Compression Testing of Rock-like materials by a Simplified Triaxial Apparatus

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Abstract

A triaxial compression apparatus having simple mechanism was constructed by the authors in order to investigate the failure condition of rock-like materials under the stress state in which the values of three principal stresses differ from one another. Triaxial compression tests applying uniform confining pressure and biaxial compression tests were performed using three types of rock and cement mortar.

Two failure curves obtained by the triaxial test showed different feature, one of which shows precipitous decrease in region where ratio of two principal stresses σ_1 and σ_2 approaches to unity, while the other did not show such a feature. Such difference may be due to difference in magnitude and direction of maximum tensile stresses along the periphery of minute three dimensional voids which are supposed to pervade the material.

Introduction

Numerous works have hitherto been done for studying the strength and deformation characteristics of brittle materials, such as rocks and concrete. Triaxial compression test in which the values of the three principal stresses in the specimen differ from one another, is necessary in order to make study of the criterion of failure under multiaxial compressive stresses. Triaxial testing apparatus which consists of three loading equipments for uniaxial compression testing machine[1)2)3)], triaxial apparatus in which a loading mechanism for horizontal loading is added to the ordinary hydraulic triaxial apparatus and maximum and intermediate compressive stresses are applied by rigid platens while minimum compressive stresses are applied by hydraulic pressure[4)5)], or a triaxial apparatus in which lateral loads are applied by thin flat-jacks have hitherto been used for triaxial testing in which the values of the three principal stresses differ from one another.

A simplified triaxial apparatus in which a cubic specimen of rock-like material is loaded through six rigid platens was recently constructed by the authors. Though this apparatus is similar to the triaxial testing apparatus above mentioned which consists of three loading equipments for uniaxial compression testing machine, its loading capacity was kept down to the order sufficient for triaxial compression test for rock-like materials, and its mechanism was simplified. Triaxial compression tests applying uniform confining pressure and biaxial tests on specimens of three types of rocks and ce-

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ment mortar were performed by this triaxial apparatus.

Triaxial Compression Apparatus

Schematic configuration of the simplified triaxial compression testing apparatus constructed by the authors is shown in Fig. 1. Jacks A and B, C for vertical and horizontal loading are set up on the vertical and horizontal frames as shown in this figure, for applying loads having different magnitude on the six surfaces of the cubic specimen. These jacks can be shifted by adjusting plugs D in axial direction according to the edge length of specimen.

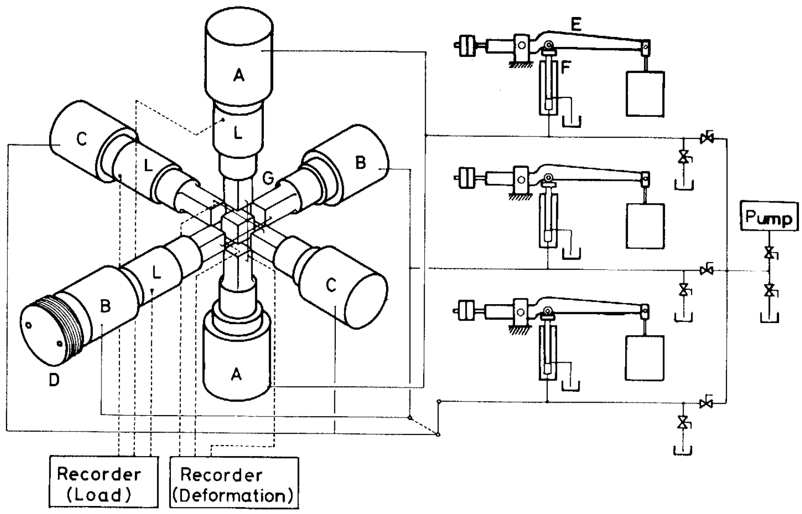

Fig. 1 Schematic configuration of the triaxial compression testing apparatus.

The maximum loads of this apparatus are 40 t in vertical direction and 20 t in each horizontal directions, and the oil pump produces oil pressure up to 420 kg/cm^2. The oil pressure is controlled by three pressure controll equipments. As the axial load on piston F applied by case-shots in a bucket and weight hung at the end of lever E becomes equal to the load acting on lower end of the piston by oil pressure, the piston is shifted upwards up to a definite position, and then the oil pressure is kept constant at this position, the oil being discharged through exhaust hole.

Two kinds of loading platens G, in which dimensions of loading surfaces are 34.8 mm $\times$ 34.8 mm and 33.1 mm $\times$ 33.1 mm were used. Magnitude of applied loads in the three directions is detected by three load cells L set up between jacks and loading platens, and is recorded by X-Y recorders. Load capacities of the load cells for vertical and horizontal direction were 50 t and 20 t respectively, and their sensitivity was 3000×10^{-6} for maximum load in both directions.

Deformation perpendicular to each surface of the specimen is measured by cantilever type displacement gages set up on the loading platens, and is recorded by strain recorder. Sensitivity of the displacement gages is $2695 \sim 2835 \times 10^{-6}$ for displacement

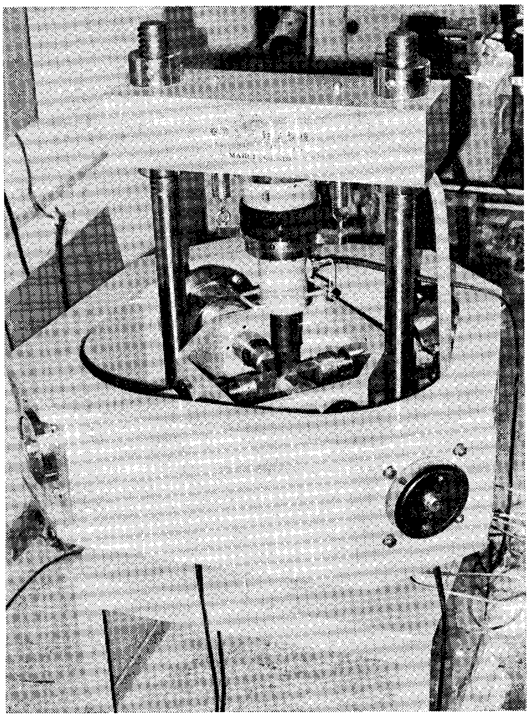

Fig. 2 General view of the triaxial apparatus.

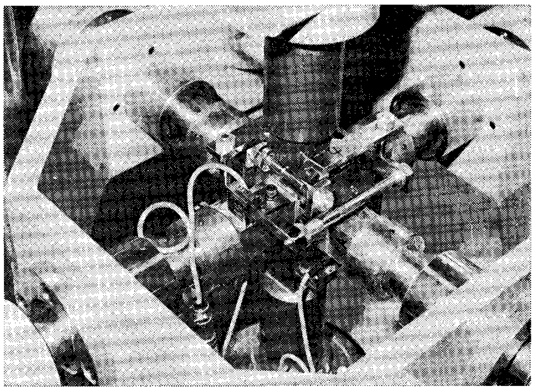

Fig. 3 Main part of the triaxial apparatus.

of 1 mm, and capacity in displacement is 2 mm. Piping connection is changed when triaxial test applying equal confining pressure in two horizontal directions is performed, so that oil pressure delived into jacks B and C becomes equal. Figs. 2 and 3 show general view and main part of the triaxial apparatus.

Experimental Technique

Ogino tuff, Akiyoshi marble, Izumi sandstone and cement mortar were used as samples for this investigation. Rock specimens were shaped into cubes with edge length of about 38 mm, in accordance with "Recommended Practices for Determination of Rock Strength" proposed by MMIJ Committee for Determination of Rock Strength in 1968, and were tested after being dried in desiccator.

Specimens of cement mortal were made by mixining ordinary Portland cement, Toyoura standard sand and water by weight ratio 1: 2: 0.65, and by placing it into cubic molds having 35 mm edge length. These specimens were cured in water at 20°C for 138 ~ 146 days before testing.

Teflon sheets 0.1 mm thick were attached to the loading surface of the platens in order to eliminate the frictional effects between specimen and the platens and to make the distribution of stresses as uniform as possible for tests in which deformation of the specimen was not determined. Since the deformation of specimen was determined by change in distance between two platens in this apparatus, teflon sheet was not used for test in which deformation of the specimen was measured.

In triaxial test applying uniform confining pressure, magnitude of loads in the three directions was increased firstly up to a prescribed value of the horizontal confining pressure, keeping state of hydrostatic pressure, and then magnitude of vertical load was increased by jack A for vertical loading, keeping the magnitude of the horizontal confining pressure constant. Although there are various definitions for failure in triaxial compression test applying uniform confining pressure, intensity of the maximum vertical load was defined as failure stress in this study.

In biaxial compression test, load was applied with approximately similar rate on two pairs of loading surface of a specimen up to prescribed value, and then magnitude of the load in one direction was increased keeping magnitude of load in the other direction constant until failure takes place.

Experimental results and discussion

Stress-strain curves of cement mortar obtained by the triaxial compression testing applying uniform confining pressure are shown in Fig. 4. σ_1 indicates horizontal

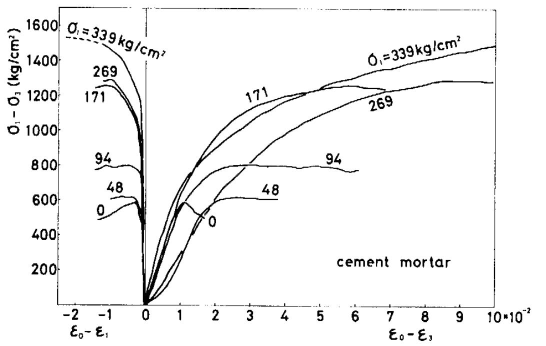

Fig. 4 Stress-strain curves of cement mortar obtained by the triaxial compression test applying uniform confining pressure.

principal compressive stresses corresponding to the uniform confining pressure, and σ_3 indicates vertical principal compressive stress. Signs of stresses are chosen so that tensile stresses are positive and compressive stresses are negative in this paper. ε_0 indicates longitudinal strain in a specimen subject to hydrostatic pressure stress state, magnitude of which is equal to the magnitude of prescribed horizontal confining pressure. ε_1 and ε_3 indicate longitudinal strain in σ_1- and σ_3-direction as magnitude of the vertical load increases. It may be recognized from this figure that the higher the magnitude of confining pressure is the more ductile the material becomes.

Relation between σ_1 or σ_2, horizontal principal compressive stresses corresponding to the uniform confining pressure, and σ_3, failure stress in vertical direction obtained by the triaxial compression test with uniform confining pressure is shown in Fig. 5, in which *Sc* indicates uniaxial compressive strength of the specimen. Four failure curves showing results of experiment in which $\sigma_3 \neq 0$, indicate that position of curves for tuff and cement mortar, the brittleness index of which is lower than that of sandstone or marble is nearer to hydrostatic pressure line than that of curves for sandstone and marble.

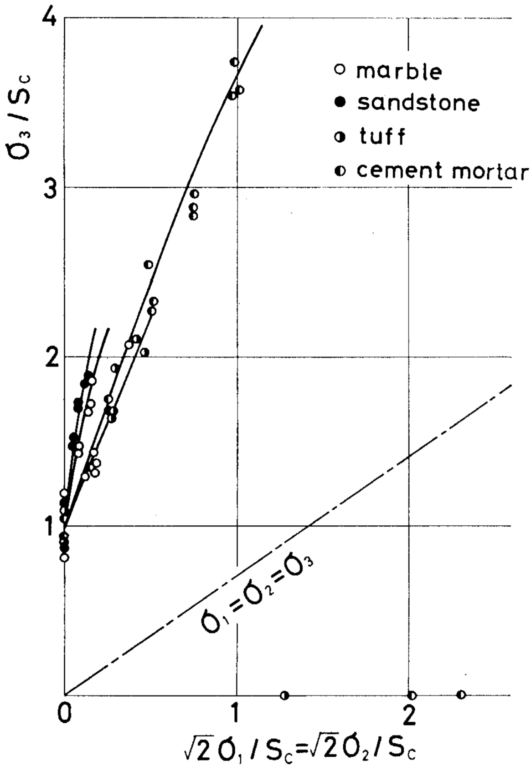

Fig. 5 Relation between σ_1 or σ_2 and σ_3 obtained by triaxial compression test.

Mohr's stress circles showing stress state at failure and Mohr's envelopes for these stress circles obtained by the triaxial compression test applying uniform confining pressure using Ogino tuff, Izumi sandstone, Akiyoshi marble and cement mortar are shown in Figs. 6, 7, 8 and 9. It can be seen that slope of tangent along the Mohr's envelopes for Izumi sandstone and Akiyoshi marble shows larger values than that for Ogino tuff and cement mortar.

Results of the biaxial compression tests are shown in Figs. 10 and 11. Fig. 10 shows relation between principal stress σ_2 which is equal to the intensity of load in one direction, and the other principal stress σ_3 which is equal to the intensity of load at failure in direction perpendicular to σ_2, obtained by the biaxial test of Ogino tuff.

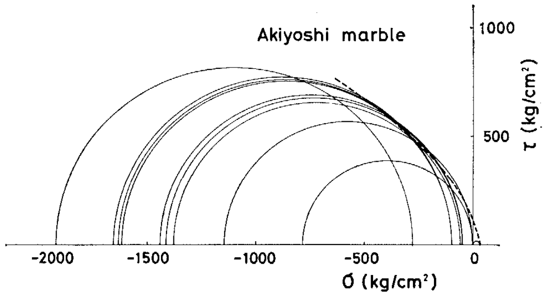

Fig. 6 Results of triaxial compression test on Akiyoshi marble.

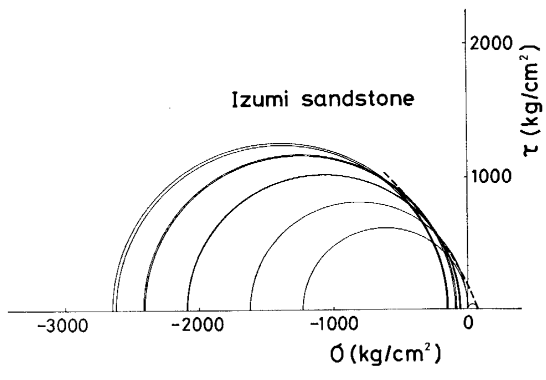

Fig. 7 Results of triaxial compression test on Izumi sandstone.

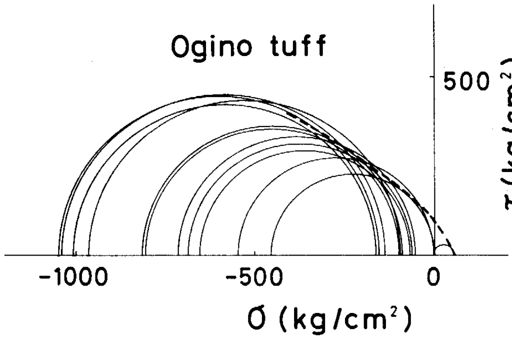

Fig. 8 Results of triaxial compression test on Ogino tuff.

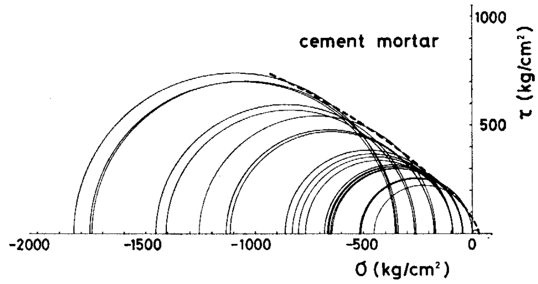

Fig. 9 Results of triaxial compression test on cement mortar.

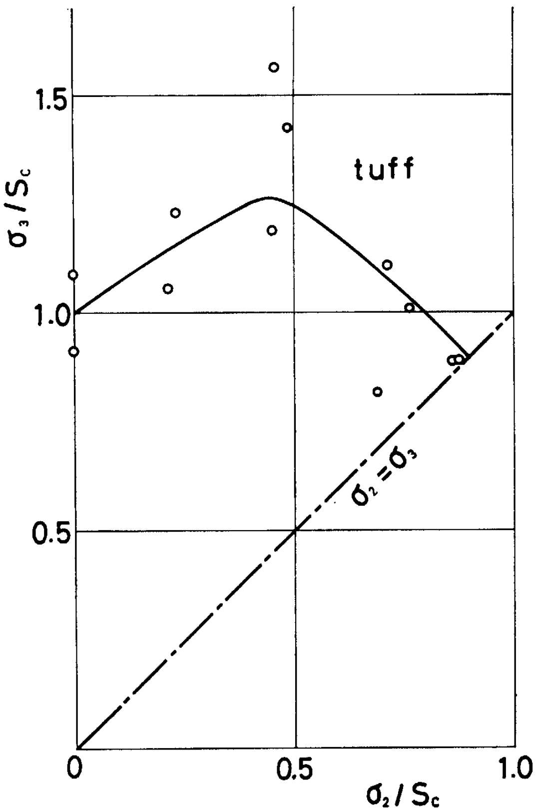

Fig. 10 Results of biaxial compression test on Ogino tuff.

Although this experimental results show cosiderable fluctuation, it can be seen from this figure that the value of σ_3 varies with value of σ_2, and that in the region where ratio σ_2/σ_3 is small, the value of σ_3 increases with increase of ratio σ_2/σ_3, while the value of σ_3 decreases precipitously with increase of ratio σ_2/σ_3 in the region where σ_2/σ_3 approaches to unity, and the failure stress σ_3 at $\sigma_2=\sigma_3$ shows lower value than uniaxial compressive strength.

Fig. 11 shows results of biaxial compression test for cement mortar specimens. Although experimental data show considerable fluctuation as well, it can be seen that the value of σ_3 varies with the value of σ_2. However, precipitous decrease of σ_3 with increase of σ_2 in the region where the ratio σ_2/σ_3 approaches to unity is not recognized,

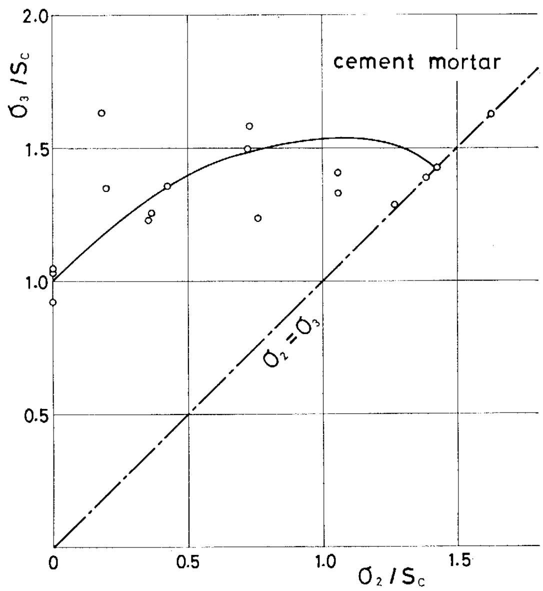

Fig. 11 Results of biaxial compression test on cement mortar.

contrarily to the case of Ogino tuff, and failure stress at $\sigma_2=\sigma_3$ shows higher value than uniaxial compressive strength.

It may be indisputable from above mentioned results of biaxial compression tests, that the maximum stress σ_1 at failure is affected not only by the minimum stress σ_3 but also by the intermediate stress σ_2. In order to explain the reason why the slope of failure curves shown in Figs. 9 and 10 differ in the region where σ_2/σ_3 approaches to unity the following consideration was made. Supposing now that minute voids the shape of which are ellipsoids of revolution as shown in Fig. 12 pervade the specimen on which loads are applied with instensity σ_3 in vertical and σ_2 in horizontal directions,

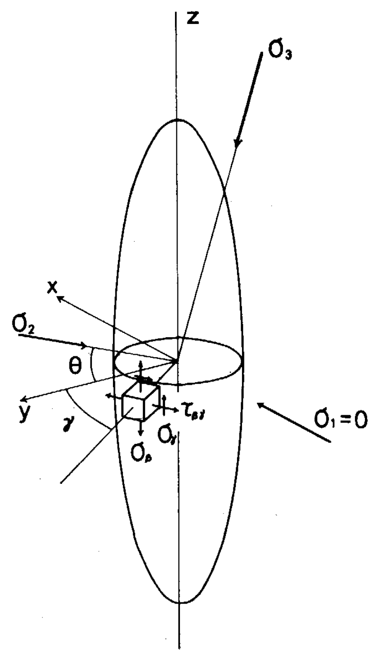

Fig. 12 Stress components at a point on periphery of a minute void, the shape of which is ellipsoid of revolution.

the maximum value of tangential stresses σ_t on periphery of the void is given by three stress components σ_β, σ_γ and $\tau_{\beta\gamma}$, where β indicates direction along the ellipse and γ indicates direction along the circle[7]. Then, if failure of brittle materials is caused by maximum value of σ_t as Griffith criterion asserts, maximum tangential stresses generally occurs at points near both ends of the ellipsoid, and their value is largely affected by value of σ_β. Fig. 10 may indicate such stress condition at failure. However, in some material, maximum tangential stresses may be governed by σ_γ in the region where ratio σ_2/σ_3 approaches to unity. Fig. 11 may indicate such stress condition at failure.

Fracture patterns in specimens being subjected to the triaxial compression tests applying uniform confining pressure and the biaxial compression test are shown in Fig. 13. Fig. 13(a) shows the fracture pattern of Ogino tuff submitted to triaxial compression test, in which condition of stresses at failure was $\sigma_1=\sigma_2=-137$ kg/cm^2 and $\sigma_3=-1040$ kg/cm^2. Inclination of fracture planes to the σ_3-direction was 22~25°. Fig. 13(b) shows the fracture pattern of Izumi sandstone submitted to triaxial compression test, in which condition of stresses at failure was $\sigma_1=\sigma_2=-148$ kg/cm^2 and $\sigma_3=-2630$ kg/cm^2. Inclination of fracture planes to the σ_3-direction was 10~15°. Fig. 13(c) shows the fracture pattern of Ogino tuff submitted to the biaxial compression test, in which condition of stresses at failure was $\sigma_2=-438$ kg/cm^2 and $\sigma_3=-446$ kg/cm^2. Tabular fracture in planes parallel to two surfaces of the specimen on which no load was applied can be seen in this photograph.

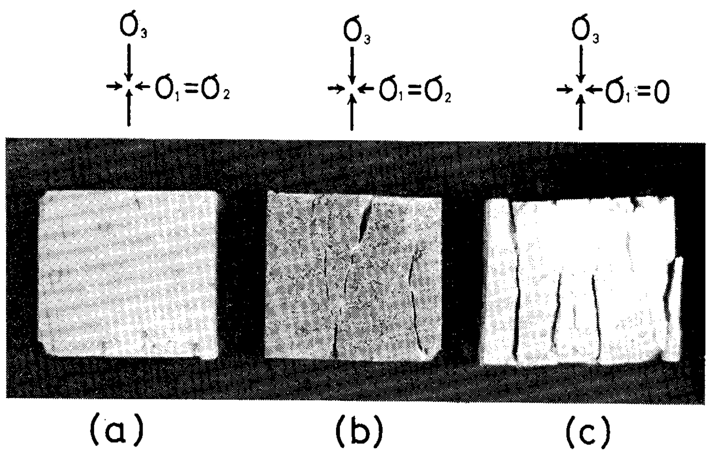

Fig. 13 Fracture patterns in specimens being subjected to the triaxial and biaxial compression test.

(a) Ogino tuff submitted to triaxial compression test.
(b) Izumi sandstone sudmitted to triaxial compression test.
(c) Ogino tuff submitted to biaxial compression test.

Relation between $\sigma_m=(\sigma_1+\sigma_3)/2$, magnitude of mean principal stress, and θ, inclination of the fracture planes in the specimens to the σ_3-direction, obtained by the triaxial compression test, is shown in Fig. 14. Solid curves indicate angles determined by measurement of inclination angle of the fracture planes, while broken curves indi-

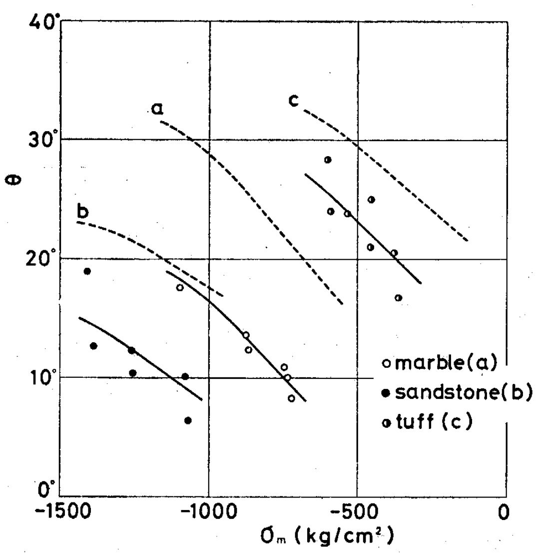

Fig. 14 Relation between mean principal stress σ_m and inclination of the fracture plane θ.

cate angle of inclination of fracture planes determined by the envelope of Mohr's stress circles in Figs. 6, 7 and 8. In the latter case θ was determined by the formula $\theta=\pi/4-\phi/2$ where ϕ represents angle between τ-axis and normal of the envelope. It can be seen from Fig. 14 that angle θ, inclination of the fracture plane increases with increase of mean principal stress σ_m. Angle of inclination determined by the Mohr's envelope shows higher value than that obtained by measurement of inclination of the actual fracture plane.

Conclusions

A simplified triaxial apparatus was constructed by the authors in order to investigate the failure condition of rock-like materials. Triaxial compression tests applying uniform confining pressure and biaxial compression tests were performed using samples of three types of rock and cement mortar. Stress conditions at failure in the cases: (i) $\sigma_1=\sigma_2\neq 0$, $\sigma_3\neq 0$ and (ii) $\sigma_1=0$, $\sigma_2\neq 0$, $\sigma_3\neq 0$ were obtained and stress-strain curves in case (i) were determined. Following conclusions were obtained by this study:

(1) Failure curves obtained by the triaxial test of materials having low brittleness index takes nearer position to the hydrostatic pressure line than the curves of materials having high brittleness index.

(2) Inclination of fracture plane to the σ_3-direction, obtained by the triaxial test, increases with increase of mean principal stress σ_m.

(3) Failure condition of rock-like materials are markedly affected not only by the maximum and the minimum principal stress, but also by the intermediate principal stress, when the values of the three principal stresses differ from one another.

(4) Two failure curves obtained by the biaxial test show different feature, one of which shows precipitous decrease in region where the ratio σ_2/σ_3 approaches to unity, while the other does not show such a feature. Such difference may be due to differ-

ence in magnitude and direction of maximum tangential stresses on the periphery of minute voids which are supposed to pervade the specimen.

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