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An experimental study of scale effect on the shear behavior of rock joints

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Abstract: Mechanical behavior of rock joints usually can be characterized by small-scale laboratory shear tests due to economical and technical limitations, but their applicability to the behaviour of rock mass has been always questioned by a number of researchers because of scale effect. Though there have been several researches regarding the scale effect, it has been a controversial problem how to apply the result of small-scale laboratory shear test directly to field design from different conclusions among researchers. In order to grasp the trend of scale effect of shear behavior, a series of direct shear tests on replicas of natural rock joint surfaces made of gypsum cement with different size and roughness were conducted and analyzed. Result showed that as the size of the specimen increased, average peak shear displacement increased, but average shear stiffness and average peak dilation angle decreased. As for the dependency of scale on shear strength, the degree of scale effect was dependent on normal stress and roughness of rock joint. For the condition of low normal stress and high roughness, decrease of average peak shear strength with increasing size of joint was evident.

1. Introduction

Barton & Bandis (1981), in their well-known experimental study on the scale effect of natural rock joint, pointed out a clear decrease of peak shear strength as the sample size increased, and an increase of the peak shear displacement with increasing specimen size. However, some reports showed reverse results about the scale dependency of the shear behaviors. For example, Leal Gomes (1999) observed that peak shear strength increased as the sample size increased.

In order to grasp the controversial trend of scale effect of shear behavior, a series of direct shear test of replicas of 3 types of natural rock joint surfaces were conducted and analyzed under different magnitudes of normal stresses (0.25, 0.5 and 1 MPa). For case 1 (Joint 1 at normal stress = 0.25 MPa) the specimen size was 12 cm in width and 5 10, 20 and 40 cm in length and for other cases the specimen size was 12 in width and 10, 20 and 40 cm in length, respectively.

2. Test specimen and apparatus

For experiments, three natural rock joint surfaces were collected in field (Fig. 1). The joint surface roughness was measured by 3D roughness measurement system equipped with a laser displacement meter. The measured JRC according to the Tse & Cruden's method (1979) showed that Joint 1, Joint 2 and Joint 3 was 13.4, 8.6 and 6.0, respectively.

The cast-aluminum wares were used for replicating rock joint surfaces, which took advantage of reproducing many samples without damage (Fig. 2). The material of replica consisted of a mixture of gypsum cement (Diastone, MR-150) and water combined in 100 : 26 proportions by weight. Table 1 lists the basic physical and mechanical properties of the mixture of gypsum cement. The joint replicas were air-dried for 7 days. For 40 cm length specimen replica was used whole, for 20 cm length specimen replica was subdivided by half, for 10 cm length specimen replica was subdivided by 1/4 and for 5 cm length specimen replica was subdivided by 1/8 (Fig. 3).

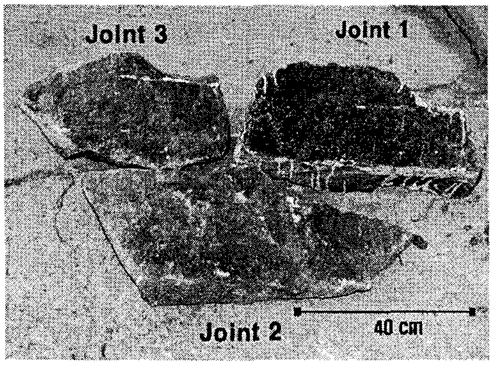

Fig. 1. The view of natural rock joint surfaces collected in field.

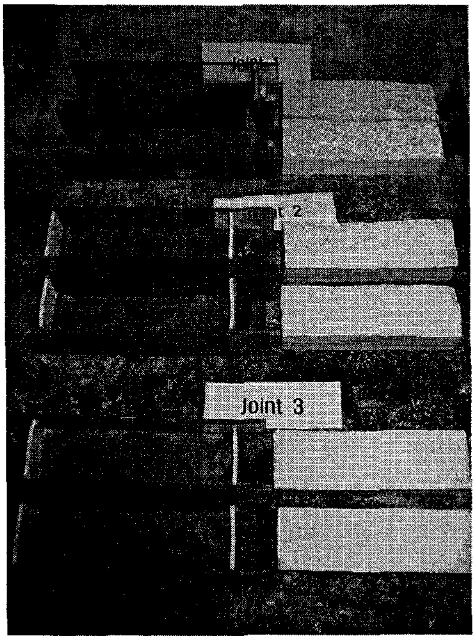

Fig. 2. The view of moulds made by cast-aluminum ware and replicas

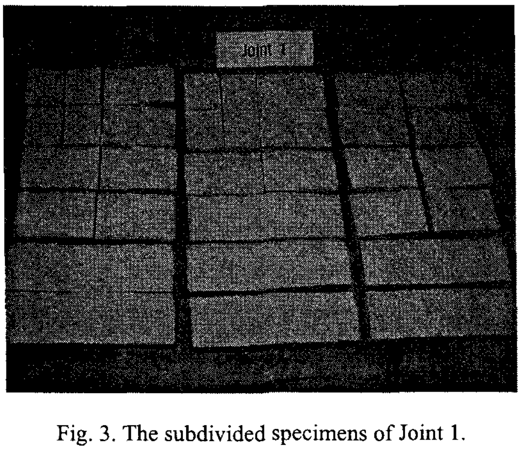

Fig. 3. The subdivided specimens of Joint 1.

Table 1. Physical and mechanical properties of the mixture of gypsum cement.

Properties	Gypsum cement
Bulk specific gravity	1.86
P-wave velocity (m/sec)	3470
S-wave velocity (m/sec)	1760
Elastic modulus (GPa)	11.6
Poisson's ratio	0.23
Uniaxial compressive strength (MPa)	32.9
Tensile strength (MPa)	3.6
Basic friction angle (°)	32.5

The direct shear testing was performed at Samsung Engineering & Construction, Research Institute of Technology. The direct shear tests were carried three times for case 1, but for other cases only one time direct shear tests were preformed. The testing procedure was automatic and both loading systems were servo-controlled. The shear displacement rate was maintained at 0.05 mm/sec. The testing procedure and data collection were controlled by a computer.

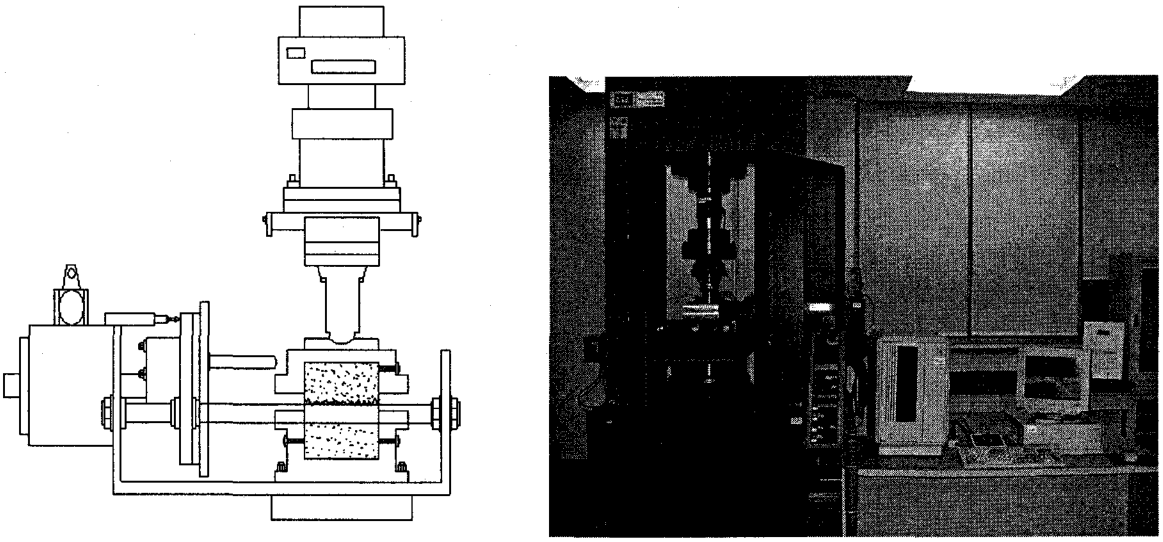

Fig. 4. Schematic diagram of shear testing apparatus.

3. Experimental results

Effect of scale on peak shear strength

The peak total friction angle (ϕ_p = peak arctan (τ_p / σ_n)) was used as an introduction to the magnitude of the scale effect on peak shear strength. An overall summary of the results in presented in table 2, where ϕ_p was described by the mean and standard deviation values. A comparison showed that only the mean ϕ_p value of joint 1 decreased as the length of specimen increased, but the remarkable scale effect was not observed in joint 2 and 3.

Table 2. Summary of mean peak arctan (τ_p / σ_n) values of joints.

Specimen size (cm)	Joint 1	Joint 2	Joint 3
5	59.3°± 6.2° (8)	-	-
10	56.1°± 5.7° (12)	51.1°± 4.4° (12)	46.0°± 5.4° (12)
20	54.3°± 5.6° (6)	51.4°± 2.1° (6)	46.3°± 5.8° (6)
40	53.6°± 3.8° (3)	49.9°± 2.2° (3)	43.0°± 2.7° (3)

Another illustration of the scale effect on peak shear strength was shown in Fig. 5 where the average peak shear strength (τ_p) had been plotted against the average joint area (A). In five cases, peak shear strength decreased with increasing A, but those dependencies were ambiguous in four cases. In case 1 (joint 1 at σ_n = 0.25 MPa), the scale dependency was more evident. In case 1, joint roughness was highest and normal stress was lowest. We found that average peak stress decrease with increasing average joint area. For this case 1, an exponential approximations were presented in the Fig 5. The exponential law which had been suggested by J.Muralha & A. Pinto da Cunha (1990) was as follows;

$$\tau = c + a \times e^{-bA}$$

where a, b and c are constants.

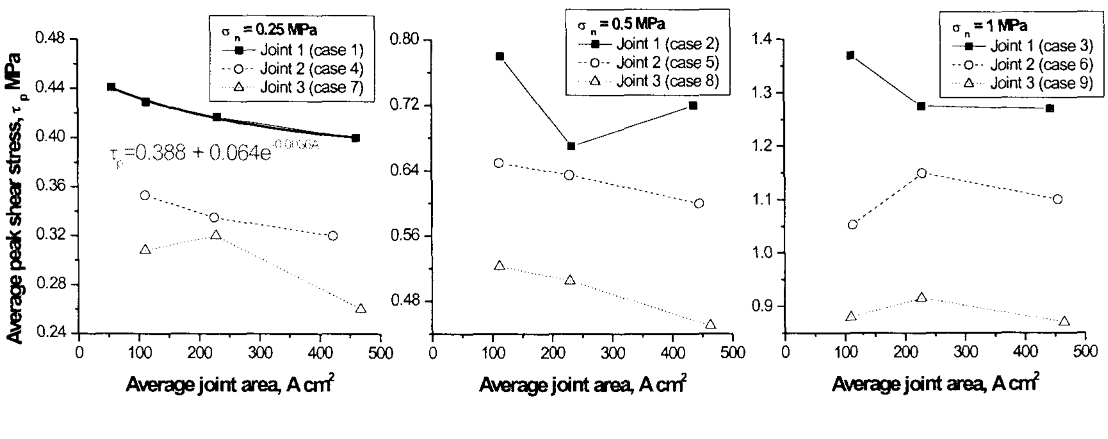

Fig. 5. A plot of average peak shear stress vs. average joint area.

Effect on scale of peak shear displacement

Average peak shear displacement (u_p) with specimen length (L) was illustrated in Fig. 6. This figure showed that average peak shear displacement increased with increasing specimen length. We found scale effect on peak shear displacement in all cases. As the specimen length increased from 10 to 40 cm, the magnitudes of increment were 80%, 203% (case 1), 13%, 306% (case 2), 105%, 162% (case 3), 15%, 99% (case 4), 67%, 129% (case 5), 61%, 200% (case 6), 35%, 105% (case 7), 46%, 140% (case 8) and 33%, 150% (case 9).

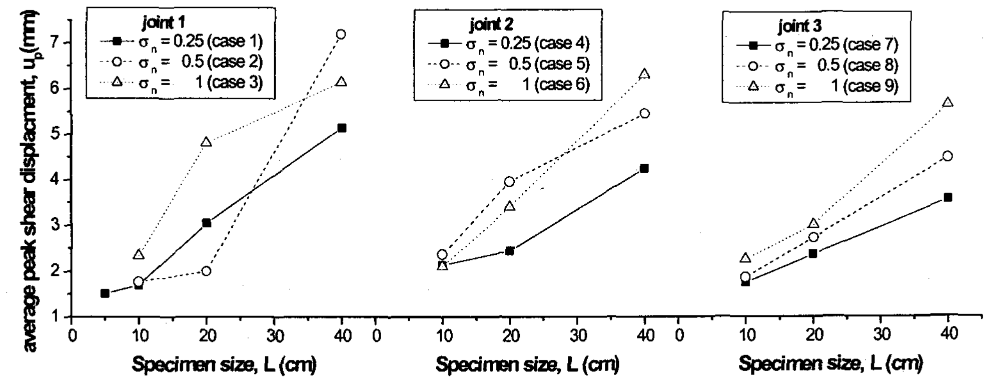

Fig. 6. A plot of average peak shear displacement vs. specimen size.

Effect of scale on average shear stiffness

Fig. 7 showed the average shear stiffness (K_s) with different specimen size. We observed that average shear stiffness decreased with increasing joint length. As the specimen length increased from 10 to 40 cm, the magnitudes of reduction were 34%, 72% (case 1), 35%, 73% (case 2), 41%, 73% (case 3), 39%, 80% (case 4), 55%, 68% (case 5), 51%, 70% (case 6), 44%, 72% (case 7), 38%, 62% (case 8) and 35%, 66% (case 9)

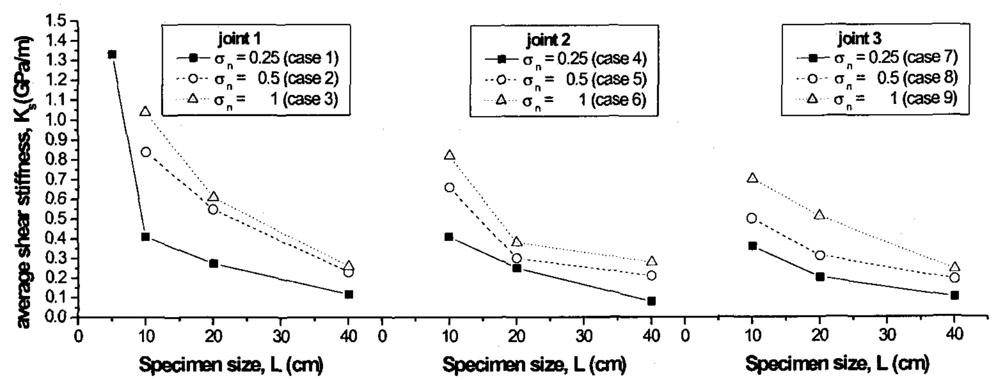

Fig. 7. A plot of average peak shear stiffness vs. specimen size.

Effect of scale on average peak dilation angle

Fig. 8 showed the average peak dilation angle (d_n) with different specimen size. Average peak dilation angle decreased with increasing joint length in most of cases. The degree of scale effect was dependent on normal stress and roughness of rock joint. For the condition of low normal stress and high roughness, decrease of average dilation with increasing size of joint was evident. As the normal stress increased and the roughness of rock joint decreased, the scale dependency had ambiguity.

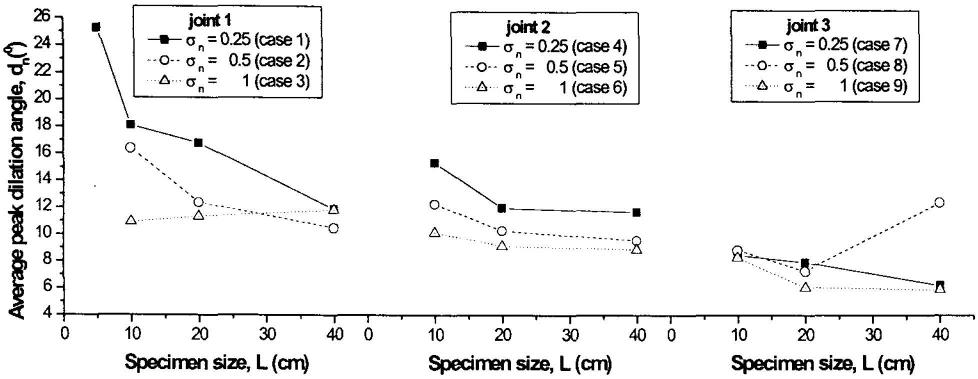

Fig. 8. A plot of average peak dilation angle vs. specimen size.

4. Conclusions

In these study, in order to grasp the trend of scale effect of shear behavior, a series of direct shear tests on replicas of natural rock joint surfaces made of gypsum cement with different size and roughness were conducted. Result showed that as the size of the specimen increased, average peak shear displacement increased, but average shear stiffness and average peak dilation angle decreased. As for the dependency of scale on shear strength, the degree of scale effect was dependent on normal stress and roughness of rock joint. For the condition of low normal stress and high roughness, decrease of average peak shear strength with increasing size of joint was evident. However, more detailed experiments for obtaining quantitative conclusions are needed.

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