechanical properties of specimen JJ-2.0 in table 5. The development process of mechanical properties was shown in fig.2. The test results indicated that with the increase of curing time under the condition of 60□, the splitting tensile strength, bending strength and axial tensile strength of concrete specimen JJ-2.0 decreased to 84.1%, 77.3% and 76.5%, respectively, while the compressive strength of specimen JJ-2.0 increased to 133.0%.

Table 4：Results of concrete mechanical properties under 60℃（MPa）

Sample code	Value of mechanical properties	Curing age under 60℃（d）					
		0	8	15	22	29	41
JJ-2.0	Compressive strength	26.1	28.8	30.1	31.7	33.1	34.7
	Splitting tensile strength	2.27	2.18	2.11	1.99	1.92	1.91
	Bending strength	4.94	4.67	4.46	4.29	4.13	3.82
	Ultimate tensile strength	2.89	2.83	2.65	2.51	2.34	2.21

Table 5：Relative value of mechanical properties of JJ-2.0 concrete under 60□ (%)

Curing age under 60℃（d）		0	8	15	22	29	41
Expansion ratio of AAR（%）		0	0.0099	0.0296	0.0597	0.092	0.1223
relative	Compressive strength	100	110.3	115.3	121.5	126.8	133.0
	Splitting tensile strength	100	96.0	93.0	87.7	84.6	84.1
	Bending strength	100	94.5	90.3	86.8	83.6	77.3
	Ultimate tensile strength	100	97.9	91.7	86.9	81.0	76.5

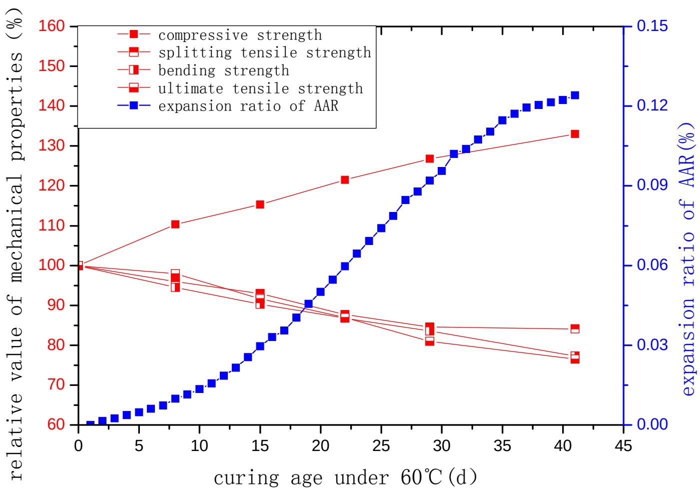

Fig.2：Development of JJ-2.0 concrete chemical properties along with time（60℃）

The test results of dynamic modulus of elasticity of specimen J-0.23 and specimen JJ-2.0 cured under 60□ were shown in table 6 and fig.3. The development curves of dynamic modulus of elasticity and AAR expansion ratio of JJ-2.0 were shown in fig. 4.

Table 6：Concrete dynamic modulus of elasticity of curing age under 60℃

Curing age under 60℃（d）	Concrete dynamic modulus of elasticity，×10^4MPa（Edt）	
	J-0.23	JJ-2.0
0	4.49	4.15
7	4.84	3.99
13	4.99	3.92
17	5.04	3.81
22	5.07	3.70
34	5.13	3.50
41	5.12	3.53

From above test results, high reaction speed of AAR and great AAR expansion ratio brought about obvious declining of concrete tensile strength and bending strength. At late age, AAR expansion speed lowered down, thus the change of splitting strength slowed.

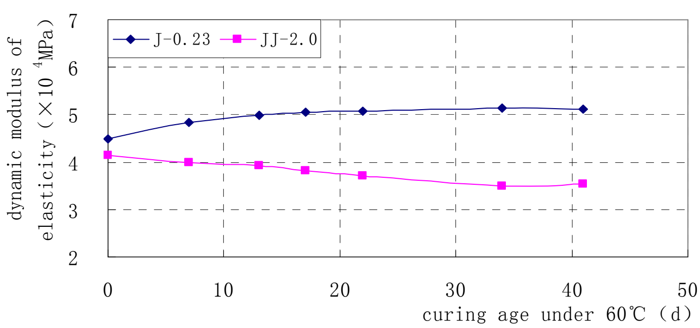

Fig.3：Control curve between J-0.23 and JJ-2.0 concrete under 60℃

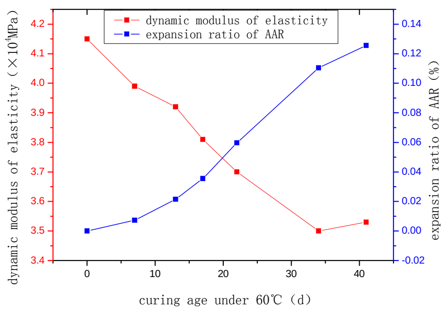

Fig.4：Concrete dynamic modulus of elasticity and AAR expansion ratio curve

5. PREDICTION MODELS OF MECHANICAL PROPERTIES OF AAR-DAMAGED CONCRETE BASED ON THEORY OF DAMAGE MECHANICS

Alkali-aggregate reaction can bring about concrete expansion, inner micro-cracks and micro-structural damages, which consequently resulted in the declining of concrete mechanical properties. According to theory of damage mechanics, damage amount of AAR-damaged concrete was defined as follows:

$$D = 1 - \frac{E}{E_0} \quad (1)$$

Where, D was damage amount, E_0 was initial dynamic modulus of elasticity, and E was dynamic modulus of elasticity of AAR-damaged concrete.

According to Equation 1 and test results in section 4, damage amount corresponding to the expansion ratio of specimen JJ-2.0 with JP aggregates can be calculated. Through data fitting, the relationship between damage amount and AAR expansion ratio can be plotted as in fig.5. The fitting results showed a favorable linear relationship as equation 2.

$$D = 1.136\xi + 0.035 \qquad (2)$$

Where, ξ was Expansion ratio of AAR-damaged concrete.

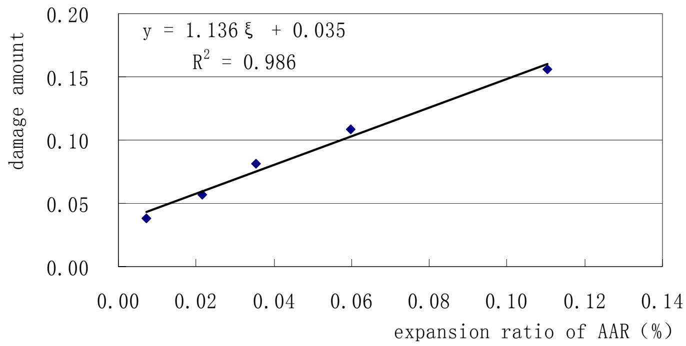

Fig.5：Fitting results of damage amount and AAR expansion ratio

At a high reaction speed of AAR, the results of splitting strength, bending strength and axial tensile strength dropped notably. To study the deterioration rules of mechanical properties of AAR concrete, relative value of mechanical properties was defined as

$$R = \frac{f}{f_0} \qquad (3)$$

Where, R was relative values of mechanical properties, f was mechanical properties of AAR-damaged concrete, and f_0 was mechanical properties of AAR concrete before cured at 60□;

According to equation 2 and equation 3, damage amount of concrete at different AAR expansion ratios and relative mechanical properties corresponding to certain damage amount can be calculated, as shown in table 7.

Table 7：Relative strength of concrete under different damage amount

Expansion ratio of AAR（%）	Damage amount	Relative splitting tensile strength	Relative bending strength	Relative ultimate tensile strength
0.0000	0.000	1.000	1.000	1.000
0.0099	0.046	0.961	0.945	0.979
0.0296	0.068	0.930	0.903	0.917
0.0597	0.103	0.877	0.868	0.869
0.0920	0.139	0.846	0.836	0.810

The relationship between damage amount and relative values of mechanical property of AAR concrete can be analyzed through fitting. Fitting analyses showed that the relationship between them can be favorably built with modified power function showed in Equation 4. The fitting results were listed in table 8, and fitting curve in fig.6-fig.8.

$$y = \frac{1}{1 + bx^{c}} \qquad (4)$$

Where, b and c were parameters of the fitting equation, x was damage amount under AAR process, and y was relative mechanical properties.

Table 8：Results of regression analysis between concrete relative strength and damage amount

	b	c	S	r
Regression result of relative splitting tensile strength	2.261	1.254	0.008	0.996
Regression result of relative bending strength	1.402	0.984	0.008	0.996
Regression result of relative ultimate tensile strength	5.398	1.570	0.015	0.990

Note: S – standard error; r – correlation coefficient.

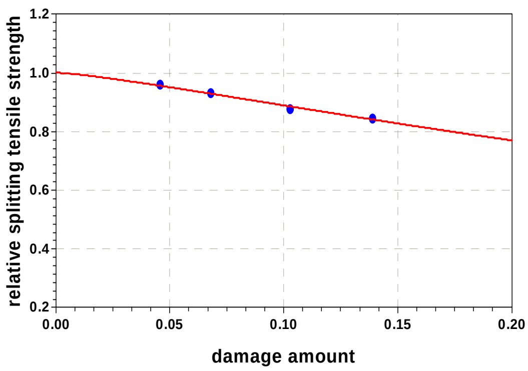

Fig.6：Relation curve between relative splitting tensile strength and damage amount

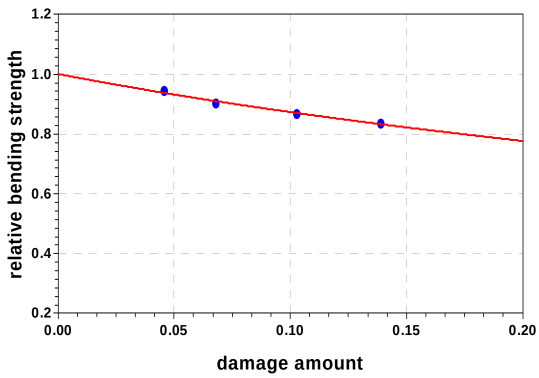

Fig.7：Relation curve between relative bending strength and damage amount

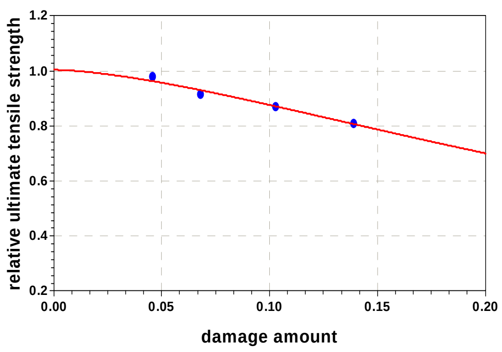

Fig.8：Relation curve between relative ultimate tensile strength and damage amount

The fitting results based on equation 4 indicated that, there were satisfactory correlations between damage amount and relative values of splitting strength, bending strength and axial tensile strength of AAR-damaged concrete. Therefore, the prediction model of JP aggregate concrete tensile or bending strength under AAR condition can be established as follows:

$$R = \frac{1}{1 + b\mathrm{D}^{c}} \qquad (5)$$

For JP aggregate, based on the prediction model, relative tensile or bending strength at different AAR expansion ratio can be calculated. According to the development level of AAR in concrete, this model can be used to predict the effect of AAR on tensile or bending strength of concrete with JP aggregate, and thus evaluate the deterioration degree and safety condition of certain concrete structures.

6. CONCLUSIONS

- For JP aggregate, under the experiment conditions, at an low AAR expansion ratio of 0.1223%, alkali-aggregate reaction had relatively obvious effect on concrete splitting tensile strength, bending strength and axial tensile strength, but little effect on compressive strength.
- The relationship between damage amount and AAR expansion ratio can be well fitted with linear equation.
- The relationship between damage amount and relative concrete tensile and bending strength can be satisfactorily built up with modified power function. Therefore, prediction model of relative tensile or bending strength of AAR-damaged concrete (with JP aggregate) could be established. The model can be used to predict the effect of AAR on tensile or bending strength of certain concrete, and thus evaluate the deterioration degree and safety condition of hydraulic concrete structures.
- For other kinds of active aggregate used in hydraulic projects, the applicability of the prediction model must be verified through further experiments.

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