Fundamental Study on Fault Triaxial Compression Test for In-situ Rock Mass

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Summary In-situ triaxial compression tests of rock mass are uncommon, since these tests have the disadvantage of being time-consuming and expensive in comparison to the direct shear tests. In order to diminish these disadvantages, the author has concentrated on the fault triaxial compression test (FTCT) in this study. The FTCT introduced the idea of the conventional triaxial compression test (CTCT) in the laboratory to the field. The FTCT and the CTCT were conducted in the laboratory using model rock made of cement mortar. The mechanical indices yielded from both tests were compared. It was found that the FTCTs gave about 10% lower shear strength and 5% smaller angle of internal friction than those of CTCTs.

1. INTRODUCTION

Rock mass is a quite peculiar material in comparison to other engineering materials, since rock mass consists of rock materials and discontinuities. Consequently, the engineering properties of rock mass should be estimated by assembling both the characteristics of the rock material and the discontinuity. However, there are some difficulties in order to test the discontinuity independently. Hence the tests of rock mass in situ are indispensable for assessing its engineering properties. As for the in-situ strength tests of rock mass, they are roughly divided into two groups, namely, direct shear test (DST) and triaxial compression test (TCT). From these tests, we can obtain the failure criterion. Shear strength (S_s) and angle of internal friction (ϕ) are considered as the indices of engineering properties of rock mass.

In the DST, the primary purpose is to measure the resistance to stress along the failure plane. A square rock block cut out from the bedrock or a square concrete block placed on the surface of the bedrock is prepared for the test. The test block is loaded biaxially, that is, normal load and shearing force are applied to the test block by two hydraulic jacks or rams. There are many reports which mention about the applications of these tests (ASTM, 1971). An important thing which engineers should take notices is that stress distribution within the block is not uniform. The measured strain on the sides, the observed behaviors such as uplift movement of the block and fracture pattern out of the expected failure plane (Kimishima, 1965) verify the confusion of the stresses inside the block. This fact might give rise to great complications to evaluate the mechanical indices and to understand engineering properties of rock mass.

As for the TCT, a square rock block is also used. Three hydraulic or flat jacks are used for applying the three principal stresses to the block (Nose, 1964). The stress distribution within the block is comparatively uniform since the block is tested under three-dimensional confining condition. Considering the uniform stress state within the block, this test is advisable to do rather than the DST. However, the TCTs are hardly carried out whereas the DSTs are commonly conducted in the existing circumstances. This is due to the disadvantages of being time-consuming, requiring much labor and being expensive in comparison to the DSTs. ISRM Commission on Recommendation on Site Investigation Techniques (1982) stated in its suggested methods that designing engineers are advised to do the test at a large underground opening site and should conduct the test at a construction site of arch dam when they have some concern for engineering properties of rock mass. This kind of delicate suggestion might consider the disadvantages of the TCT in-situ mentioned above.

In order to diminish these disadvantages and to make it easy to apply, the author has concentrated on the FTCT. Small-scale model tests were conducted to investigate the mechanical indices obtained from the test and its performance.

2. AN OUTLINE OF FAULT TRIAXIAL COMPRESSION TEST

The testing method of the FTCT is essentially similar to that of the CTCT in the laboratory. Generalized illustration of the FTCT is shown in Figure. 1. A cylindrical specimen is obtained by incomplete core cutting of rock mass, that is, an annulus is cut by deep groove and the bottom part is left as it was. Outside and inside laterals of the groove are covered with rubber membrane and a piston cap is put over the specimen. The confining pressure is applied to the specimen by fluid medium such as water and oil injected into the deep groove. Outside rock mass of the groove has, therefore, the function of the pressure cell body. Only one hydraulic jack is required for applying the axial force. Testing apparatus as well as preparation procedure of the specimen are extremely simple in comparison to the present TCT in-situ.

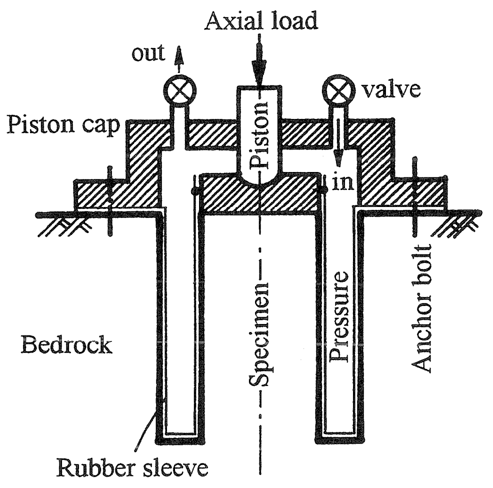

Figure 1. Conception of the FTCT.

3. MODEL TEST

Two types of model tests were carried out; one is fault uniaxial compression test (FUCT) and the other is FTCT.

3.1 Rock mass model

Geometry of rock mass model is arranged based on the applicable testpiece size of the existing load unit. Rock mass models, made of cement mortar, are cylinders of 150 mm in diameter and 300 mm in height. Two values of uniaxial compressive strengths (UCSs), 45 MPa and 40 MPa, were specified as the target strength of cement mortar. Higher strength models were furnished to the FUCT and lower strength models were to the FTCT. In order to restrict the increase of the strength during testing period, they were cured for more than 13 weeks before testing. During the first 4 weeks, they were kept in water, and after that left in the air. Actual UCSs of rock mass models were 47.2 MPa and 40.8 MPa, respectively.

3.2 Fault uniaxial compression test

3.2.1 Testing method

This test was assigned to investigate the influence on the compressive strength which originates in the continuation of the bottom part of the specimen with the rock mass model. The specimens for the FUCTs were produced by incomplete core cutting in the cylinder axis direction at the center of the top end of the rock mass models. Specimen's diameter (D) was fixed at 50 mm, while coring depth (H) was changed in accordance with appointed height-to-diameter (H/D) ratio values of 2.0, 2.5, 3.0 and 3.5. Three specimens were tested in each H/D ratio. Axial compressive load was applied at the loading rate of 2.9 kN/min. Figure 2 shows the operation view of the FUCT. Uniaxial uniaxial compression tests (UCTs) of standard specimens with 50 mm in diameter and 100 mm in height were also carried out with the same loading condition.

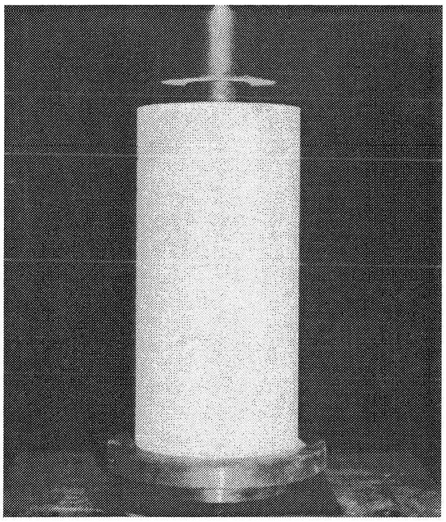

Figure 2. Operation view of the FUCT.

3.2.2 Results and discussion

The obtained UCSs are summarized in Table 1. The FUCT specimen with the H/D ratio of 2.0 gave 7 % larger strength than the standard specimen. This is attributed to the continuation of specimen at the bottom. It can be regarded that applied axial stress within the specimen is softened at the bottom. The variation of the UCSs can be seen in the results of the FUCTs. Specimen with the H/D ratio of 2.5 gave the minimum UCS.

Table 1. Results of FUCTs.

H/D	2.0	2.5	3.0	3.5
UCS (MPa)	50.6	49.3	53.0	53.4

UCS of standard specimen : 47.2 MPa

Figure 3 shows a typical fracture state of the FUCT specimen. In the specimen with the H/D ratio of 2.5, a clear shearing failure plane cut across the specimen diagonally. On the contrary, in the specimen with the H/D ratio of 3.5, the shearing failure plane appeared at the middle part of the specimen. Based on these results, it may be concluded that the most appropriate H/D ratio of specimen for the FTCT is 2.5.

3.3 Fault triaxial compression test

3.3.1 Allowable confining pressure

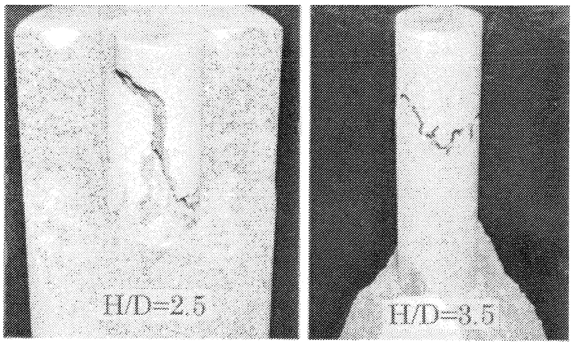

Figure 3. Typical fracture state of the specimen.

As to this cylinder rock mass model, the outer part of the deep groove forms a hollow cylinder. This part plays the role of the pressure cell body. Based on the theory of thick-walled vessel subjected to a uniform pressure on the inner surface (Young,1989), maximum stress in the direction of tangent denoted by $\sigma_{t\max}$ is given by

$$\sigma_{t\max} = \frac{a^2 + b^2}{a^2 - b^2} p_i \tag{1}$$

where a and b are outer and inner radii of thick-walled vessel, respectively, and p_i is the internal uniform pressure. Supposing $\sigma_{t\max}$ reaches the tensile strength of the vessel material, denoted by S_t, thick-walled vessel will be broken. Hence it follows that allowable confining pressure denoted by p_a is derived from the Equation (1) as follow.

$$p_a = \frac{a^2 - b^2}{a^2 + b^2} S_t \tag{2}$$

Allowable confining pressure level of this cylinder rock mass model is strongly dependent upon radial thickness of hollow cylinder and the tensile strength of the material. From the Brazilian test of the material, 2.5 MPa was obtained as S_t. It is necessary for improving the allowable confining pressure to increase the radial thickness of the hollow cylinder. This means the reduction of specimen's diameter for the FTCT. If a 35 mm specimen diameter is considered, 2.1 MPa is yielded as p_a from Equation (2). This value is about 5 % of the UCS, which is too small to investigate the characteristics of the FTCT. Some reinforcement of the hollow cylinder is, therefore, necessary for conducting the model test.

3.3.2 Testing method

Taking into account the results of the FUCTs and pre-examined bearing capacity of the hollow cylinder part against internal pressure, specimen's diameter and H/D ratio were decided as 35 mm and 2.5, respectively. Besides, the hollow cylinder part was reinforced by inserting the steel tube with 1 mm in thickness into the deep groove, and caulking material was filled in the space between the hollow cylinder part and steel tube. Top end of the specimen for FTCT before installing the piston cap is shown in Figure 4.

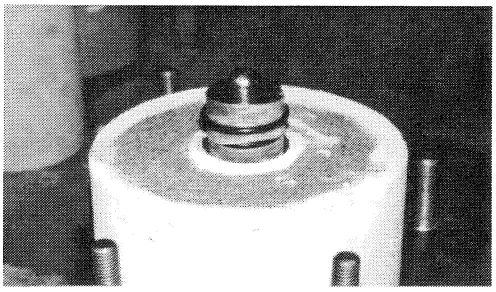

Figure 4. Top end of the specimen for FTCT.

Four levels of confining pressures, 0, 0.98, 1.96 and 2.94 MPa, were applied to the specimen, and four specimens were tested in each confining pressure level. The confining pressure was applied to the specimen by nitrogen gas pressure supplied from a gas cylinder. Axial compressive load was applied at the loading rate of 1.96 kN/min. The operation view of the FTCT is shown in Figure 5. After the FTCTs, three standard specimens with 35 mm in diameter and 70 mm in height were taken out from every rock mass models for the CTCTs. The loading rate of axial compressive load

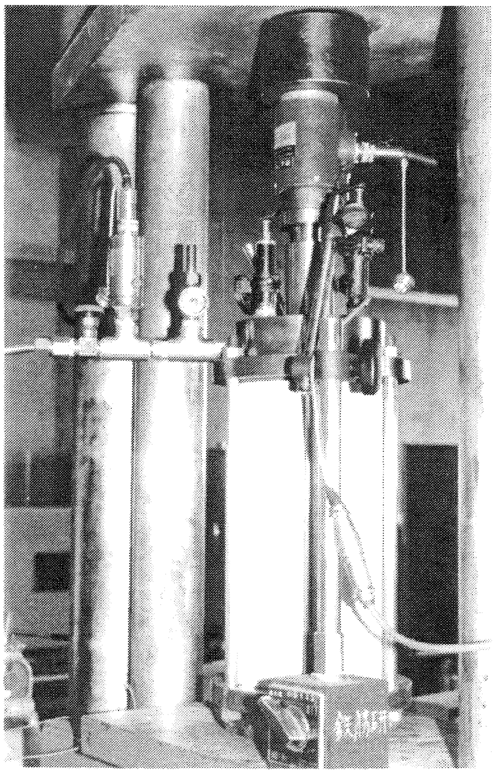

Figure 5. Operation view of the FTCT.

and variation of confining pressure levels were the same as FTCTs. The piston cap was common to both FTCT and CTCT tests.

3.3.4 Results and discussion

3.3.4.1 Stress-strain relations

Figures 6 and 7 show the typical differential stress-strain curves obtained from CTCTs and FTCTs, respectively. It is difficult to trace the complete relation in the post-failure range, since the Amsler type testing machine was used in these tests. For the FTCTs, it is found that strain level at strength failure point on the curve increases with an increase in confining pressure level. This feature is the same as in the CTCTs. Thus, it is regarded that the FTCT specimens behave similar to the CTCT specimens during the test. Some points where strain shifts with small magnitude can be seen on the curves of the FTCTs. As regards this noise, deformation and rigid body movement of the rock mass model itself might be involved unexpectedly. With respect to the inclination angles of the curves in the early pre-failure range, the FTCTs give somewhat smaller angles than those of the CTCTs. This feature is also derived from the continuation of the bottom part of the FTCT specimen. Continuation gives rise to the reduction of apparent axial loaded stress at the bottom part of the specimen.

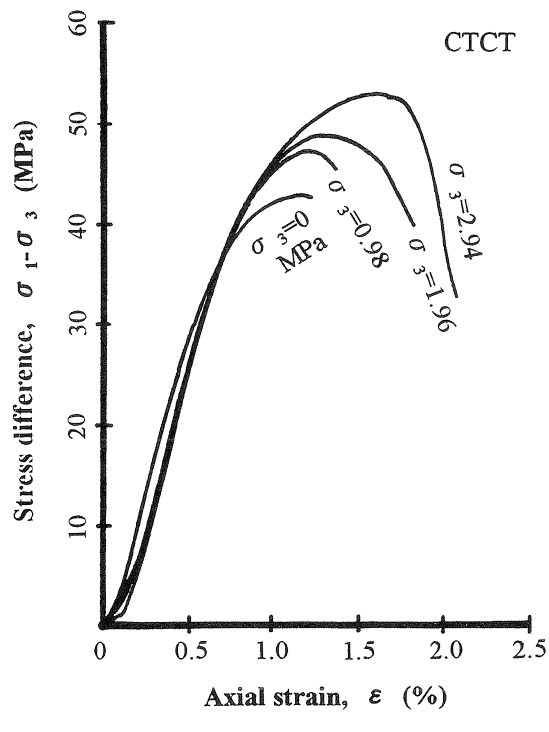

Figure 6. Differential stress-strain curves.

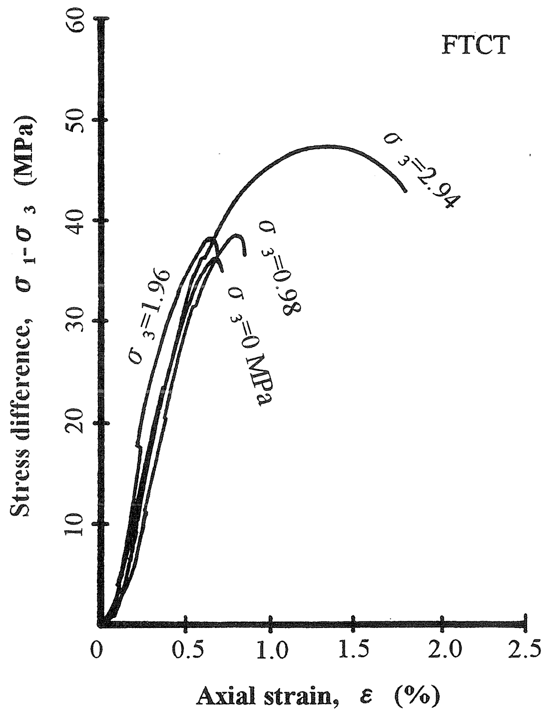

Figure 7. Differential stress-strain curves.

3.3.4.2 Compressive strength

The average compressive strengths in both FTCTs and CTCTs are summarized in Table 2. In every confining pressure levels, the FTCTs give about 14 % lower compressive strength than those of the CTCTs. In order to make clear whether this tendency is a universal character of the FTCT or not, further tests are required to accumulate the experimental evidence.

Table 2. Results of CTCTs and FTCTs.

σ_3 (MPa)		0	0.98	1.96	2.94
σ_1	CTCT	42.3	48.1	49.3	53.0
(MPa)	FTCT	36.7	39.8	43.6	45.6

σ_3: Confining pressure.
σ_1: Sum. of axial stress and confining pressure.

Taking notice of the unconfined condition, this outcome is a reversal of the result of the FUCTs. Standard specimens in the FUCTs were manufactured by using cylinder forms whereas the CTCT specimens were extracted from the rock mass models by coring. The different preparation procedures of specimens and size effect are considered as the cause of this inversion.

3.3.4.3 Failure envelope

Figures 8 and 9 show the Mohr's stress circles at failure of the CTCTs and the FTCTs which are drawn from the data in Table 2. It can be recognized that the stress circle enlarged with an increase in confining pressure level. This also implies that the FTCT specimens behave as the CTCT specimens do. Considering the data in Table 2, it can be noticed that stress circles of the FTCTs are smaller than those of the CTCTs.

It is difficult to describe reasonable failure envelope from these stress circles. The result of Brazilian test, which is drawn by dotted circle, is considered to assist the drawing of failure envelope. Table 3 shows the shear strength (S_i) and angle of internal friction (ϕ_i) at intercept yielded from failure envelopes of the CTCT and the FTCT. The FTCTs give about 10% lower S_i and about 5% smaller ϕ_i than those of the CTCTs. It can not be concluded that these rates are universal character of the FTCT, since these are obtained from a small number of specimens and the applied confining pressures are not enough to make the final judgment in comparison to the UCS of the model material.

According to the results of elasto-plastic analysis of these models by FEM (Ishibashi, 1993), The FTCT yielded at a stress about 15% higher S_i than that of the CTCT, and almost equal ϕ_i to that of the CTCT. In this analysis, compressive strengths in every confining pressure condition were evaluated in consideration of plasticized area. The limit of simulation on tracing the failure behavior due to idealization is well-known. Some extent of the differences between experimental and analytical results, especially the compressive strengths, are unavoidable at present state. The compressive strengths are sensitive to the evaluation of S_i rather than ϕ_i. It can be noted that there is no significant difference between internal friction angles yielded from both tests.

Table 3. Indices of engineering properties.

Index	S_i (MPa)	ϕ_i (Deg.)
CTCT	7.9	56.7
FTCT	7.1	53.7

3.3.4.4 Fracture state of the FTCT specimen

Figure 10 shows typical fracture states of the FTCT specimens which are picked up from rock mass models after the tests. Shearing failure plane can be clearly seen within the specimen, and this feature is the same as the appearance observed in the UCTs of standard specimens. In the context of fracturing process, the FTCT specimens are very similar to the CTCT specimens.

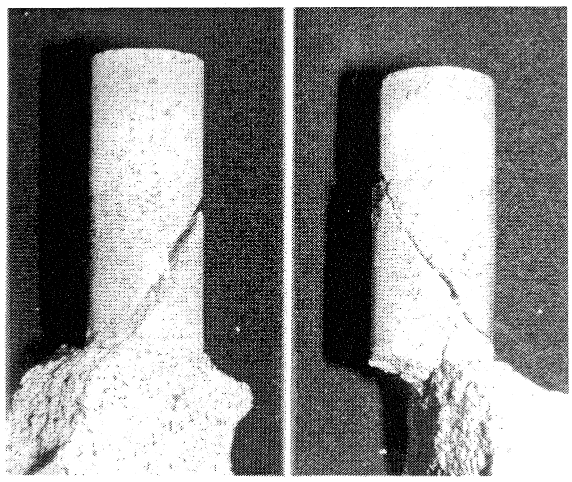

Figure 10. Typical fracture state of the specimen. (Confining pressure is 2.94 MPa.)

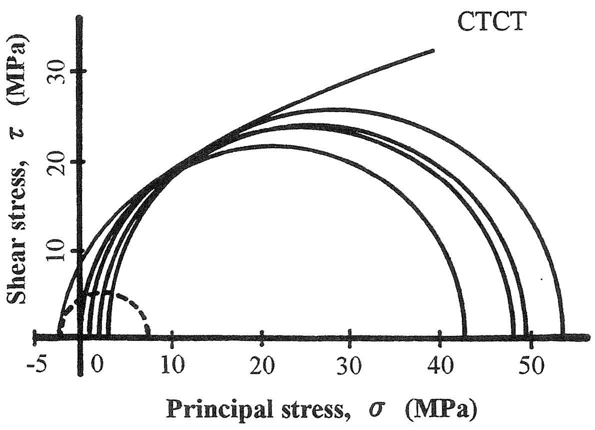

Figure 8. Mohr's stress circles at failure.

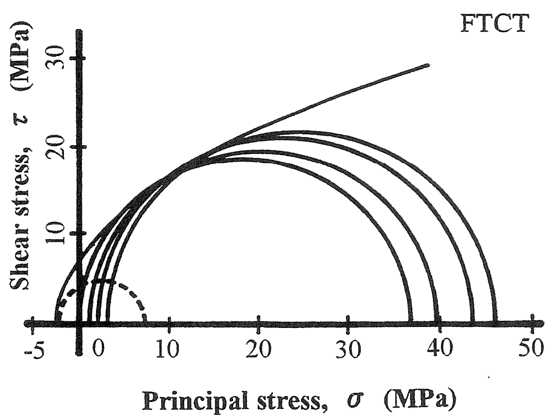

Figure 9. Mohr's stress circles at failure.

4. CONCLUSIONS

Due to inadequate test data, definite characteristics of the FTCT cannot be clarified at present state. However, it can be noted at this fundamental stage that the FTCTs yielded ϕ_i with good engineering accuracy. On the other hand, S_i was underestimated by the FTCTs. It is regarded that underestimation of the compressive strengths in the FTCTs shown in Table 2 gave rise to the underestimation of S_i. It is suggested that H/D ratio of the specimen for the FTCT should be reduced, since the lower H/D ratio of specimen gives the higher compressive strength. Concerning the deformation index, which is the modulus of elasticity or deformation, it can be emphasized that the FTCT brings smaller deformation modulus than the CTCT. Accordingly, it should be noticed that designed results will be the safe side, and that economical investigation of the results is necessary as well.

In any event, the FTCT is certainly performable and it will continue to be applied to the field. Fundamental as well as realistic investigations are still required for reaching final stage. The author is continuing to do research on the FTCT emphasizing on improvements of testing apparatus.

5. ACKNOWLEDGMENTS

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