EFFECT OF TYPES OF REACTIVE AGGREGATE ON MECHANICAL PROPERERTIES OF COCNRETE AFFECTED BY ALKALI-SILICA REACTION

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Abstract

Recently, in Japan some concrete structures deteriorated severely by Alkali silica reaction have been reported. Those concrete structures had a reduction of compressive strength in inside concrete and occurrence of breaking down of steel bar at bending part due to excessive ASR expansion. ASR and its expansion in concrete structures are very complicated. In Japan, mechanical data of ASR affected concrete with different type of reactive aggregate and with different ASR expansion levels is not arranged for strengthening design and maintenance.

In this study, mechanical properties of ASR affected concrete specimens with various type of reactive aggregate and were investigated in order to clear the influence of reactive aggregate. As the results, it is clear that the influence of types of reactive aggregate on the compressive strength of ASR affected concrete is not significant. However, deformation properties of ASR affected concretes depend on the type of reactive aggregate.

Keywords: Alkali-silica reaction, expansion, mechanical properties, deformation properties, Andesite, Chart

1 INTRODUCTION

The influence of ASR on the mechanical properties of deteriorated concrete members has been reported to be insignificant by many researchers when these ASR expansions in concrete member were appropriately confined by steel bar arranged in these concrete members. Recently, in Japan, some concrete structures severely deteriorated by Alkali silica reaction have been reported. Those concrete structures had a reduction in the compressive strength of inside concrete and the occurrence of breaking down of steel bar at a bending part due to excessive ASR expansion [1,2,3]. Therefore, a rehabilitation technique, which is appropriate to repair and to strengthen these severely deteriorated concrete structures, is very important. Also, it is important to establish the method to estimate the mechanical performance of these severely deteriorated concrete structures for properly executing the repair and strengthening. Mechanical data of ASR deteriorated concrete such as compressive strength, Young's modulus and stress-strain curve are needed to design the repair and/or strengthening. In Japan, mechanical data of ASR affected concrete with different types of reactive aggregates and with different ASR expansion levels is not available for strengthening design and maintenance. As an alternative approach, strengthening design was based on compressive strength and Young's modulus of ASR affected concrete obtained by concrete cores extracted from existing structure. In this case, these data included the size effect and the stress release, and these data were carefully used for strengthening design of ASR deteriorated concrete member in order to keep enough safety.

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In previous study on the effect of ASR expansion [4], where maximum ASR expansion was 0.7 % and Andesite was used as reactive coarse aggregate, a reduction of compressive strength of ASR affected concrete was not significant until ASR expansion attained at 0.3 % and a reduction of compressive strength of ASR affected concrete was about 30 % at 0.5 % of ASR expansion. Furthermore, on the influence of W/C, the influence of W/C of ASR affected concrete on compressive strength was not significant until maximum ASR expansion was 0.3 % [4]. In Europe, there were the recommendation data of the mechanical properties of ASR affected concrete that correspond to reduction of that caused by ASR expansion [5] and mechanical data of ASR affected concrete obtained by researchers were reviewed by L. A. Clark [6].

Andesite and chert were typical reactive aggregate in Japan. In previous study, the mechanical properties of concrete were investigated using above reactive aggregate and there were the difference in compressive strength and microstructure of ASR affected concrete. And also, it has been reported that the microstructure of ASR affected concrete was influenced by ASR expansion rate due to the different types of reaction and it resulted in different behavior of the mechanical property of ASR affected concrete [7]. Therefore, it should be clear that the influence of type of reactive aggregate on the mechanical property of ASR affected concrete.

In this study, three types of reactive aggregates (Andesite, Chert and river gravel that include reactive mineral) were selected as typical reactive aggregate in Japan. The effect of type of reactive aggregate on the mechanical properties of ASR affected concrete was investigated using above aggregates. In addition, the investigation was continued until ASR expansion extended to 0.8 %.

2 MATERIALS AND METHODS

2.1 General

ASR deteriorated concrete used with three types of reactive aggregates was prepared in order to investigate the influence of the type of reactive on the mechanical properties according to ASR expansion. The compressive test for these ASR deteriorated concrete was conducted at different expansion level as described later. Various mechanical parameters (compressive strength, Young's modulus, Poisson's ratio and strain at maximum stress) were calculated based on the data obtained in the compressive strength test.

2.2 Materials and mixture proportions

Normal Portland cement (density: 3.16g/cm^3) was used. River sand and River gravel (taken from the Tedori River) was used as non-reactive aggregate. Three types of coarse aggregates (Andesite (aggregate A), Chert (aggregate C) and reactive river gravel (aggregate R)) were selected and were used as a reactive coarse aggregate. In Japan, ASR in concrete was mainly caused by a reactive aggregate that contained frequently Andesite and Chert. The content of reactive aggregate in this reactive river gravel varied widely and concrete structures were severely damaged by ASR due to this aggregate when volume of reactive aggregate in concrete was at the pessimum ratio. These physical properties of these aggregate are shown in Table 1. Pessimum ratio of these reactive coarse aggregate were 100 %(A), 80 % (C) and 100 % (R), respectively. In addition, the volume of sand aggregate was kept at constant volume in every concrete mixture and the volume of total coarse aggregate (non-reactive and reactive) was same in every concrete mixture, since the critical stress as a fracture mechanics parameter was influenced by water cement ratio of concrete and the volume ratio of the sand and the coarse aggregate in concrete. For the same reason, water cement ratio was the same in every concrete mixture and water cement ratio of concrete was 55 % that is standard water cement ratio to make concrete structure durable in Japan. Concrete mixtures are shown in Table 2. NaCl was used as additional alkali and total equivalent alkali content of concrete was 8.0 kg/m^3.

2.3 Experimental parameters

Reactive aggregate

Expansion of concrete used with Andesite as reactive aggregate is faster than other reactive aggregate in Japan. ASR rim was formed around a reactive aggregate such as Andesite, since the reaction initiated near the surface of aggregate as shown in Figure. 1 (a). Andesite crushed stone (aggregate A) was used in this study as reactive coarse aggregate with faster reaction rate and larger expansion of ASR.

Content of reactive component in the reactive river gravel (aggregate R) depended on the sampling location. Therefore, this resulted in a variation of the alkali-silica reactivity of the reactive river gravel. Incidentally, in a previous study [1,2], it has been reported that the main reactive component of reactive river gravel used in this study was Andesite. This river gravel had a larger compressive strength than other crushed stone.

Reactive particles of Chert were included in the aggregate as shown in Figure. 1 (b). This results in a slow reaction rate and the expansion of concrete due to ASR. Chert crushed stone (aggregate C) was used in this study as reactive coarse aggregate with a slower reaction rate.

Alkali-silica reactivity of all reactive aggregate used in this study was judged as nocuous tested by chemical method (JIS A 1145). And, the alkali-silica reactivity of Andesite crushed stone and reactive river gravel was judged as harmful when tested by the mortar bar method (JIS A 1146).

Level of ASR deterioration

Three level of ASR deterioration (Initiation of ASR expansion stage, Crack propagation stage, and Excessive expansion stage) were selected to investigate the influence of ASR expansion on the mechanical properties of ASR affected concrete. Visible crack on the concrete surface was not caused by ASR during the initiation of ASR expansion stage and ASR expansion of the concrete specimen during this stage ranged from 0.03 % to 0.05 %. Secondly, during crack propagation stage, macro crack on the concrete specimens can be observed and ASR expansion of the concrete specimens was attained at around 0.3 %. Finally, during the excessive expansion stage, ASR expansion of concrete specimens was more than 0.5 %.

Additionally, concrete specimens that were cured at 20 ^{0}C under water were prepared. After curing, compressive loading test was done to determine the mechanical properties of the control specimen. Mechanical properties of the control specimen correspond to that of concrete without damage due to ASR expansion; ASR expansion of control specimen was assumed to be 0 %.

2.4 Preparation of specimen for loading test and acceleration method of ASR

Specimen

The size of concrete cylinder specimen was 100 mm in diameter, 200 mm in height. Three kinds of specimen was made using three types of reactive aggregates. One day after casting, the mold was removed and the concrete specimen to be tested was exposed under ASR acceleration condition at once. During ASR acceleration condition, concrete was immersed in a saturated 50 ^{0}C NaCl solution to promote ASR and to attain a large expansion within a short term. After the exposure to ASR acceleration condition, the expansion of concrete specimens was measured.

The compressive loading test was done to determine the mechanical properties of ASR deteriorated concrete when the expansion of each concrete was attained at the prescribed level of ASR deterioration.

Measurement of expansion of concrete specimen

Stainless bands with stainless balls were attached to concrete specimens to measure the expansion of concrete specimens before exposure of ASR acceleration condition (see Figure. 2). Expansion was measured using a contact gauge with 0.001 mm of accuracy (the base length was 100 mm). Measurement interval was every weeks before 100 days of the exposure under ASR acceleration condition and the intervals was every month after 100 days of the exposure.

2.5 Compressive loading test for concrete specimen

Uniaxial loading test was done when prescribed expansion of concrete specimen was attained. Load, displacement, and strain (in both axial and lateral direction) was measured by load cell, displacement gauge and strain gauge attached on the concrete surface, respectively. The maximum capacity of the load cell was 500 kN. Accuracy of displacement gauge was 0.001 mm. Base length of strain gauge was 60 mm. Compressive strength, Young's modulus, Poisson's ratio, Critical stress and axial and lateral strain at Maximum load were calculated from the data obtained in uniaxial compressive loading test.

3 RESULTS

3.1 Expansion behavior

The expansion behavior of the specimen is shown in Figure 3. The expansion Specimen used with aggregate A and aggregate R started about 20 days after exposure. The expansion of specimen used with aggregate C started about 80 days after exposure. ASR expansion rate of aggregate A and R was generally fast, since ASR of these types of aggregates was generated from outer edge of these aggregate. On these reactive aggregate, a reaction rim (see Figure 1(a)) was observed in a cut section of the aggregate. Aggregate C contained reactive components that were scattered in the aggregate (see Figure 1(b)) and it took a long time for the alkali amd OH^- to reach these reactive components within aggregate C. For this reason, the initiation of ASR expansion of concrete used with aggregate C was generally later than that of concrete used with aggregate A and R. Expansion of concrete depended on type of reactive aggregate and the difference in expansion behavior of concrete was predictable response from types of reactive aggregate. On the other hand, the expansion rate of specimens was similar regardless of types of reactive aggregate (see Figure 3).

3.2 Compressive strength

The influence of the expansion of concrete on the compressive strength is shown in Figure 4. The compressive strength was reduced with increasing expansion regardless of the types of aggregate. In previous studies [2-5], compressive strength of ASR deteriorated concrete was gradually reduced as increase of ASR expansion. Therefore, it is considered that the compressive strength of ASR deteriorated was gradually reduced as increase of ASR expansion regardless of type of reactive aggregate. In addition, the reduction rate of compressive strength of concrete was almost the same except for aggregate C.

The influence of the expansion on the compressive strength ratio (compressive strength of ASR deteriorated concrete specimen divided by that of the control specimen) is shown in Figure 5. Data (lower bound) obtained in previous studies [5] is highlighted in Figure 5 and these data were recommended as the minimum compressive strength ratio of ASR deteriorated concrete corresponding to ASR expansion.

Compressive strength ratio was reduced with increasing ASR expansion regardless of the type of aggregate and this tendency of reduction in compressive strength ratio was similar to reduction in compressive strength. These compressive strength ratios were larger than lower bound shown as red line in Figure 5.

3.3 Young's modulus

The influence of the expansion on Young's modulus is shown in Figure 6. In the specimen incorporating the aggregate A, the drastic reduction in Young's modulus was observed within the initiation expansion stage (less than 0.05 % of expansion) due to ASR expansion. After then, Young's modulus was gradually reduced as expansion become larger. This tendency was similar to that obtained in previous studies [4,6]. In the specimen incorporating the Aggregate C, the reduction in Young's modulus due to ASR expansion that was observed within the initiation expansion stage was smaller than that in specimen incorporating the aggregate A. After the initiation expansion stage, the reduction of Young's modulus of specimen incorporating the aggregate C was slight smaller than of the specimen incorporating the aggregate A. For this reason, it is inferred that there were different properties on the crack propagation and the crack pattern inside concrete between the specimen incorporating the aggregate A and specimen incorporating the aggregate C, since the type of reactive aggregate was difference in both aggregate. In addition, the initiation of ASR expansion of concrete incorporating the aggregate C was later than that of concrete incorporating the aggregate A and this may resulted in difference influence on reduction of Young's modulus of concrete due to ASR expansion.

In previous study [7], concrete incorporating the reactive aggregate similar to aggregate C had slow and late expansion. Authors reported that this expansion behavior results in different properties on a crack propagation and a crack pattern inside concrete compared to concrete incorporating the reactive aggregate that show rapid expansion and first initiation of expansion. In this study, expansion rate of concrete used with all reactive aggregate was almost the same and/or the expansion rate of concrete used with aggregate C was slightly slower than that used with the other aggregates. Therefore, it is considered that the different behavior of Young's modulus between aggregate A and C was not strongly influenced by the difference expansion rate between them and that the different tendency of the reduction in Young's modulus of concrete between aggregate A and C was caused by different type of reaction.

The influence of the expansion on Young's modulus ratio (Young's modulus of ASR deteriorated concrete specimen divided by Young's modulus of control specimen) is shown in Figure 7. Lower bound [5] is indicated in Figure 7 as red line. All reactive aggregate showed smaller Young's modulus than lower bound at any expansion. The reduction in Yong's modulus of concrete was significant in the initiation expansion stage. Typical reactive aggregates found in concrete structures deteriorated by ASR in Japan show rapid expansion and Normal Portland cement made in Japan has faster hydration of cement than that of cement made in other country. It is possibly inferred that this phenomenon was caused by rapid expansion rate, faster initiation of the expansion and rapid hydration of cement. However, further detail investigation was needed to find the reason why this phenomenon was caused.

3.4 Poisson's ratio

The influence of the expansion on Poisson's ratio is shown in Figure 8. Poisson's ratio of concrete at a different stress level was calculated. 33 % of maximum stress was defined as the first stress level where normal concrete showed an elastic behavior. 90 % of maximum stress was defined as the second stress level where stress was very closed to the compressive stress. Incidentally, Poisson's ratio of normal concrete ranges from 0.14 to 0.20.

At 33 % of the maximum stress, Poisson's ratio was almost constant until the expansion reached 0.5 % and Poisson's ratio showed a larger value according to increase of the expansion. It is considered that excessive ASR expansion results in early reduction in a deformation resistance and shows larger Poisson's ratio of concrete in excessive expansion stage. In previous study [4], it was reported that Poisson's ration was almost constant where the expansion of concrete was less than 0.7 %.

At 90 % of the maximum stress, Poisson's ratio showed much larger values according to the increase of ASR expansion. It is considered that these micro and macro cracks due to ASR expansion result in a loosely-bound concrete matrix and makes concrete to deform more easily in the lateral direction. And, it was inferred that the lateral strain of ASR deteriorated concrete around the maximum stress level was much larger than that of normal concrete.

In above results, Poisson's ratio showed scattering values and the influence of aggregate type on Poisson's ratio is not cleared.

3.5 Strain at maximum stress

The influence of the expansion on the axial and lateral strain at maximum stress was shown in Figure 9. At maximum strain, some strain gauges to measure the strain were out of range due to large deformation and crack. For this reason, in these cases, strain at maximum stress was calculated based on the deformation of concrete specimen obtained by displacement gauge.

Both axial and lateral strains of concrete at the maximum stress increased with increasing level of ASR expansion regardless of the type of aggregate. It is considered that concrete which have a larger expansion due to ASR shows a larger deformation at maximum stress. In the concrete incorporating the aggregate C, the increase in both axial and lateral strain of concrete was slightly smaller than that of concrete incorporating other aggregate. For this phenomenon, a further investigation is needed to clarify the mechanism involved.

4 DISCUSSION

In this study, there were some different influences of expansion on these mechanical properties of concrete specimens incorporating aggregates A and C. And, further investigation is needed to clarify these mechanisms of some phenomenon. However, the effect of ASR expansion on these mechanical properties (compressive strength, Yong's modulus, Poisson's ratio and strain at maximum stress) was almost the same regardless of the type of reactive aggregate. In other words, regardless of the type of aggregate, a proper numerical model of ASR deteriorated concrete on mechanical properties can be established as far as this model can keep enough redundancy to estimate the structural performance and to design the reinforcing for concrete structure. It is noted that the reduction in Young's modulus of concrete with typical reactive aggregate in Japan was significant and was larger than that of concrete with reactive aggregate in other country. In the fact, in Japan, Young's modulus of concrete taken from concrete structure severely deteriorated by ASR was significantly small. Furthermore, studies are needed to evaluate the influence of the expansion on mechanical properties of ASR deteriorated concrete under confined condition due to a reinforcement and/or an applied stress.

5 CONCLUSIONS

Main results obtained in this study were shown as follows.

1) The influence of the expansion on these mechanical properties of ASR deteriorated concrete was almost similar regardless of the type of reactive aggregate.
2) The influence of the type of reactive aggregate on compressive strength of concrete was not significant. Based on the results obtained in this study, lower bound of compressive strength can be established for similar water cement ratio compared to that of concrete used in this study.
3) Deformation properties of ASR affected concrete were influenced by the type of reactive aggregate. Difference in crack propagation and crack pattern inside concrete due to ASR expansion was inferred as this reason.
4) Especially, Young's modulus and strain at maximum stress of concrete affected by ASR expansion was influenced by type of reactive aggregate.

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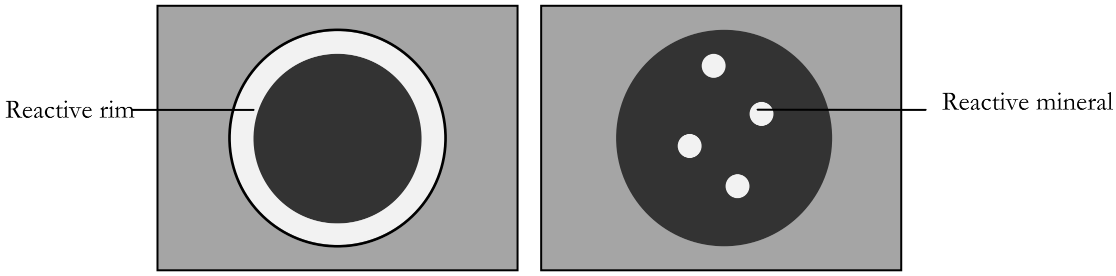
TABLE 1: Physical property of aggregate.

Type of aggregate	River sand (non-reactive)	River gravel (non-reactive)	Aggregate A (andesite)	Aggregate C (chert)	Aggregate R (river gravel)
Density（g/cm^3）	2.56	2.60	2.66	2.69	2.66
Absorption（%）	2.88	2.18	2.65	0.90	1.67
Fineness modulus（F.M.）	3.08	6.77	6.81	7.18	7.12
Sc(mmol/l)	-	67	196	403	184
Rc（mmol/l)	-	118	111	63	83

TABLE 2: Mixture proportions (kg/m^3).

Type of aggregate	Aggregate A	Aggregate C	Aggregate R
w/c(%)	55	55	55
Water	163	163	163
Cement	300	300	300
Non-reactive sand	787	787	787
Non-reactive coarse aggregate	0	206	0
Reactive coarse aggregate	1016	822	1016
NaCl	12.5	12.5	12.5
Air entraining and water reducing agent	0.9	0.9	0.9
Air entraining agent	0.7	0.7	0.7



a) gel rim reaction

b) gel pockets reaction

FIGURE 1: Reaction type of Aggregate

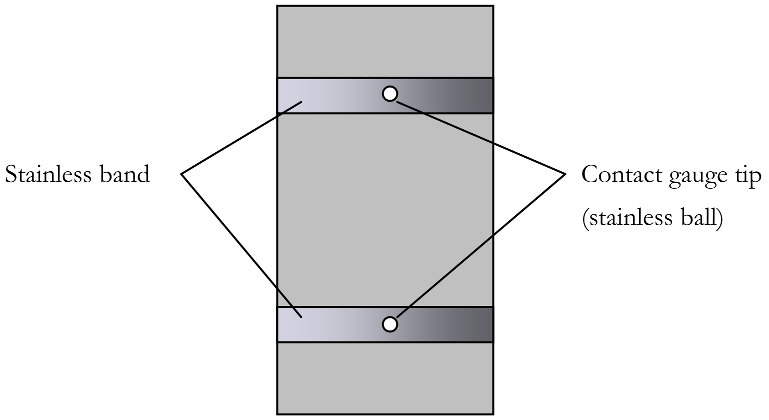


FIGURE 2: Specimen

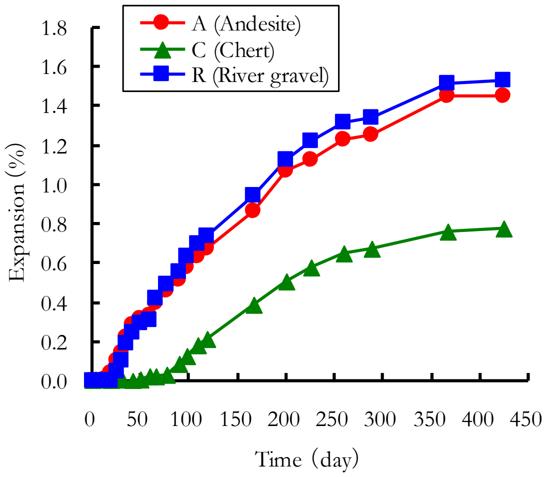
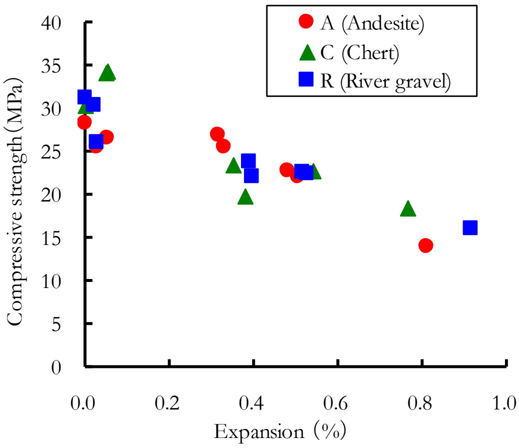


FIGURE 3: Expansion behavior



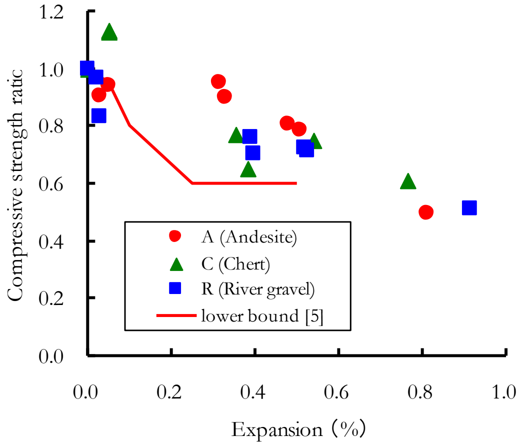


FIGURE 4: Compressive strength

FIGURE 5: Compressive strength ratio

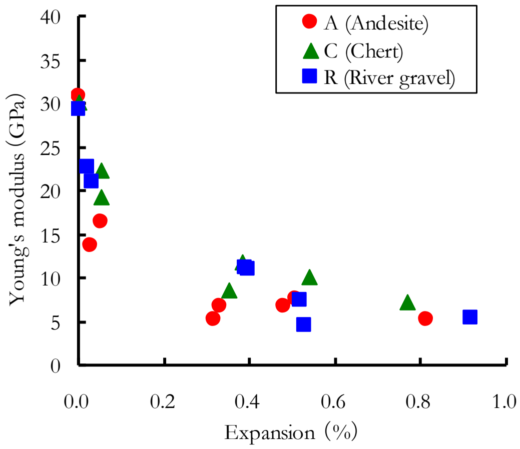


FIGURE 6: Young's modulus

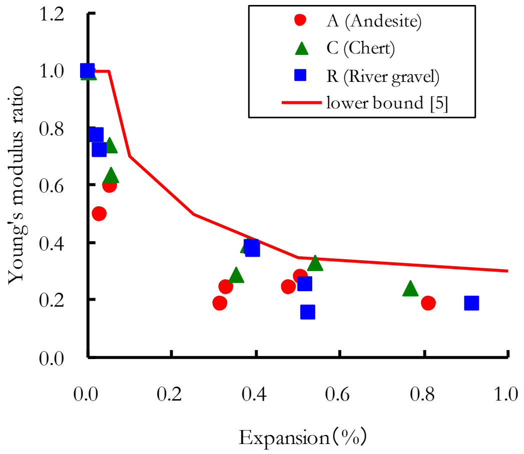


FIGURE 7: Young's modulus ratio

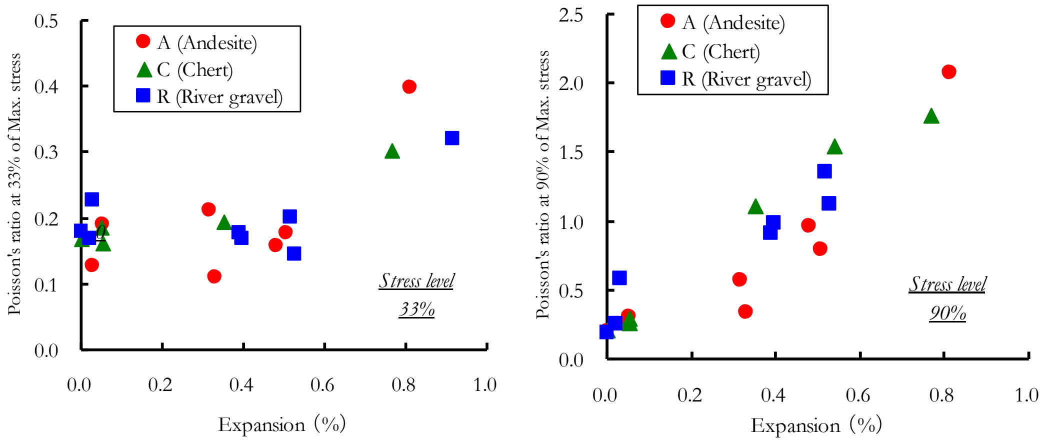


FIGURE 8: Poisson's ratio

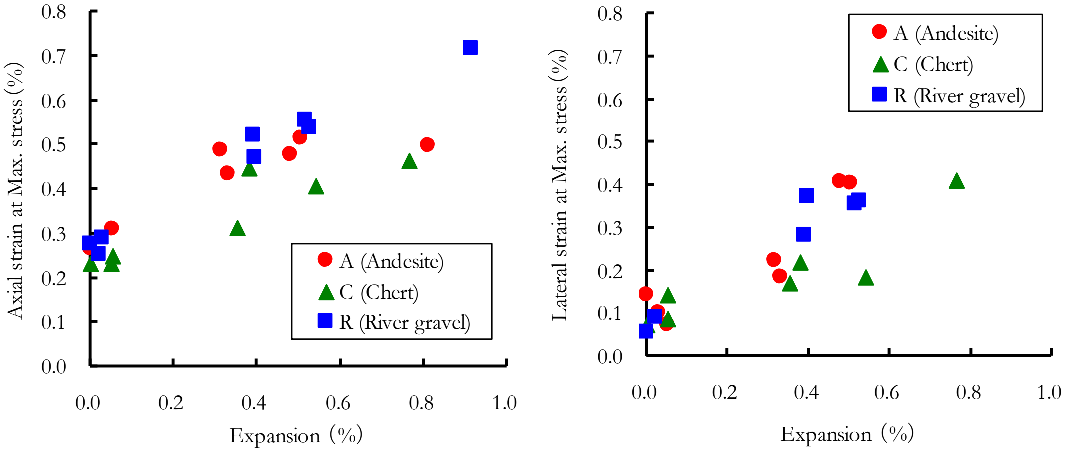


FIGURE 9: Strain at Max. stress (axial and lateral)