MECHANICAL PERFORMANCE OF ASR AFFECTED NEARLY FULL-SCALE REINFORCED CONCRETE COLUMNS

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ABSTRACT

Mechanical characteristics of ASR affected reinforced concrete column were experimentally investigated in comparison with those of normal concrete column. Those test results indicate; (1) ASR improved the ductility of reinforced concrete column. (2) Although ASR reduced the compressive strength about 40 to 50 percent, ultimate load bearing capacity (N'ou) of the column was not so reduced than that we had expected. When columns have small transverse reinforcement, however, transverse reinforcement yielded before axial reinforcement yielded, so that N'ou was about 30 percent lower than that of normal concrete column. (3) Larger the size of test unit, effect of ASR on mechanical characteristics of reinforced concrete column became smaller.
Keywords: ASR, ductility, reinforced concrete columns, stress-pass, ultimate load

INTRODUCTION

During last some 15 years, many concrete structures deteriorated by alkali aggregate reaction (ASR) have been confirmed at various regions in Japan. As has been well known, compressive strength of ASR affected concrete decreases to about one half that of normal sound concrete. Reduction in modulus of elasticity is larger than that in compressive strength. Many experimental test results on reinforced concrete beam affected by ASR, subjected to bending moment, have been reported. There are, however, few researches on the reinforced concrete column subjected to axial force.

On the other hand, ultimate load bearing capacity of reinforced concrete column made with normal concrete is known almost proportional to compressive strength of concrete. Therefore, the authors fear that decrease in compressive strength of concrete due to ASR will cause a significant loss on bearing load capacity of reinforced concrete column.

Spirally reinforced and tied columns ($\phi 20\times60$ cm and $20\times20\times60$ cm sized) were tested. Variables were axial reinforcement ratio, transverse reinforcement ratio, water-cement ratio and expansion of concrete due to ASR. Finally, spirally reinforced concrete columns $\phi 85\times270$ cm and $75\times75\times240$ cm tied columns in size were tested.

TEST DETAILS

Materials and concrete

Ordinary portland cement having alkali content of 0.62% was used. Pit sand and river sand were used as fine aggregate. Reactive (determined by chemical method) crushed chert was used as coarse aggregate for ASR concrete. Non-reactive crushed stone for normal concrete. Sodium hydroxide was used as additional alkali. Water-cement ratio and alkali content (Na_2Oeq.) of concrete used were shown in Table 1.

Table 1 Water-cement ratio and alkali content of concrete

Mix No.	W/C (%)	Na_2Oeq.(kg/m³)
N1	94.1	1.16*
N2	74.6	1.32*
N3	58.8	2.11*
N4	50.0	2.42*
A1	65.0	7.00
A2	58.8	7.00
A3	50.0	7.00
A4	40.0	7.00

* Alkalinity from cement
N; Normal concrete, A; ASR concrete

Test specimens

Compressive strength was determined by $\phi 10\times20$ cm cylindrical specimens. Free expansion of concrete was measured by $10\times10\times40$ cm prismatic specimens. Reinforced concrete columns were, for the most part, $\phi 20\times60$ cm sized spiral columns and $20\times20\times60$ cm sized tied columns, as shown in table 2 and 3. Variables were axial reinforcement ratio (P), transverse reinforcement ratio (Ps or Ph), water cement ratio of concrete (W/C) and free expansion of concrete (Ex.). Finally, four spirally reinforced concrete columns $\phi 85\times270$ cm and four $75\times75\times240$ cm tied columns were prepared to investigate the size effect.

All specimens and columns made with ASR concrete were cured under ambient condition of 38℃ and 100% RH. Normal concretes were cured in the 20 ℃ water tank.

ASR concrete columns were tested as of free expansion of concrete 1500μ, except unit No. S17, S22, H19, H21 and H27. Nearly full-size column specimens were tested

Table 2 Experimental program in spirally reinforced concrete column test and its results

Unit No.	P=Ast/Ae (%)	Ps=Aspe/Ae (%)	Concrete	f'c (MPa)	N'ou (KN)
S1	0.95	1.89	N3	37.8	1259
S2	1.44	1.89	N3	37.8	1309
S3	1.93	1.89	N3	37.8	1333
S4	3.03	1.89	N3	33.4	1255
S5	1.44	1.13	N3	33.0	1091
S6	1.44	1.89	N3	33.0	1177
S7	1.44	2.83	N3	33.0	1363
S8	1.44	1.89	N1	13.7	628
S9	1.44	1.89	N2	22.3	903
S10*	2.25	1.04	N3	32.9	19.3 MN
S11	1.14	1.89	A2	19.1	945
S12	1.71	1.89	A2	19.1	1028
S13	2.30	1.89	A2	19.1	1047
S14	1.71	0.93	A2	20.8	863
S15	1.71	1.13	A2	22.2	924
S16	1.71	1.89	A2	22.2	1074
S17	1.71	1.89	A2	21.2	1170**
S18	1.71	2.80	A2	20.8	1194
S19	1.71	1.89	A1	15.2	898
S20	1.71	1.89	A3	25.6	1192
S21	1.71	1.89	A4	33.2	1400
S22*	2.25	1.04	A2	23.1	18.4 MN

* $\phi 85\times270$cm sized
** free expansion of concrete: Ex.=2700x10^{-6}

Table 3 Experimental program in tied column test and its results

Unit No.	P=Ast/Ac (%)	Ph=Phoe/Ac (%)	Concrete	f'c (MPa)	N'ou (KN)
H1	0.68	0.41	N3	33.7	1373
H2	1.35	0.41	N3	33.7	1398
H3	2.03	0.41	N3	33.7	1516
H4	3.80	0.41	N3	33.7	1683
H5	1.35	0.27	N3	32.0	1348
H6	1.35	0.41	N3	32.0	1398
H7	1.35	0.82	N3	32.0	1441
H8	1.35	1.37	N3	32.0	1571
H9	1.35	0.41	N1	14.5	755
H10	1.35	0.41	N2	24.0	1130
H11	1.35	0.41	N4	43.4	1816
H12*	1.69	0.29	N3	32.9	19.4 MN
H13	0.68	0.41	A2	22.4	1128
H14	1.35	0.41	A2	22.4	1165
H15	2.03	0.41	A2	22.4	1187
H16	3.80	0.41	A2	22.4	1351
H17	1.35	0.27	A2	20.2	1081
H18	1.35	0.41	A2	20.2	1124
H19	1.35	0.41	A2	19.2	1120**
H20	1.35	0.82	A2	20.2	1185
H21	1.35	0.82	A2	19.2	1281**
H22	1.35	1.37	A2	20.2	1269
H23	1.35	0.41	A1	16.5	915
H24	1.35	0.41	A2	20.7	1149
H25	1.35	0.41	A3	28.8	1493
H26	1.35	0.41	A4	36.8	1818
H27*	1.69	0.29	A3	23.1	16.7 MN

* $75\times75\times240$cm sized
** free expansion of concrete: Ex.= 2500x10^{-6}

at free expansion came up to about 3000μ. Axial and transverse strain of concrete surface and of reinforcing bars and displacement of the columns at each applied load stage were measured. Initial strain of reinforcing bars of ASR concrete columns before loading were also measured.

RESULTS AND DISCUSSION

Ultimate load bearing capacity of column

Ultimate load bearing capacity (N'ou) of each column and compressive strength of concrete at the time of column tested are in table 2 and 3. Hoop reinforcement ratio (Ph) in the Table 3 is defined as follows:

$$Ph = Ahoe / Ac = As \cdot L / s / Ac \quad (1)$$

where Ph = hoop reinforcement ratio (%)
Ahoe = effective area of hoop reinforcement (cm^2)
As = area of hoop bar (cm^2)
L = one hoop length (cm)
s = pitch of hoop reinforcement (cm)
Ac = total area of concrete (cm^2)

Compressive strengths of ASR concretes are 35 to 50% lower than those of normal concretes at the same water-cement ratio. Reduction in ultimate load of ASR affected columns, however, are 1 to 25%. Especially, when columns have adequate transverse reinforcement, the reduction ratio does not increase, even if the expansion of concrete is larger. The reduction ratio of nearly full-size spiral column is small as 5%.

The relationship between compressive strength and ultimate load of column is shown in Fig.1. Ultimate load is almost proportional to compressive strength. Ultimate loads of ASR affected concrete columns are 5 to 30% higher than those of normal concrete column at the same compressive strength.

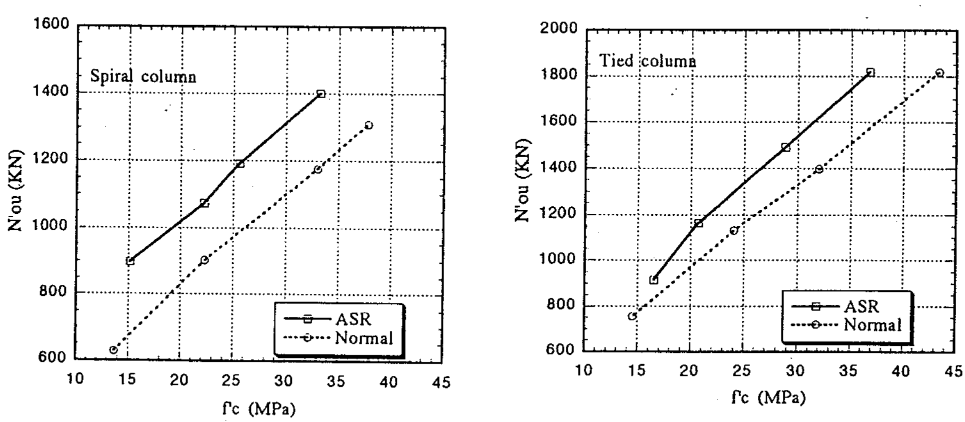


Fig.1 Effect of f'c on N'ou of column

Displacement of column

Typical examples of applied load versus strain curve of columns are shown in Fig.2. Strains of ASR concrete columns at a certain load are higher than those of normal concrete columns. As the Young's modulus of ASR concrete is remarkably decreased, strains become high. Consequently, displacement of the columns at a certain load are larger than those of normal concrete column. When columns have adequate transverse reinforcement, however, the ductility of ASR concrete columns is higher than that of normal concrete columns, as shown in Fig.3.

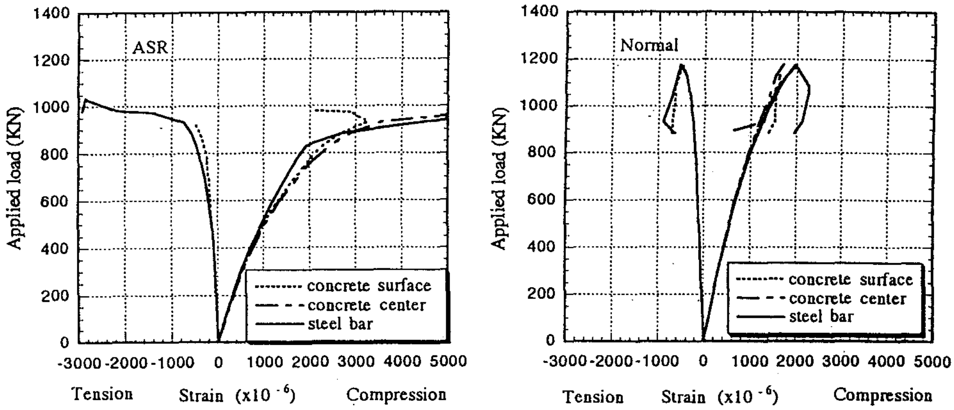


Fig.2 Typical examples of applied load versus strain curve

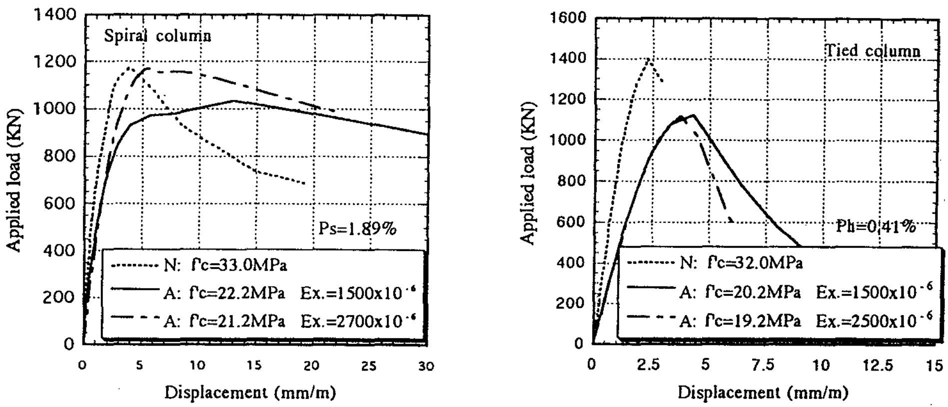


Fig.3 Effect of expansion of concrete on applied load versus displacement

Stress-pass of core concrete

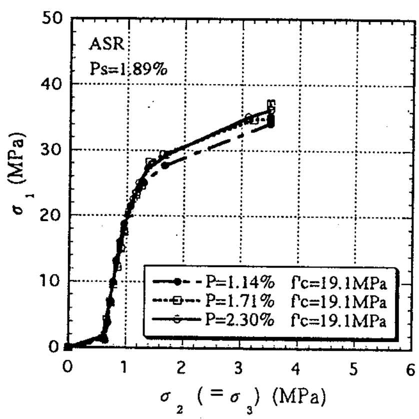
Confining stress σ_2 $(=\sigma_3)$ to be generated in circular core concrete of spirally reinforced columns, is given as follows:

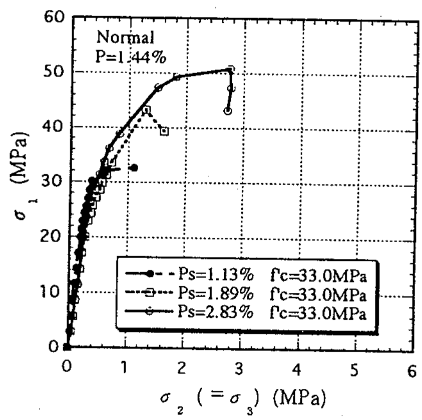
$$\sigma_2 = (2 As \cdot \sigma_{sp}) / (s \cdot De) \tag{2}$$

where As = area of spiral reinforcement (cm^2)
σ_{sp}= stress of spiral reinforcement (MPa)
s = pitch of spiral reinforcement (cm)
De = effective diameter of spirally reinforced concrete column (cm)

Stress of spiral reinforcement (σ_{sp}) is determined by strains of spiral reinforcement as shown in Fig.2 and Young's modulus of steel. On the other hand, axial stress of core concrete σ_1 can be calculated as follows:

$$\sigma_1 = (N'_o - N'_s - N'_{cover}) / (\pi De^2 / 4) \tag{3}$$





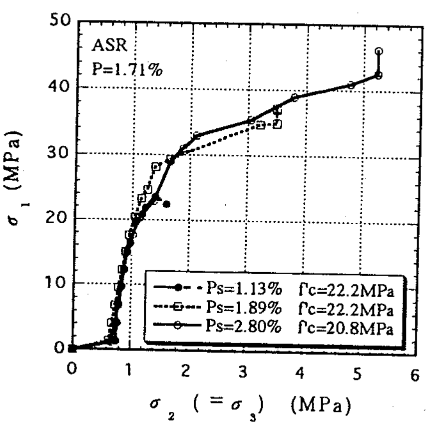


Fig.4 Stress-pass of core concrete

where N'o = applied load (N)
N's = share of load by axial reinforcement (N)
N'cover = share of load by cover concrete (N)

N's is obtained by strains of axial reinforcement, Young's modulus and total area. N'cover is calculated by stress-strain curve which is determined with plain concrete column and area of cover concrete.

As shown in Fig.4, σ_1 increases with σ_2 ($=\sigma_3$) for ASR concrete column. Substituting yield strength of spiral reinforcement (f_{spy}) for σ_{sp} in equation (2), the maximum confining stress σ_{2max} can be obtained for this case. Stress-pass of normal concrete starts from origin, but for ASR concrete a sharp breakpoint is observed at about 2 MPa of axial stress and 0.6 to 0.8 MPa of confining stress. This may be caused by the initial stress in ASR concrete before loading. Stress-pass is hardly affected by axial reinforcement ratio (P) and σ_{2max} increases with spiral reinforcement (Ps), so that σ_{1max} increases with Ps. In normal concrete columns, however, increments of σ_1 are smaller than those of ASR concrete column, at the same Ps since σ_2 does not reach to σ_{2max}. Consequently, N'ou of ASR concrete columns becomes higher than those of normal concrete columns at the same compressive strength of concrete (Fig.1).

Three dimensional stress of column

Confining stress of concrete in tied column cannot be obtained easily. Three dimensional stress diagram which express transverse reinforcement stress (σ_{sp} or σ_{sh}), axial reinforcement stress (σ_s) and axial concrete stress (σ_1) is devised (Fig.5). Axial stress of core concrete of tied column is calculated as : $\sigma_1 = (N'_o - N'_s) / A_c$.

In normal concrete columns, stress of axial reinforcement reaches to the yield value before that of transverse reinforcement does. Prior to loading, on the other hand, the initial tensile stresses are generated in reinforcements of ASR affected columns. At 1500μ of concrete expansion, axial reinforcement yields before transverse

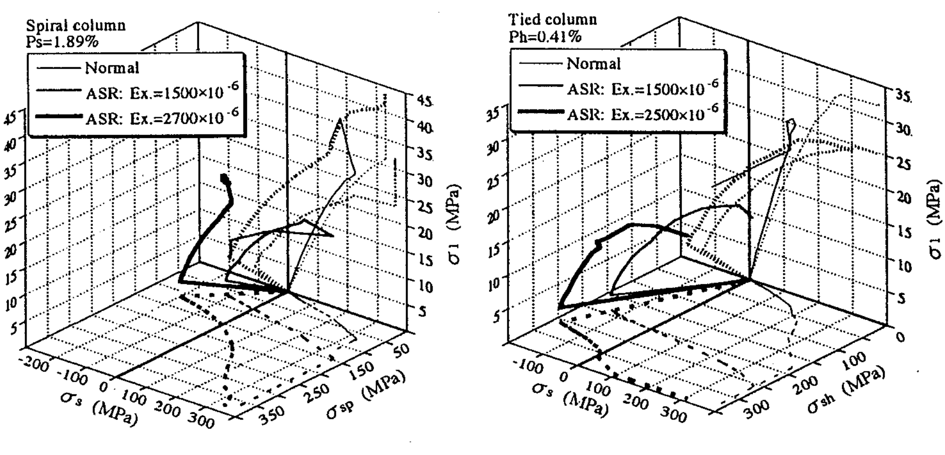


Fig.5 Three dimensional stresses of different expansion of concrete

reinforcement yields. Stress of transverse reinforcement σ_{sp} or σ_{sh} of ASR columns is larger than that of normal columns. Consequently, confining stress becomes higher at the time of yielding of axial reinforcement. At 2700μ of expansion, when columns have adequate transverse reinforcement, axial and transverse reinforcement yield almost at the same time. When columns have small transverse reinforcement, however, transverse reinforcement yields before axial reinforcement yields. In this case, confining stress does not increase more, so the ultimate load bearing capacity of the column does not increase thereafter.

Performance of nearly full-scale test specimen

Applied load versus displacement curve of nearly full-scale column is shown in Fig.6. Displacement of ASR affected columns after the ultimate load, is larger than that of normal concrete column. The ductility of the columns is improved by ASR. As for

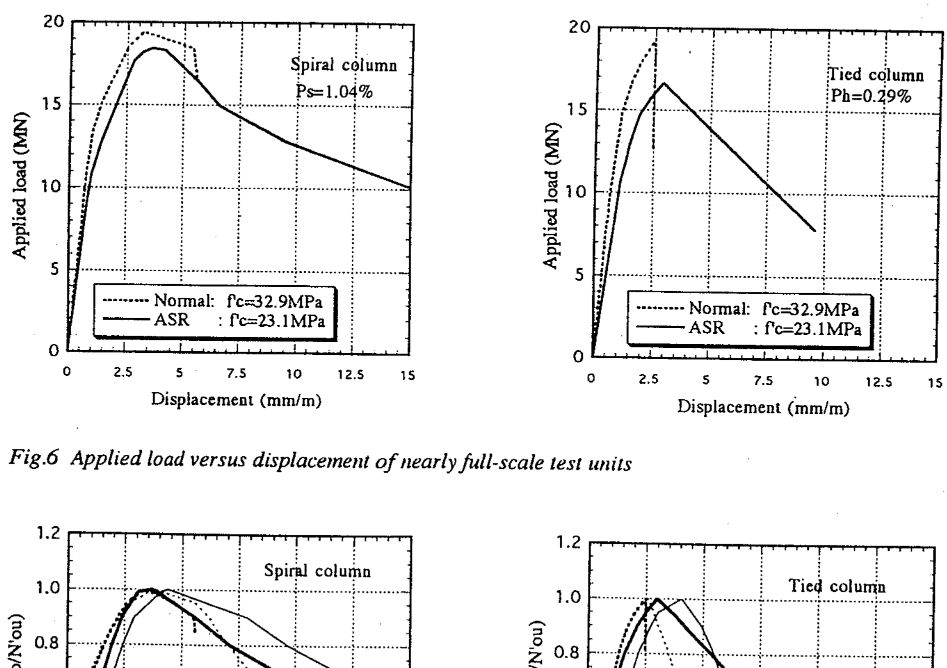


Fig.6 Applied load versus displacement of nearly full-scale test units

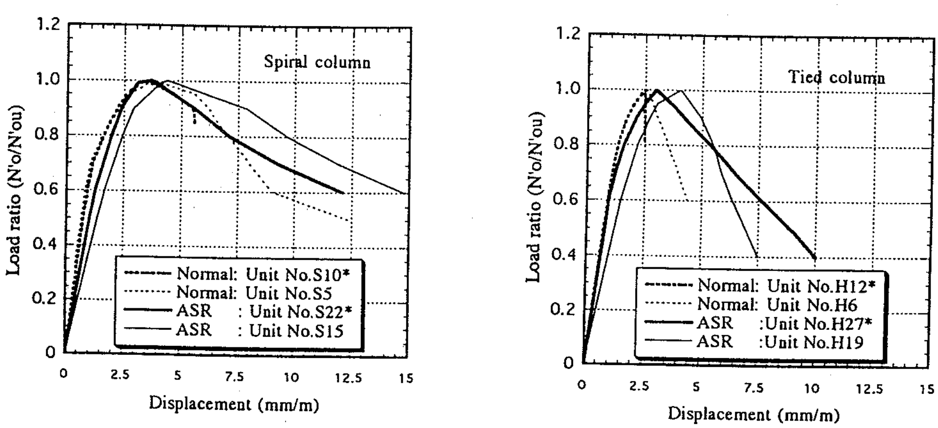


Fig.7 Effect of test unit size on load versus displacement

tied column of normal concrete, corner of hoop reinforcement is fractured in a brittle manner and load is suddenly decreased.

In normal concrete column, load ratio versus displacement curve is about the same regardless of test specimen size. Also it is clear that load ratio corresponding to the same displacement is higher for ASR affected column than that of normal concrete column. In ASR affected column, however, displacement of nearly full-sized column is smaller than that of small size test unit, as shown in Fig.7.

CONCLUSIONS

Conclusions are summarized as follows within the scope of the experimental works.

(1) The ductility of reinforced concrete column is improved by ASR.

(2) Initial tensile stress before loading in axial reinforcement due to expansion of concrete is profitable for load bearing capacity of columns, because a part of compressive stress caused by external force is off-set.

(3) Prior to loading, confining stress (σ_2) is generated in ASR affected core concrete. When columns have adequate transverse reinforcement, σ_2 is higher than that of normal concrete at the final loading stage, then the ratio of σ_1 to f'_c of ASR concrete is higher than that of normal concrete. Accordingly, reductions in ultimate load bearing capacity of ASR affected columns are 1 to 20%, though the compressive strength of concrete is reduced 35 to 50% by ASR at the same water-cement ratio. When columns have small transverse reinforcement, however, transverse reinforcement yields before axial reinforcement yields, so that σ_1 is not so increased. In those cases, ultimate load bearing capacity of columns is about 30% lower than that of normal concrete column.

(4) Ultimate load bearing capacity of ASR affected columns is 5 to 30% higher than that of normal concrete column at the same compressive strength.

(5) Larger the size of test specimun, effect of ASR on mechanical characteristics of reinforced concrete column becomes smaller.

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