INFLUENCE OF ALKALI-AGGREGATE REACTION ON FLEXURAL PROPERTIES OF STEEL FIBER REINFORCED CONCRETE

Qian Chunxiang, Guo Hongding, Wang Jin and Yan An

Department of Materials Science and Engineering
Southeast University, Nanjing, China

ABSTRACT

In accelerated tests of 3 days at 100°C, with silica glass aggregate, alkali-aggregate reaction (AAR) causes a reduction of both flexural strength and compressive strength, and an increase in the flexural toughness in both plain concrete (PC) and steel fibre reinforced concrete (SFRC). The steel fibre in SFRC can reduce AAR expansion to a certain extent and thus its effect on the flexural strength of the concrete, when the AAR expansion is in the low range. In SFRC the thresholds of alkali content and the amount of reactive aggregate can be slightly increased with respect to that of PC.

***Key words*:** alkali-aggregate reaction, steel fibre reinforced concrete, strength

INTRODUCTION

Alkali aggregate reaction results in an expansion of the concrete. Steel fibres in concrete may suppress this kind of expansion to a certain extent. This paper discusses whether the thresholds of alkali content and the amount of reactive aggregate can be increased and whether the attack of AAR on the properties of reinforced concrete can be reduced by the use of steel fibre.

MATERIALS

The cement used in this experiment is manufactured by the Jiang Nan Cement Group, Nanjing, China. Its mineral composition, chemical composition and physical properties are listed in Tables 1, 2 and 3 respectively.

Table 1 Mineral Composition of Cement

Mineral Composition	C_3S	C_2S	C_3A	C_4AF	Free-CaO
%,by weight	55.21	21.59	4.54	16.29	0.29

Table 2 Chemical Composition of Cement

Composition	SiO_2	Al_2O_3	CaO	MgO	SO_3	Fe_2O_3	Na_2Oequiv.
%,by weight	22.06	5.13	65.37	1.06	2.03	5.36	0.40

Table 3 Physical Properties of Cement

Fineness(%,by weight)		Flexural Strength(MPa)			Compressive Strength(MPa)			Specific Area
80μm Sieve Residue	20μm Sieve Residue	1d	3d	28d	1d	3d	28d	
0.06	2.64	4	6.7	9.5	18	40.5	68.9	$3560cm^2/g$

The steel fibre being used was a straight type of fibre with a square cross section and was 35 mm in length. Its length to equivalent diameter ratio was 44. The coarse aggregate was crushed stone with a range in size of 5mm -- 20mm and was inert. The fineness module of the sand was 2.7. Artificial silica glass with a particle size range of 0.16mm--5mm was used as the reactive aggregate. Potassium hydroxide (KOH) was used to increase the alkali content of the concrete, which was 1.94 kg/m^3.

EXPERIMENTAL METHODS

Cross Tests

Firstly, cross tests were designed to determine the proper amount of steel fibre to be used from the point of economics and its effectiveness in suppressing AAR expansion. Three factors were evaluated in the cross tests:

(a) volume percentage of steel fibre - V_f : 0, 0.5, 1.0, 1.5%

(b) the additional alkali content - AL: 0, 4, 6, 8 kg/m^3

(c) the amount of reactive silica glass- RA: 0, 15, 25, 35 kg/m^3.

It was found that steel fibres with a volume percentage of 1.0% will be sufficient.

Mix Proportions

The amount of the main materials in the concrete specimens being used for flexural tests are shown in Table 4. The water cement ratio was 0.42. The specimens are divided into two groups. The first group did not contain steel fibre (Specimens P1 to P5). The second group (Specimens S1 to S5) contained 1.0% steel fibre. The range of additional alkali (Na_2O equiv.) was 0 to 8 kg/m^3 of concrete. The reactive silica glass ranged from 0 to 32 kg/m^3 (Table 5).

Table 4 Amount of Main Materials Used in Concrete Specimens

Cement(kg/m^3)	Coarse Aggregate(kg/m^3)	Sand(kg/m^3)	Water(kg/m^3)
486	1004	669	204

Table 5 Volume Percentage of Steel Fibre, Alkali Content and Amount of Silica Glass in Concrete

Specimens	*P1*	*P2*	*P3*	*P4*	*P5*	*S1*	*S2*	*S3*	*S4*	*S5*
Volume of Fibre (Vf,%)	0	0	0	0	0	1.0	1.0	1.0	1.0	1.0
Alkali Content (kg/m^3)	0	2	4	6	8	0	2	4	6	8
Silica Glass (kg/m^3)	0	8	16	24	32	0	8	16	24	32

Expansion Test and Flexural Test

The size of the specimens used for the expansion and flexural tests were 100×100×500mm. After being cast and demoulded, the specimens were cured at 20±3°C, 90% R.H. for 7 days, and then the initial length (Lo) was measured. They were then put in a curing box and cured at 100°C water vapour for 72 hours. After the box was turned off and the specimens were cooled to room temperature in the box, they were withdrawn from the box at a day before their final length(Lt) was measured. The expansion ratio of the specimens was calculated as follows:

$$\varepsilon = \frac{L_t - L_o}{L_b} \times 100\%$$

in which, ε: expansion ratio(%); L_t: the length of concrete specimens after being cured; L_o: the initial length of specimens; L_b: the gauging distance.

After the concrete specimens were measured, flexural tests were carried out. The flexural strength of the concrete was calculated using the following formula:

$$\sigma = \frac{PL}{bh^2}$$

in which, σ: flexural strength; P: ultimate flexural load; L: span distance, 300 mm; b: width of specimens, 100mm; h: height of specimens, 100mm.

The flexural toughness of concrete is expressed by the flexural toughness index, σ_b as stated by the Japan Concrete Institute.

$$\sigma_b = \frac{TL}{\delta_b h^2}$$

in which, δ, the deflection, equals L/150, in this case it is equal to 2mm; T equals the area under the load-deflection curve at the point of δ.

Ultrasonic Test

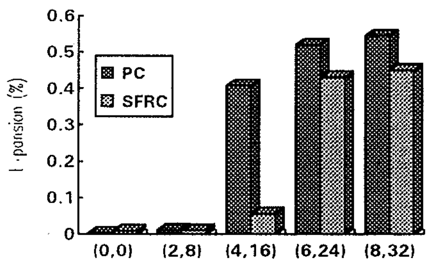
In order to detect the microfracture of the concrete which was due to the alkali-aggreagte reation, an ultrasonic test was carried out on the specimens prior to the flexural tests being carried out. Emission and receiving detectors were fixed on the two ends of the specimens. The transmission distance of the ultrasonic wave was 500mm, which was equal to the length of the specimens.

RESULTS AND DISCUSSION

The expansion ratio(ε), the velocity of ultrasonic wave transmission through the concrete specimen(v), the ultimate flexural strength and the compressive strength of the various specimens are shown in Table 6 and Figs.1--4.

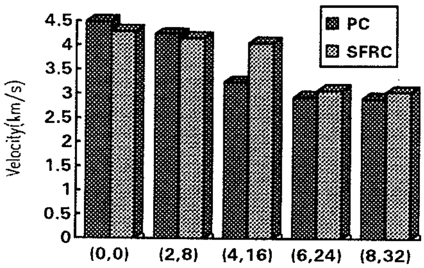
Table 6 Main Test Results

Specimen	*P1*	*P2*	*P3*	*P4*	*P5*	*S1*	*S2*	*S3*	*S4*	*S5*
Expansion(%)	0.003	0.012	0.407	0.520	0.545	0.009	0.011	0.056	0.430	0.450
Velocity(km/s)	4.49	4.24	3.25	2.94	2.90	4.29	4.16	4.06	3.08	3.04
Flexural Strength(MPa)	8.82	7.38	3.06	2.88	2.79	11.62	9.42	8.57	5.38	4.99
Compressive Strength(MPa)	57.0	51.8	44.0	31.5	24.8	68.3	58.5	51.8	34.5	27.8



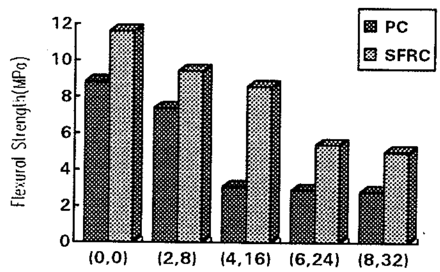
(Alkali Content, Amount of Silica Glass, kg/m^3)

***Fig.1** Expansion Ratio vs Alkali Content and the Amount of Silica Glass in Plain Concrete(PC) and Steel Fibre Reinforced Concrete(SFRC)*



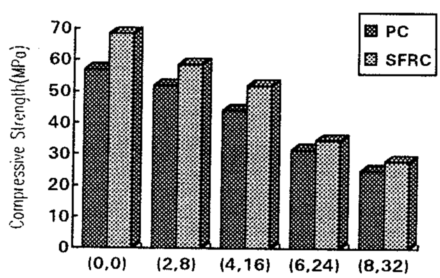
(Alkali Content, Amount of Silica Glass, kg/m^3)

Fig.2 Velocity of Ultrasonic Wave Transmitting Through Concrete vs Alkali Content and Amount of Reactive Silica Glass in PC and SFRC



(Alkali Content, Amount of Silica Glass, kg/m^3)

Fig.3 Influence of AAR on Flexural Strength of PC and SFRC



(Alkali Content, Amount of Silica Glass, kg/m^3)

Fig.4 Influence of AAR on Compressive Strength of PC and SFRC

From Fig.1, it can be seen that the expansion ratio of the SFRC is lower than that of the PC at the same alkali content and at the same amount of reactive silica glass. In other words, the thresholds of the alkali content and the amount of reactive aggregate in SFRC is able to be increased compared to that of PC . This is due to the restriction on AAR expansion as a result of the steel fibre. For example, if the expansion ratio of the SFRC is specified as 0.05%, the alkali content can be increased by about 1.8 kg/m^3 and the amount of silica glass can be increased by 8 kg/m^3 when compared to that of PC.

These results can also be confirmed by the ultrasonic wave test. The velocity of ultrasonic wave transmission through plain concrete specimens is lower than that through steel fibre reinforced concrete while the alkali content and the amount of silica glass in SFRC is the same as that in PC (Refer to Fig.2). This shows that the microfracture caused by AAR in the SFRC is less than that in the PC and it is the the steel fibre which reduces the AAR attack.

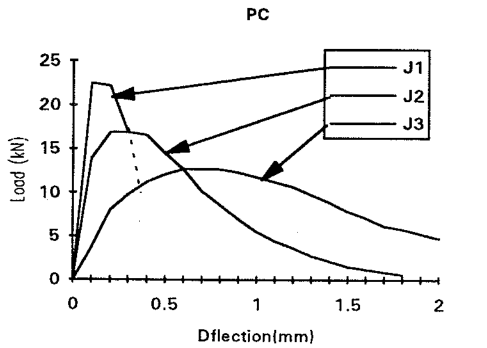
Alkali silica reaction causes a dramatic loss of flexural strength and a reduction of compressive strength both in SFRC and PC (Fig.3 and Fig.4). When alkali content and silica glass are at 4 kg/m^3 and 16 kg/m^3 respectively , the expansion of the plain concrete reaches 0.407% and its flexural strength is reduced from 8.82 MPa to 3.06 MPa, while its compressive strength is decreased from 57.0 MPa to 44.0 MPa. Under the same conditions, the expansion of steel fibre reinforced concrete was only 0.056%. Its flexural strength and compressive strength are decreased from 11.62 MPa to 8.57 MPa and from 68.3 MPa to 51.8 MPa respectively, this loss of flextural strength in SFRC is far less than that in the PC.

Alkali-silica reaction also influences the shape of the load-deflection curve of both plain concrete and steel fibre reinforced concrete. The curve of the concrete without AAR is steep and narrow, this is changed to flat and broad when AAR exists (Refer to Fig.5 and Fig.6). Alkali silica reaction results in an increase of the flexural toughness index. For example, the flexural toughness index of plain concrete increases from 8.93 to 16.25 when AAR expansion reaches 0.426% (Fig.5 Curve J3), and the flexural toughness index of the SFRC with steel fibres 0.5% improves from 9.25 to 21.26, while expansion ratio reaches 0.50% (Fig.6 curve J6). These changes can be attributed to more original microcracks caused by the AAR. When the concrete is loaded, the cracking pattern of concrete changes from a few points of propagation to many points of propagation and as a result the concrete is able to absorb more energy before it is damaged.

The principle of steel fiber on AAR expansion is similar to its effect on creep, drying shrinkage and deformation of concrete under loading. Some researches[1-3] have shown that steel fibers restrained the creep of cement matrixes and reduced the free shrinkage of concrete. The deflection of reinforced concrete beams was reduced and the stiffness after cracking was enhanced because of the addition of steel fibers[4-5] .

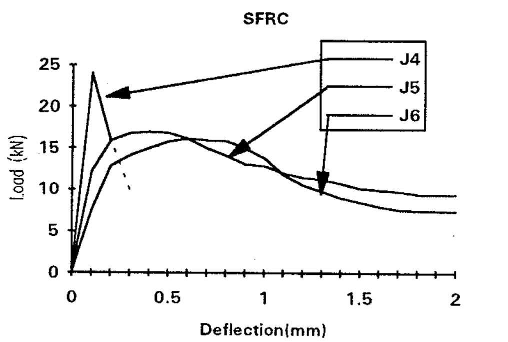
Koyanagi etc[6] also indicated that addition of steel fiber made the AAR crack length of reinforced concrete beams shorter with respect to plain concrete beams.

Steel fibers restrain the physical expansive process of AAR other than the chemical reaction of AAR.



	AL, kg/m^3	RA, kg/m^3	ε, %	V, km/s	δb
J1	0	0	0.010	4.40	8.93
J2	6	25	0.311	3.22	8.86
J3	8	35	0.426	3.26	16.25

Fig. 5 Influence of AAR on Load-Deflection Curve of Plain Concrete



	AL, kg/m^3	RA, kg/m^3	ε, %	V, km/s	δb
J4	0	15	0.021	4.07	9.26
J5	6	25	0.325	3.04	23.74
J6	8	35	0.467	2.97	21.26

Fig.6 Influence of AAR on Load-Deflection Curve of SFRC (Vf=0.5%)

CONCLUSIONS

Steel fibre in concrete can restrict AAR expansion at low expansions. The thresholds of alkali content and the amount of reactive aggregate can also be increased slightly when compared to those of plain concrete.

Alkali silica reaction causes a reduction of flexural strength and compressive strength both in plain concrete and steel fibre reinforced concrete. It also substantially changes the pattern of the load-deflection curve. The flexural toughness index of concrete is improved when the alkali silica reaction exists.

Future research could determine if deformed, hooked, crimped, paddled or enlarged ends steel fibres may be better than straight fibres in restricting the expansion of the alkali-silica reaction. Steel fiber may be useful in concrete structural practice in reducing sensitivity to small expansions.

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