INFLUENCE OF ASR EXPANSION ON MECHANICAL PROPERTIES OF CONCRETE DETERIORATED BY ASR

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Abstract

Recently, in Japan, alkali-silica reaction (ASR) deteriorated concrete structure, which has reduction of compressive strength in inside concrete and occurrence of yield and/or rupture of steel bar due to excessive alkali-silica expansion, have been reported. Therefore, a rehabilitation technique, which is appropriate to repair and to strengthen for the severely deteriorated concrete structure, is very important in concrete maintenance engineering.

On the other hand, in Japan, the environmental condition is very severe for concrete structures influenced by ASR, since a lot of chloride ions are supplied from seawater and de-icing salts. Furthermore, ASR and ASR expansion in concrete structures is very complicated and varies, since many types of reactive aggregates which are composed of many types of rocks are used. In Japan, in-depth data of mechanical properties of concrete deteriorated by various levels of ASR expansion is not arranged for strengthening design and maintenance.

In this study, mechanical properties (compressive strength, Young's module, Poisson's ratio and deformation properties) of concrete specimens with various expansion levels caused by ASR were investigated. As the results, it is clear that the influence of expansion on the compressive strength of ASR deteriorated concrete was not significant. However, deformation properties of ASR deteriorated concrete were significantly influenced by ASR expansion.

Keywords: ASR, expansion, water cement ratio, mechanical properties, deformation properties

1 INTRODUCTION

Recently, some concrete structures deteriorated by excessive ASR (Alkali Silica Reaction) expansion have been reported in Japan [1]. In these concrete structures, the reduction of the compressive strength in inside concrete and the occurrence of yield and rupture of steel bar have been found. In previous studies [2,3], bearing capacity of ASR deteriorated concrete member was not influenced by ASR expansion, since ASR expansion is largely restrained by steel bars arranged in concrete members. Thus, a repair has been applied to control ASR expansion for these deteriorated concrete members.

On the other hand, in Japan, strengthening was carried out in some case where the reduction of compressive strength of inside concrete and the rupture of steel bar occurred [4,5,6,7]. Therefore, in Japan, the rehabilitation technique, which is appropriate to repair and strengthen for the severely deteriorated concrete structure, is very important in concrete maintenance engineering. In addition, diagnosis and assessment method for bearing capacity of these deteriorated concrete structure should be established as soon as possible.

Numerical data of mechanical properties of ASR deteriorated concrete are not enough to design and to select a strengthening method, although some studies for mechanical properties of ASR deteriorated concrete with aggregate used in Japan have been carried out. In other countries, mechanical properties of ASR deteriorated concrete (compressive strength, tensile strength and Young's modulus) have been studied by some researchers. Lower bounds to residual mechanical properties of ASR deteriorated concrete were suggested on the basis these research [8,9]. The

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applicability of the lower bounds of ASR deteriorated concrete for reactive aggregate used in Japan was not clear.

Therefore, in this study, mechanical properties (compressive strength and Young's modulus) of ASR deteriorated concrete with reactive aggregates used in Japan were investigated. Furthermore, deformation property of ASR deteriorated concrete in axial loading was investigated.

2 MATERIALS AND METHODS

2.1 General

In this study, experiments consisted of two experiment series. In **Series 1**, the influence of ASR expansion on the mechanical properties of ASR deteriorated concrete was investigated. In **Series 2**, the influence of ASR expansion on the mechanical properties of deteriorated concrete with various water cement ratio was investigated. The mechanical property of ASR deteriorated concrete was measured by uniaxial compression test in both Series.

2.2 Materials and mixture proportion of concrete

Ordinary Portland cement (density: 3.16 g/cm3 in Series 1, 3.00 g/cm^3 in Series 2, respectively) were used. Fine non-reactive aggregates (density: 2.61 g/cm^3 in Series 1, 2.64g/cm^3 in Series 2, respectively) were used.

Coarse aggregate as reactive aggregate (density: 3.16 g/cm^3, Gmax: 20 mm) was used. Another coarse aggregates as non-reactive aggregate (density: 2.61 g/cm^3 in Series 1, 2.64g/cm^3 in Series 2, respectively) were used. Reactive aggregate content were mixed with the pessimum weight ratio (reactive/non-reactive = 6:4).

W/C of concrete mixture selected in the Series 1 was 65%. In the Series 2, 65% and 45% were selected to investigate the influence of the ASR expansion on the mechanical properties of ASR deteriorated concrete with the different water cement ratio. NaCl was added to adjust the alkali content of the concrete that was 8 kg/m^3 as Na_2O_{eq}. Mixture proportion of concrete used in the both Series is shown in Table 1.

2.3 Experimental factor

Deterioration level (ASR expansion)

Six levels (0, 500, 1000, 2000, 3000, 5000-μ) of ASR expansion were prepared to investigate the change of the mechanical properties of ASR deteriorated concrete where the concrete were expanded by ASR in the Series 1. And three levels (0, 2000, 5000-μ) were prepared in the Series 2. In the Series, the influence of the compressive strength level on the mechanical properties of ASR deteriorated concrete was mainly investigated. In this study, maximum expansion of concrete was 3000μ in the experiment term and the investigation was carried out within the range of ASR expansion.

Compressive strength level of concrete

The influence of ASR expansion on the mechanical properties of ASR deteriorated concrete can be affected by compressive strength level of an original concrete. In the Series 2, two types of compressive strength of concrete were prepared for the above reason. One type of concrete (normal strength level) was designed to correspond with RC structure and water cement ratio of this type concrete was 65%. In addition, another type of concrete was designed to correspond with PC structure and water cement ratio of this type concrete (high strength level) was 45% by weight.

Acceleration condition of ASR

In the Series 1, concrete specimens were exposed in 40°C/NaCl saturated solution to accelerate ASR expansion and to obtain a large expansion at a shot term. In the Series 2, concrete specimens were exposed in 40°C/100% RH atmosphere (wet and high temperature).

Experimental conditions are summarized in Table 2.

2.4 SPECIMENS

The size of the concrete specimen was Ø100 × 200mm. The concrete specimens were cast and were demoulded after one day. And, the specimens were cured at wet condition (20°C) for two weeks.

After the curing of specimens, contact gauge tips were attached to measure the ASR expansion of the specimen (see Fig. 1). And, these specimens were exposed in each of acceleration condition where ASR expansion was accelerated. The mechanical properties of the specimen, where the expansion level was attained at a prescribed expansion level (as above mentioned in 2.3), were tested by uniaxial compression test.

2.5 UNIAXIAL LOADING TEST

Uniaxial compression test was performed at the prescribed expansion level and load, displacement and strain (axial and lateral direction) of specimen was measured. And, compressive strength, Young's modulus, Poisson's ratio and strain obtained at maximum load was determined from uniaxial compression test. Load was measured by load cell (loading capacity: 500 kN) and the axial deformation was measured by high sensitive displacement gauge (capacity: 5mm and 10mm). The axial and lateral strains of concrete were measured by strain gauge attached to specimen. Poisson's ratio was determined at two load levels (33% and 90% of maximum load). Since Elastic behavior of a sound concrete was kept at Low load level (33%), Poisson's ratio was determined at low load level (33%). On the other hand, Poisson's ratio was measured to investigate the deformation property of ASR deteriorated concrete at the near maximum load.

3 RESULTS AND DISSCUSSION

3.1 INFLUENCE OF ASR EXPANSION (SERIES 1)

Compressive Strength

The relationship between ASR expansion and compressive strength of concrete is shown in Fig. 2. Compressive strength of concrete was not significantly affected by ASR expansion, although compressive strength of concrete was slightly reduced according to ASR expansion (up to 3000μ). Size and direction of cracks caused by ASR expansion were not a uniform state and various size of crack which ranged from macro to micro cracks were formed in ASR deteriorated concrete. It is considered that a connection of cracks caused by ASR expansion in the concrete specimen is not enough to affect the compressive strength of concrete as far as ASR expansion extends in the experiment term, although multiple cracks due to ASR expansion were complexly connected together in the concrete specimen. Therefore, it is clear that the influence of ASR expansion on compressive strength of concrete is not significant in the experiment term when the maximum ASR expansion is about 3000μ.

In the previous studies carried out in other countries, it was reported that compressive strength of ASR deteriorated concrete was reduced up to 60% of sound concrete [2,3]. In their studies, the compressive strength of concrete was gradually reduced as the expansion of concrete progressed. The tendency of reduction of concrete strength due to ASR expansion is different between this study and the previous ones. In this study, the curing time of the specimen before the acceleration of ASR was 2 weeks. It may not be enough to develop compressive strength of concrete. For this reason, the hydration of the concrete specimens may be promoted due to the acceleration conditions (high temperature and high humidity) and the compressive strength of concrete may be increased in the initial exposure. Therefore, the relationship between compressive strength and ASR expansion shifted to the upper side at the initial stage. The reduction of the compressive caused only by ASR may be gradually reduced after the exposure to the acceleration conditions. It is concluded that the tendency obtained in this study was not different from that of previous studies and that the compressive strength of concrete is gradually reduced by ASR expansion. However, the influence of ASR expansion on the compressive strength of concrete was small compared to the previous study during all the experiment term (3000μ). It is needed to investigate the influence of further ASR expansion on the compressive strength of concrete by extending the experimental period.

Young's modulus

The relationship between ASR expansion and Young's modulus of concrete is shown in Fig. 3. The reduction of Young's modulus of concrete was 60% at about 1000μ of ASR expansion. Young's modulus of concrete according to ASR expansion was rapidly reduced by an initial ASR expansion (up to about 1000μ). After the initial ASR expansion, Young's modulus of concrete was slightly and slowly reduced according to ASR expansion. In Japan, it has been reported that the reduction of Young's modulus of concrete taken from ASR deteriorated concrete structure was much smaller than the reduction of its compressive strength [4]. In the previous studies carried out in other countries, it has been reported that the reduction of Young's modulus of concrete according to ASR expansion was large at the initial ASR expansion and that it was slightly and slowly reduced according to ASR expansion before the initial ASR expansion. It is considered as the mechanism of the reduction of Young's modulus of concrete due to ASR expansion that multiple micro cracks induced by ASR expansion make concrete easy to deform and then make Young's modulus of concrete decreased.

Therefore, the reduction of Young's modulus of concrete was significant at initial ASR expansion stage, since the micro crack due to ASR expansion propagated even at initial ASR expansion.

Although the reduction of Young's modulus of concrete due to initial ASR expansion in this study was much larger than found in previous studies. The hydration of concrete was not enough at initial ASR expansion and then the influence of ASR expansion on the Young's modulus in this study may be larger than that in previous studies. Or ASR gel and cracks propagation caused by ASR with the reactive aggregate used in this study may be different from with other reactive aggregate. It is not clear the reason why the reduction of Young's modules caused by ASR expansion is very large in this study. Further research work is needed to clear this reason.

Poisson's ratio

The relationship between ASR expansion and Poisson's ratio of concrete is shown in Fig. 4. Poisson's ratio was calculated from the stress-strain curves obtained by the uniaxial loading test as an index of deformation properties of ASR deteriorated concrete, since it was expected that the deformation properties of ASR deteriorated concrete were different from sound concrete judging by load-displacement curve obtained by the uniaxial test [8]. Poisson's ratio was calculated at 33% and 90% of maximum load to investigate the deformation properties of concrete around maximum load where its property of ASR deteriorated concrete were expected to be significant different from that of sound concrete.

In their Poisson's ratios at 33% of maximum load obtained by various specimens (expansion: 0-3000μ), their Poisson's ratios were not changed by ASR expansion and their values of sound and ASR deteriorated concrete were almost the same. On the other hand, in their Poisson's ratios at 90% of maximum load, Concrete of the larger ASR expansion showed the larger Poisson's ratio.

In a low load level, the lateral deformation of ASR deteriorated concrete was not much larger than the axial deformation, although an axial deformation of ASR deteriorated concrete was very large. As the result, in the low load level, Poisson's ratio of ASR deteriorated concrete has almost the same value of sound concrete regardless of showing larger deformation of ASR deteriorated concrete at same load level.

In the high load level, micro and macro crack were complexly connected together according to the crack propagation and the crack extension due to ASR expansion. Therefore, it is considered that connection of crack in various size makes lateral deformation of concrete easy and that Poisson's ratio of ASR deteriorated concrete at high load level is decreased according to extension of ASR expansion. On the other hand, in the low load level, it is considered that lateral deformation of ASR deteriorated concrete is larger than sound concrete since ASR deteriorated concrete has a smaller Young's modulus of concrete than that of sound concrete.

Deformation at maximum load (axial and lateral strain)

The relationship between ASR expansion and strain (axial and lateral) of concrete at maximum load is shown in Fig. 5. It was clear that deformation resistance of concrete was largely changed and was reduced by ASR expansion as the results shown in the above results (Young's modulus and Poisson's ratio). And, comprehensive relationship between stress and strain of ASR deteriorated concrete is necessary to design and to select a strengthening method. In this study, axial and lateral strains at maximum load were investigated to help the modeling of strain-stress curve of ASR deteriorated concrete in the future.

Both strains of ASR deteriorated concrete with the larger ASR expansion showed the larger value. Not only deformation properties (Young's modulus and Poisson's ratio) were changed by ASR expansion, but also axial and lateral deformations of concrete were increased by ASR expansion. It is considered that cracks and its connection caused by ASR expansion make deformation of concrete easy and that the tendency is more significant in the larger ASR expansion. This phenomenon is expected to contribute confined effect of concrete. For example, in ASR deteriorated concrete structure that has low deformation resistance, a buckling of an axial steel bar arranged at the compression part of beam and column member may be easily occurred when large load is applied. It should be noted that it is necessary to make consideration about this phenomenon for selecting and designing the strength method of ASR deteriorated concrete structure.

3.2 INFLUENCE OF STRENGTH LEVEL OF CONCRETE WITH DIFFERENT WATER CEMENT RATIO (SERIES 2)

Compressive Strength

The relationship between ASR expansion and compressive strength of concrete with various water cement ratio (W/C: 60% and 45%) is shown in Fig. 6. Regardless of water cement ratio, compressive strength of concrete was not affected by ASR expansion, although compressive strength of concrete was slightly reduced according to ASR expansion. It is considered that the influence of ASR expansion on the compressive strength of concrete was not significant in the small ASR expansion level (up to 1000 μ) regardless of water cement ratio. As above mentioned (Series 1), it is needed to investigate the influence of further ASR expansion on the compressive strength of concrete by continuing the experiment.

Young's modulus

The relationship between ASR expansion and Young's modulus of concrete with various water cement ratio (W/C: 60% and 45%) is shown in Fig. 7. Regardless of water cement ratio, a reduction of Young's modulus of concrete was almost the same. On the other hand, after ASR expansion, Young's modulus of concrete with 45% of W/C was higher than that of concrete with 65% of W/C. It is considered that concrete with low water cement ratio, that has essentially cement matrix of high strength, has different resistance for crack induced by ASR expansion and the propagation of macro crack is restrained. The resistance of concrete with lower water cement ratio may be larger than that of concrete with higher water cement ratio. However, further research work is needed since data of Young's modulus of concrete with low water cement ratio are not enough.

Poisson's ratio

The relationship between ASR expansion and Poisson's ratio of concrete with various water cement ratio is shown in Fig. 8. Regardless of water cement ratio, at 33% of maximum load obtained by various ASR expansion of concrete, their Poisson's ratios were not changed by ASR expansion, and their value of sound and ASR deteriorated concrete were almost the same. On the other hand, in their Poisson's ratios at 90% of maximum load, concrete of the larger ASR expansion showed the larger Poisson's ratio regardless of water cement ratio. It is considered that Poisson's ratio is affected by ASR expansion regardless of water cement ratio.

Deformation at maximum load (axial and lateral strain)

The relationship between ASR expansion and strain (axial and lateral) of concrete with various water cement ratio at maximum load is shown in Fig. 9. Regardless of water cement ratio, both strain of ASR deteriorated concrete with the larger ASR expansion showed the larger value. In the axial direction, an increase of strain of concrete caused by ASR had the same tendency regardless of water cement ratio. On the other hand, in the lateral direction, increment of strain of concrete of 45% of W/C was larger than that of concrete of 65% of W/C, although the value of lateral strain of concrete obtained by compression test varies widely.

In the same load level, stress level of concrete with low water cement ratio was higher than that with high water cement ratio since compressive strength of concrete with lower water cement ration was higher than with higher water cement ratio. And, in concrete with low water cement ratio, high stress was worked. Therefore, it is considered that the influence of cracks and its connection caused by ASR expansion on lateral deformation at a breakdown of concrete is higher in concrete with lower cement ratio. It is noted that the properties of deformation of concrete with low cement should be reflected to estimation of performance of ASR deteriorated concrete structure and to the design and the selection of their strengthening method.

4 CONCLUSIONS

The main results obtained by this study comprise:

- The compressive strength of concrete is gradually reduced due to ASR expansion and this tendency is almost the same regardless of water cement ratio.
- The reduction of Young's modulus of concrete caused by ASR expansion is significant in the initial ASR expansion (1000μ). After initial ASR expansion, Young's modulus of concrete is slightly and slowly reduced. This tendency is almost the same regardless of water cement ratio. It is not clear the reason why the reduction of Young's modules caused by ASR expansion is very large in this study.

- ASR expansion affects significantly on the deformation properties. Poisson's ratio of concrete around a maximum load was increased by ASR expansion and this tendency is promoted according to ASR expansion. Furthermore, the both strain (axial and lateral) of concrete at the maximum load is extended by ASR expansion.
- It is also noted that the property of deformation of concrete with low cement should be reflected to estimation of performance of ASR deteriorated concrete structure and to the design and the selection of their strengthening method.

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Table 1: Mixture Proportion

	W/C	Unit (kg/m^3)						
	(%)	W	C	S	Gr	G	Admix1	Admix2
Series 1	60	180	300	781	579	386	0.6	0.02
Series 2	60	180	300	803	581	387	0.6	0.02
	45	180	400	763	554	370	0.6	0.02
Gr：reactive aggregate, G：non-reactive aggregate Admix1：AE water reducing admixture, Admix2：AE admixture								

Table 2: Experiment specifications

	ASR expansion	W/C (%)	Acceleration condition of ASR
Series 1	6 levels (0, 500, 1000, 2000, 3000, 5000-μ)	60	40°C/NaCl saturated solution
Series 2	3 levels (0, 2000, 5000-μ)	60/45	40°C/100%R.H. atmosphere (wet and high temperature)

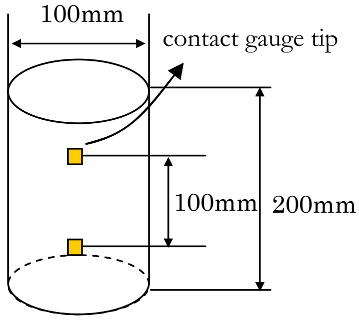

Fig. 1　Specimen dimensions

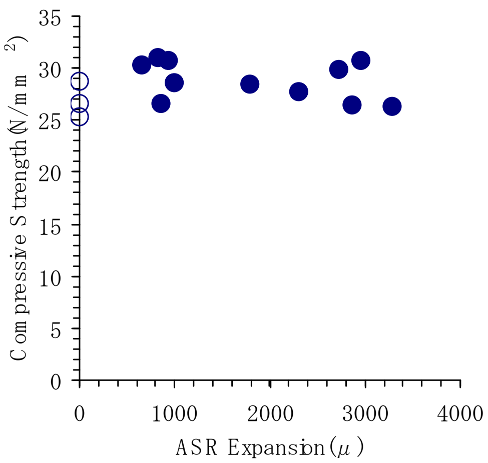

Fig. 2　Relationship between ASR expansion and compressive strength

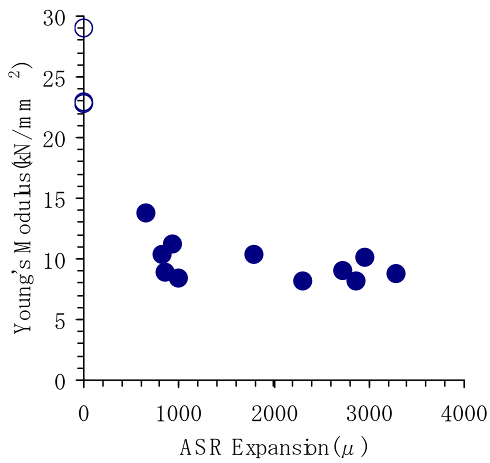

Fig. 3　Relationship between ASR expansion and Young's modulus

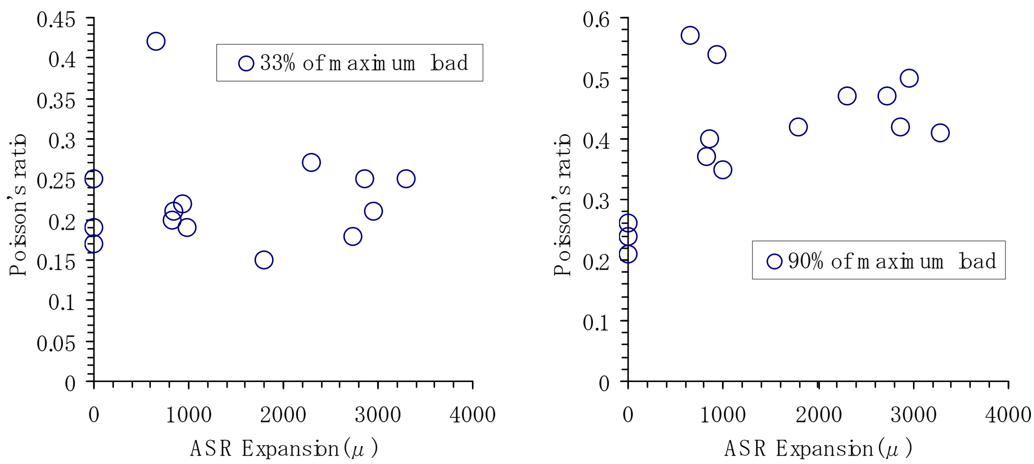

Fig. 4　Relationship between ASR expansion and Poisson's ratio

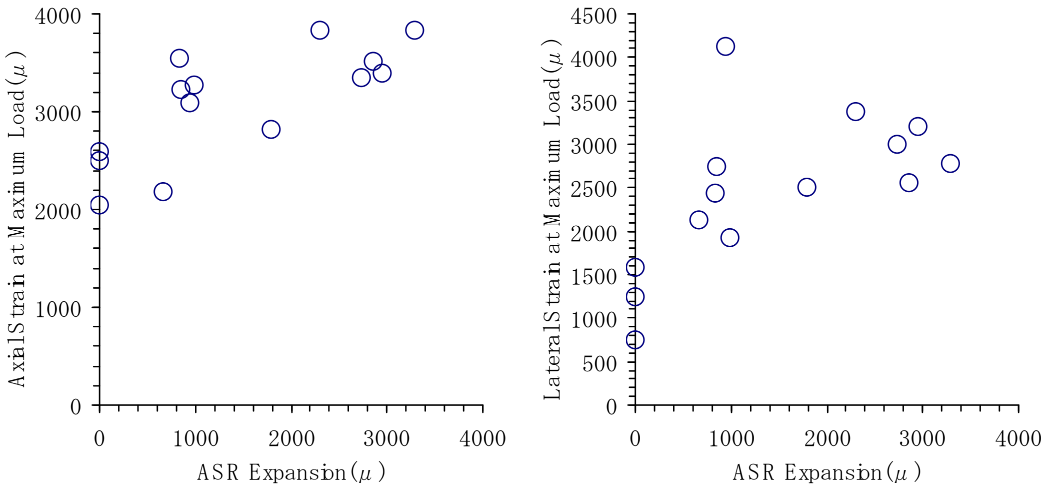

Fig. 5 Relationship between ASR expansion and strain at maximum load

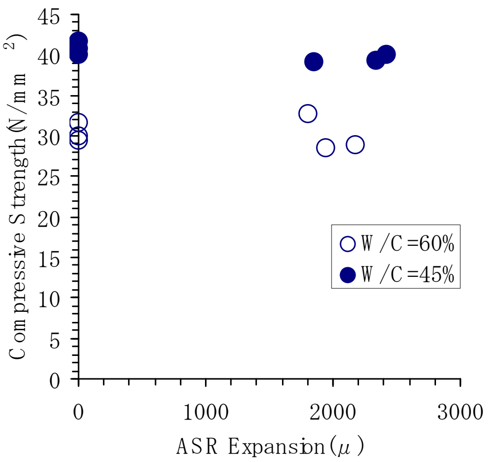

Fig. 6 Relationship between ASR expansion and compressive strength of concrete with different water cement ratio

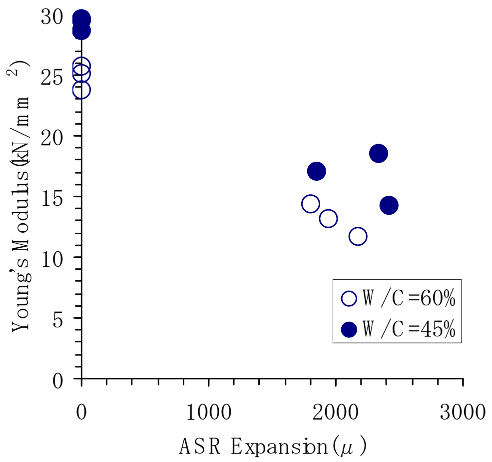

Fig. 7 Relationship between ASR expansion and Young's modulus of concrete with different water cement ratio

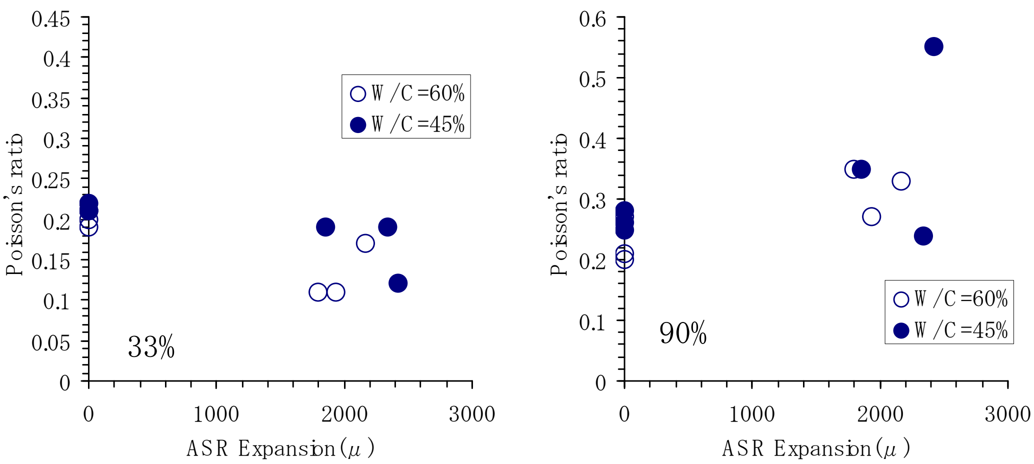

Fig. 8 Relationship between ASR expansion and Poisson's ratio of concrete with different water cement ratio

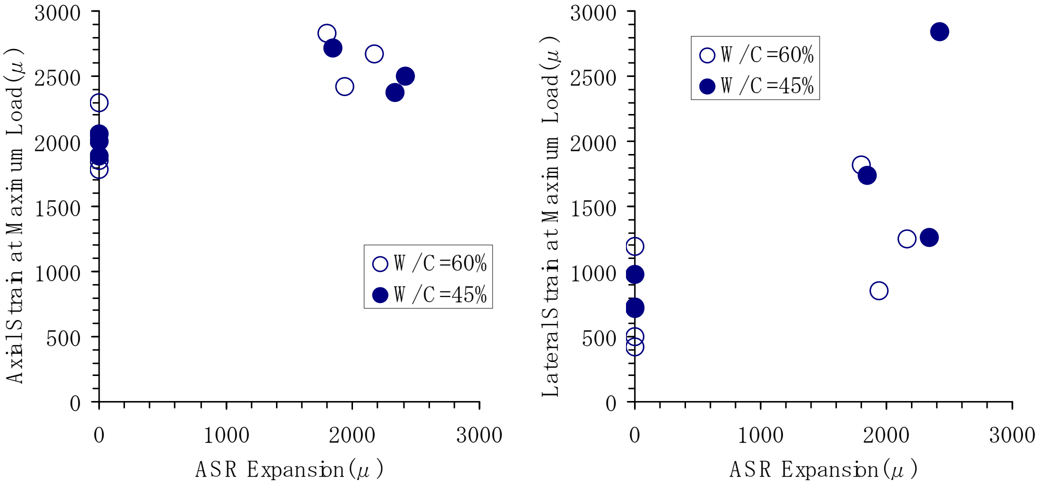

Fig. 9 Relationship between ASR expansion and strain (axial and lateral) of concrete with different water cement ratio