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EFFECTIVENESS OF SILICA FUME IN REDUCING DAMAGE DUE TO ALKALI-SILICA REACTION

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1. INTRODUCTION

In the early 1980s, many cases of concrete structures deteriorated as a result of alkali-silica reaction (ASR) have been reported in Japan, including T-shaped piers of the Hanshin Expressway. It has been suggested that a suitable method of reducing the risk of cracking due to ASR is to replace a part of Portland cement by pozzolanic materials such as pulverized fuel ash (FA), ground granulated blast-furnace slag (BFS) or condensed silica fume (SF). A recent report [1] states that use of pozzolanic materials is not necessarily a good method to prevent the damage due to ASR. It is necessary to ascertain that the adequate usage of pozzolanic materials can prevent the damage due to ASR.

In this study, firstly in order to compare the effectiveness of three kinds of pozzolanic materials used in Japan in reducing the deterioration due to ASR, mortar bars in which a part of cement was replaced by FA, BFS and SF were made by using the same aggregate as that in the deteriorated structure of the Hanshin Expressway, and expansive strain was measured. Secondly in order to investigate the availability of SF which was considered most effective in reducing the deterioration due to ASR, non-destructive tests such as ultrasonic pulse velocity, dynamic modulus of elasticity and the spectral analysis of ultrasonic pulse, were carried out on SF mortar and concrete specimens.

2. OUTLINE OF THE TEST

Experimental conditions of mortar bar test are shown in Table 1. In order to examine the effectiveness of pozzolanic materials in reducing the deterioration due to ASR, three kinds of pozzolanic materials used in Japan (SF, FA and BFS) were used as cement replacement materials. Experimental conditions to examine the availability of SF are shown in Table 2. Mix proportion of mortar bar and method of mixing were in accordance with ASTM C 227 and JIS R 5201, respectively. The value of flow was 190±10mm.

Experimental conditions of concrete specimens are shown in Table 3. Three levels of SF content (0, 5, 25%) and two levels of air content (2, 6%) were chosen to examine the effectiveness of SF in reducing

Table 1 Experimental conditions of mortar bar test

Pozzolanic material	content (%)	Total $(Na_2O)_{eq}$:(%)
not used	0	0.63, 1.5, 2.0
Condensed silica fume	5, 25	2.0
Pulverized fuel ash	5, 30	2.0
Blast-furnace slag	20, 40, 60	2.0

Table 2 Experimental conditions of silica fume mortar bar test

Type	Total $(Na_2O)_{eq}$ (%)	S F content (%)
N-0.63	0.63	0
R-1.5	1.5	0
R-2	2.0	0
5SR-2	2.0	5
25SR-2	2.0	25

Table 3 Experimental conditions of concrete specimens

Type	Total $(Na_2O)_{eq}$ (%)	S F content (%)	Air content (%)
N6	0.65	0	6
R6	2.0	0	6
R2	2.0	0	2
5SR6	2.0	5	6
5SR2	2.0	5	2
25SR2	2.0	25	2

Table 4 Properties of materials used

Ordinary Portland cement	s.g.*:3.16, total$(Na_2O)_{eq}$:0.63, 0.65
Fine aggregate(normal)	Yasu river sand, s.g.:2.60, F.M.:2.43
Coarse aggregate(normal)	Takatsuki crushed gravel, s.g.:2.69, M.S.:20mm
Coarse aggregate(reactive)	Teshima Island crushed gravel, s.g.:2.55, M.S.:20mm
Condensed silica fume	SiO_2:97%, total$(Na_2O)_{eq}$:0.26%, s.s.a.**:20m^2/g
Pulverized fuel ash	total$(Na_2O)_{eq}$:2.54%, s.g.:2.20, s.s.a.:2960cm^2/g
Blast-furnace slag	total$(Na_2O)_{eq}$:0.46%, s.g.:2.91, s.s.a.:4180cm^2/g

note; * : specific gravity, ** : specific surface area

the deterioration due to ASR. Mix proportion of concrete was W/(C+SF)=50%, W=172 kg/m^3, slump=7 to 10.8cm.

The properties of materials used in this study are shown in Table 4. In order to accelerate the ASR, surplus alkali (NaCl) was added. Total equivalent alkali content : $(Na_2O)_{eq}$ was expressed as percentage to weight of cement plus pozzolanic material. Crushed gravel (Bronzite Andesite) produced in Teshima Island was used as the reactive coarse aggregate. The proportion of reactive aggregate was 50% by weight in mortar bar test and by volume in the concrete test, and it was approximately pessimum content [2]. Superplasticizer was used to adjust the workability of mixes including SF.

The mortar bars and concrete specimens were cured in water (20±2°C) up to the age of 21 days and 14 days respectively, and then stored at 40°C, 100%RH. During accelerating curing, the specimens were stored at 20±2°C, 90±5%RH for one day before non-destructive measurements such as expansive strain, pulse velocity, dynamic modulus of elasticity and the spectral analysis of ultrasonic pulse. After the final non-destructive measurements of concrete specimens, compressive strength, poisson's ratio and critical stress were measured.

In the spectral analysis[3], rectangular impulse ($1x10^{-6}$s, 22V) which has a constant power spectrum within a region from DC to 100KHz was produced by a function generator. The output signal was consequently measured at the interval of $2.44x10^{-6}$s, and then analysed by the Fast Fourier Transform to obtain the response function. The trasducer with resonance frequency of 54KHz was used in the measurement of pulse velocity and the spectral analysis. Pulse velocity was measured by ASTM C 597.

3. TEST RESULTS AND DISCUSSIONS

3.1 Non-destructive tests of mortar bars

3.1.1 Effect of pozzolanic materials Expansive strains of mortar bars are shown in Fig.1. The level of expansion due to ASR was largely dependent on the type and the content of pozzolanic materials. SF delayed the age when mortar bar began to expand, but mortar bars including FA and BFS began to expand immediately after the start of accelerating curing. Large expansive strain was measured in the mortar bars including BFS even at the maximum replacing ratio of 60%, and the value measured at the age of 545 days was approximately 1200×10^{-6}. Remarkable increase of expansive strain was observed in the mortar bars including FA and SF at the replacing ratio of 5%. Measured strain of FA mortar bar was approximately 2360×10^{-6} at the age of 64 days, and that of SF mortar bar was approximately 1980×10^{-6} at the age of 134 days. On the other hand, only small amount of expansive strain was measured in FA mortar bar at the replacing ratio of 30%. Measured value was 240×10^{-6} at the age of 549 days. No expansive strain was observed in SF mortar bar at the replacing ratio of 25%. Even though aggregate was in the pessimum condition and alkali content was high, there was no sign of deterioration due to ASR in SF mortar bar at the replacing ratio of 25% until the age of 687 days.

3.1.2 Non-destructive tests of silica fume mortar bars Expansive strain, pulse velocity, dynamic modulus of elasticity and energy of response function of SF mortar bars are shown in Fig.2, and examples of correlation between these measured values and time are shown in Fig.3. The energy of

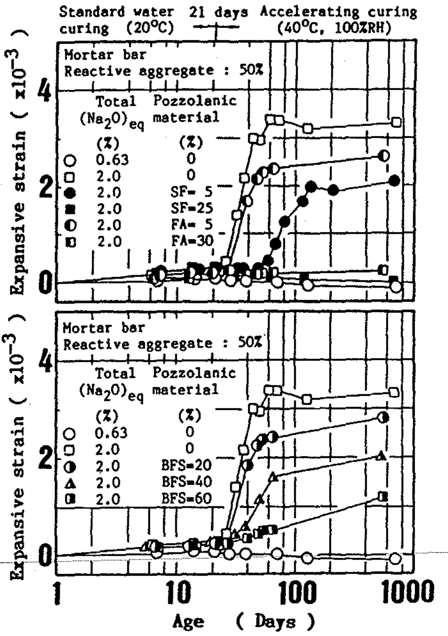


Fig.1 Expansive strains of mortar bars including pozzolanic materials

note; SF: Condensed silica fume
FA: Pulverized fuel ash
BFS: Ground granulated blast-furnace slag

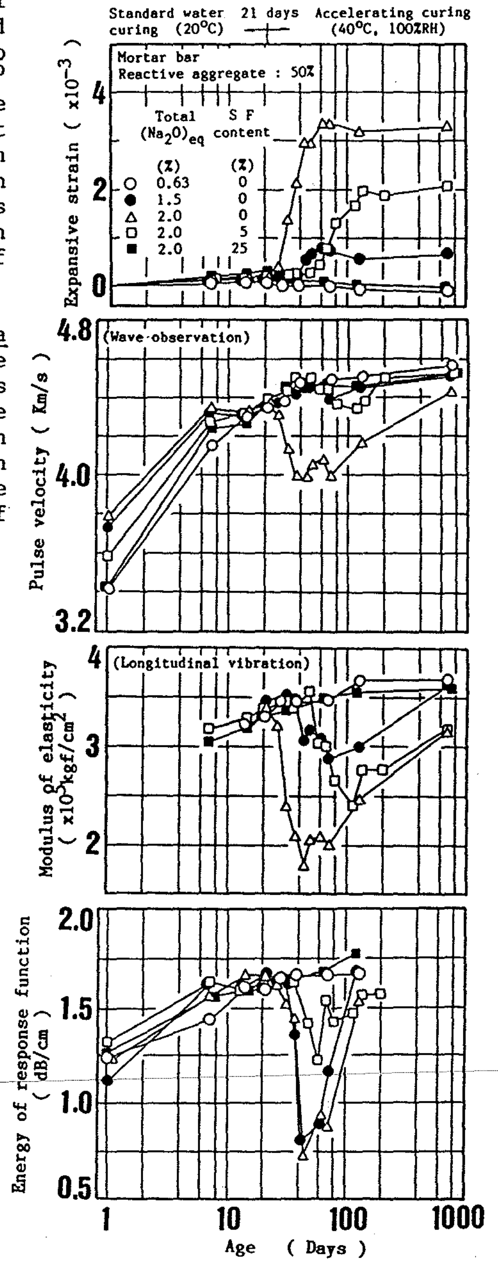
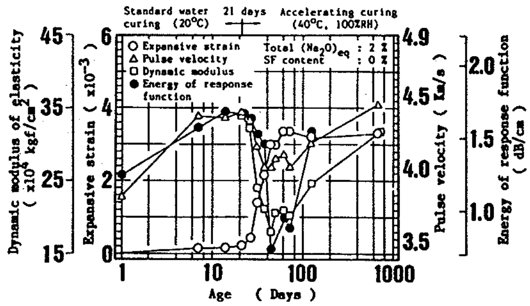


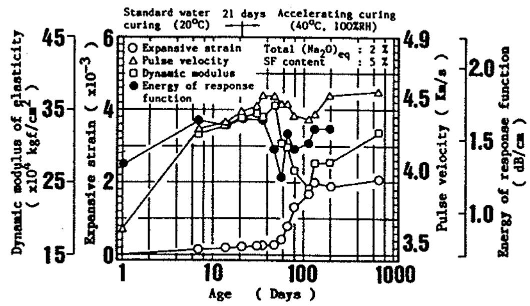
Fig.2 Results of non-destructive tests of silica fume mortar bars

response function is defined as the integrated value of power spectrum of the response function from DC to the maximum frequency of 102.3KHz. In the deteriorated mortar bars, pulse velocity, dynamic modulus of elasticity and energy of response function once decreased with expansion due to ASR, and then increased again. Reincreases of measured values may be attributed to the filling into cracks of the gel resulted from ASR.

The difference of measured values was dependent on the level of the expansion due to ASR. In the mortar bar R-2 which was severely deteriorated by ASR, the decreases from the values measured at the age of 21 days were approximately 9% in pulse velocity, 47% in dynamic modulus of elasticity and 56% in energy of response function. Those decreases were observed almost at the same time when the expansive strain increased rapidly. On the other hand, in the mortar bar 5SR-2 in which the deterioration was not so severe as that of R-2, the energy of response function began to decrease earlier than pulse velocity and dynamic modulus of elasticity, although the decrease of energy of response function was smaller than that of R-2. In addition, only small decrease of pulse velocity was observed. Also in the mortar bar R-1.5 whose expansive strain was smaller than that of 5SR-2, simillar behaviors were observed. Expansive strain of R-1.5 was approximately 840×10^{-6} at the age of 61 days. Especially in the mortar bars in which the level of the deterioration due to ASR is relatively small, the spectral analysis of ultrasonic pulse is a good techniqe to evaluate the deterioration due to ASR.



(a) Type R-2



(b) Type 5SR-2

Fig.3 Correlation between results of non-destructive tests of mortar bars and age

3.2 Non-destructive tests of concrete specimens

Pulse velocity, dynamic modulus of elasticity and energy of response function of concrete specimens (ϕ10x20cm) are shown in Fig.4, and examples of correlation between those values and time are shown in Fig.5. Although the mortar bars generally began to expand immediately after the start of accelerating curing, the start of the deterioration of concrete specimens was delayed. Pulse velocity, dynamic modulus of elasticity and energy of response function once decreased with deterioration due to ASR, and then increased again as observed in the mortar bar specimens. The effect of entrained air on ASR was not observed in the test. In R6 and R2, the decreases from the values measured at the age of 14 days were approximately 7% (320m/s) in pulse velocity, 38% (15×10^4 kgf/ cm^2) in dynamic modulus of elasticity and 12% in energy of response function. The decrease of the energy of response function was smaller than that of the mortar bar.

Severe deterioration was observed in SF concrete specimen at the replacing ratio of 5%, although the age when SF concrete specimen began to be

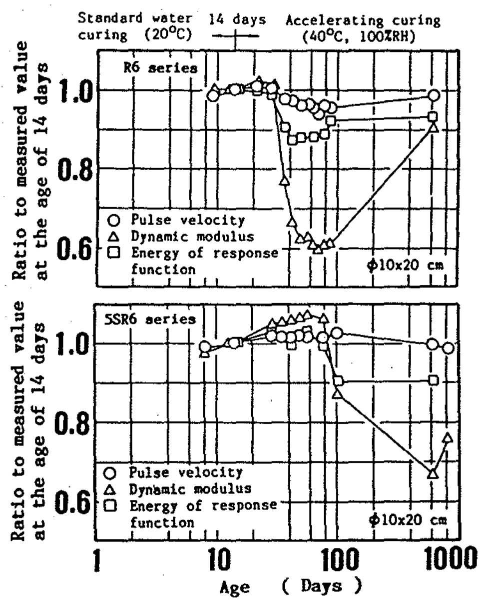


Fig.5 Correlation between results of non-destructive tests of concrete specimens and age

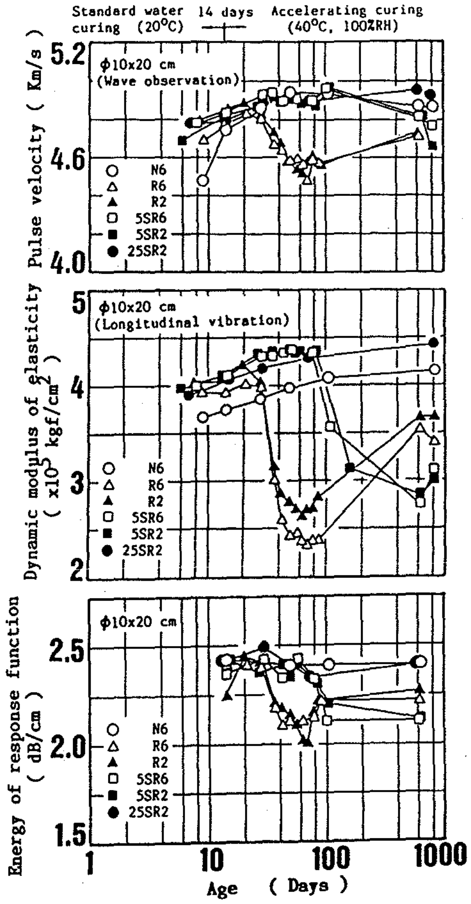


Fig.4 Results of non-destructive tests of silica fume concrete specimens

deteriorated was delayed remarkably. On the other hand, no deterioration due to ASR was observed in SF concrete specimen at the replacing ratio of 25% until the age of 798 days.

3.3 Mechanical properties of concrete specimens

The results of destructive tests are shown in Table-5. An example of the relationship between compressive stress and longitudinal, transverse and volumetric strains, is shown in Fig.6. Large decreases of compressive strength and static modulus of elasticity due to ASR were measured in the deteriorated concrete specimens. The decreases from normal concrete (N6) were 20 to 30% in compressive strength and 20 to 40% in static modulus of elasticity. The effect of entrained air in reducing the damage due to ASR was not observed in the test. Remarkable decrease of the ratio of critical stress to compressive strength was measured in the deteriorated concrete specimens. Measured ratios of R6 and R2 were 45% and 60% respectively, and that of SF concrete specimens at the replacing ratio of 5% was 28 to 38%. On the other hand, higher compressive strength of 783 kgf/cm^2 was measured in SF concrete at the replacing ratio of 25%, and no

Table 5 Mechanical properties of concrete specimen

Type	Compressive strength (kgf/cm^2)	Static modulus of elasticity (x10^5 kgf/cm^2)	Critical stress* (%)
N6	457 (1.00)	3.73 (1.00)	87
R6	372 (0.81)	2.56 (0.69)	45
R2	323 (0.71)	3.11 (0.83)	60
5SR6	366 (0.80)	2.32 (0.62)	28
5SR2	371 (0.81)	2.35 (0.63)	38
25SR2	783 (1.71)	4.17 (1.12)	97

note; * : ratio of critical stress to compressive strength

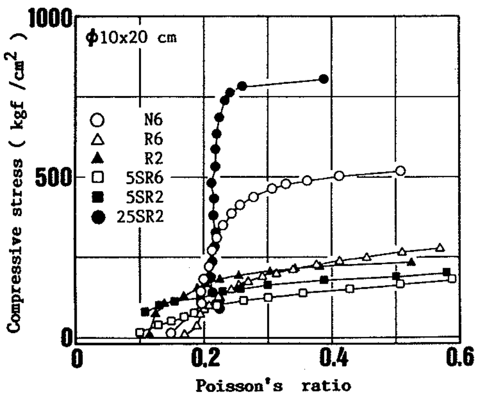


Fig.7 Relationship between compressive stress and Poisson' ratio

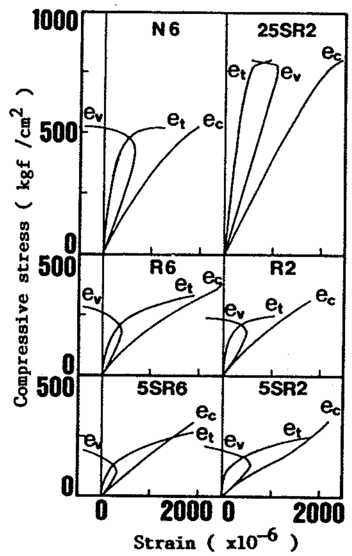


Fig.6 Relationship between compressive stress and strains

note; e_c : longitudinal strain
e_t : transverse strain
e_v : volumetric strain

decrease of critical stress was observed.

An example of the relationship between compressive stress and Poisson's ratio is shown in Fig.7. Poisson's ratio at the level of allowable stress was approximately 0.21 in both N6 and 25SR2 in which the deterioration due to ASR was not observed. On the contrary, large increase of Poisson's ratio was observed in the deteriorated concrete specimens.

4. CONCLUSIONS

The following conclusions may be drawn.

(1) SF is the most effective pozzolanic material in preventing damage due to ASR, even though aggregate was in the pessimum condition, and alkali content was high. There was no sign of deterioration due to ASR in SF mortar and concrete specimens at the replacing ratio of 25%.

(2) In the deteriorated mortar and concrete specimens, pulse velocity, dynamic modulus of elasticity and energy of response function once decreased with deterioration due to ASR, and then increased again. Reincreases of measured values may be attributed to the filling into cracks of the gel resulted from ASR. The spectral analisis of ultrasonic pulse is a good techniqe to evaluate the deterioration due to ASR, especially when the deterioration is relatively samll.

(3) The compressive strength and static modulus of elasticity of deteriorated concrete specimens decreased approximately 20 to 30% and 20 to 40% respectively, when compared with normal concrete. Large increase of Poisson's ratio was observed in the deteriorated concrete specimens.

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