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Grain Size Dependence of Ultimate Strength of Marble Under Confining Pressure and the Size of Griffith Inclusion

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Abstract

Rock specimens of marble, limestone, sandstone, and granite were deformed under confining pressure of 1 to 2000 kg/cm^2 at room temperature and at strain rate of 3.5×10^{-5}/sec. The relation between ultimate strength and grain size is obtained for five marbles and one limestone specimens, which have been tested with a tri-axial rock deformation apparatus. Their mean grain size ranges from 4 mm to 0.005 mm.

Under confining pressure of 500 kg/cm^2 and 1,000 kg/cm^2, ultimate strength of the marble, the mean diameter of which is coarser than 0.3 mm, increases linearly with the inverse square root of the mean grain size, as it is suggested by the Griffith inclusion theory of fractures. However, the strength of the limestone and marble finer than 0.3 mm in mean grain size is much smaller than the theoretical value expected from the grain size. The size of effective Griffith inclusion is the order of a single grain size in coarse-grained marbles. However, the intergranular Griffith inclusions look like to exist in the specimens of fine-grained limestone.

The Yamaguchi marble is mechanically anisotropic under the atmospheric pressure but becomes less anisotropic under higher confining pressures.

1. Introduction

The effect of grain size on the strength of marble and limestone has been studied by several investigators (HANDIN and HAGER, 1957, PATERSON, 1958, BRACE, 1961, INAMI *et al.*, 1969, OLSSON, 1974). All these investigators confirmed that finer-grained limestones are generally stronger than coarser-grained ones. However, the detailed grain size-strength relationship has not been clarified yet.

In this study, the strength of a fine-grained Egyptian micritic limestone is compared with several Japanese marbles of various grain sizes. All specimens have been tested with a tri-axial rock deformation apparatus under confining pressures from 1 to 2,000 kg/cm^2 and at the strain rate of 3.5×10^{-5}/sec.

Specimens of sandstone and granite were also tested for comparison. It is indicated that the Griffith inclusion model of fracture can explain the grain size dependence of strength.

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2. Experimental procedure

Blocks of rocks are cut into slabs of 15 cm thick. From each block, cylindrical specimens are cored with water-flushed diamond drill. The cores are then trimmed and ground into the cylinders of 39.0 mm long and 19.5 mm diameter. Finishing accuracy of the trimming is ± 0.02 mm.

Each specimen is jacketed with a thin- wall annealed copper tube, whose strength is negligibly small as compared with the strength of rock. Two ends of the cylinder are separated from the loading pistons or anvil with steel discs to prevent the penetration of high pressure kerosene into the space between the copper jacket and specimen. The testing apparatus of the Geological Survey of Japan used in this study has been described by HOSHINO *et al.* (1972). The confining pressure is applied by kerosene on the copper jacket by a pneumatic pump, and is measured with Heise pressure gauge. The pressure vessel and the specimen assembly are shown in Fig. 1.

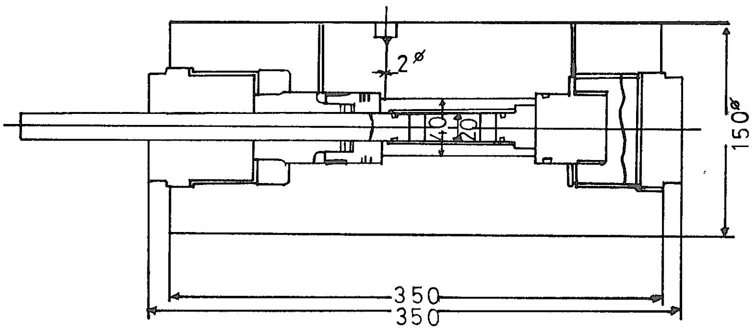

Fig. 1 Pressure vessel (unit, mm)

Axial load and specimen shortening are recorded by a x-y recorder. The shortening of the specimen is obtained from the recorder displacement substracting the elastic distortion of the apparatus. The strain under the differential stress is expressed as a percentage of the specimen length. True stress is obtained from the recorded value of the load divided by the cross-sectional area of the specimen under the assumptions that the deformation is homogeneous and no volume change occurs by differential stress.

3. Experimental Results

The tested rocks are Yamaguchi marble, Kamioka marble, Egyptian limestone, Maze sandstone and Tokuyama granite. Brief descriptions of the specimens are given in Appendix 1. Specimens are compressed to various strain percentages for ductile rocks, and until failure occurs in the case of brittle rocks.

Stress-strain curves for each rock specimen under different confining pressures are recorded, and the ultimate strength and ductility as functions of confining pressure are given. In the present investigation the ultimate strength is defined as the maximum differential stress ($\sigma_1-\sigma_3$) on the stress-strain curve. The terms "brittle" and "ductile" as defined by HANDIN (1966) have been adopted throughout the present analysis.

The experimental results are summarized in Table 1. A summary of dynamic physical properties of the rocks is given in Appendix 2.

Table 1

Rock type	No.	Conf. pressure kg/cm²	Ultimate strength kg/cm²	Mode of failure	Mechanical behaviour	Angle of fracture θ°
Yamaguchi	1	1	900	wedge	very brittle	
marble	2	100	1250	shear	brittle	6°
(SKA-1)	3	500	2150	flow	ductile	
	4	1000	3100	flow	ductile	
	5	1500		flow	ductile	
Yamaguchi	1	1	950	wedge	very brittle	
marble	2	500	2100	flow	ductile	
(SKA-2)	3	1000	3000	flow	ductile	
	4	1500		flow	ductile	
Yamaguchi	1	1	750	wedge	very brittle	
marble	2	100	1100	shear	brittle	10°
(SKA-3)	3	500	2000	flow	brittle	
	4	1000	3000	flow	ductile	
	5	1500	4200	flow	ductile	
Kamioka	1	1	700	shear	brittle	
marble	2	100	900	shear	brittle	6°
	3	500	1400	network	ductile	
	4	1000	2150	network	ductile	
	5	1500		network	ductile	
	6	2000		network	ductile	
Egyptian	1	1	2000	shattered	very brittle	
limestone	2	300	2950	shear	brittle	15°
	3	500	3400	network	transitional	
	4	700	3750	network	transitional	
	5	900	4200	network	ductile	
	6	1200	4350	uniform flow	ductile	
	7	1500	4500	uniform flow	ductile	
Maze	1	300	2500	shear	brittle	8°
sandstone	2	600	4200	shear	brittle	27°
	3	1000	5300	shear	brittle	29°
	4	1200	5500	shear	brittle	31°
	5	1500	6150	shear	brittle	30°
Tokuyama	1	1	2000	wedge	very brittle	
granite	2	100	3350	shear	very brittle	27°
	3	300	5500	shear	brittle	22°
	4	500	6200	shear	brittle	25°
	5	700	7100	shear	brittle	25°
	6	900	8250	shear	brittle	25°
	7	1200	9500	shear	brittle	26°
	8	1500	10000	shear	brittle	25°

Yamaguchi marble

The rock has been compressed under 1, 100, 500, 1,000 and 1,500 kg/cm² confining pressures. Stress-strain curves are shown in Figs. 2 to 4. Although the specimens SKA-1,

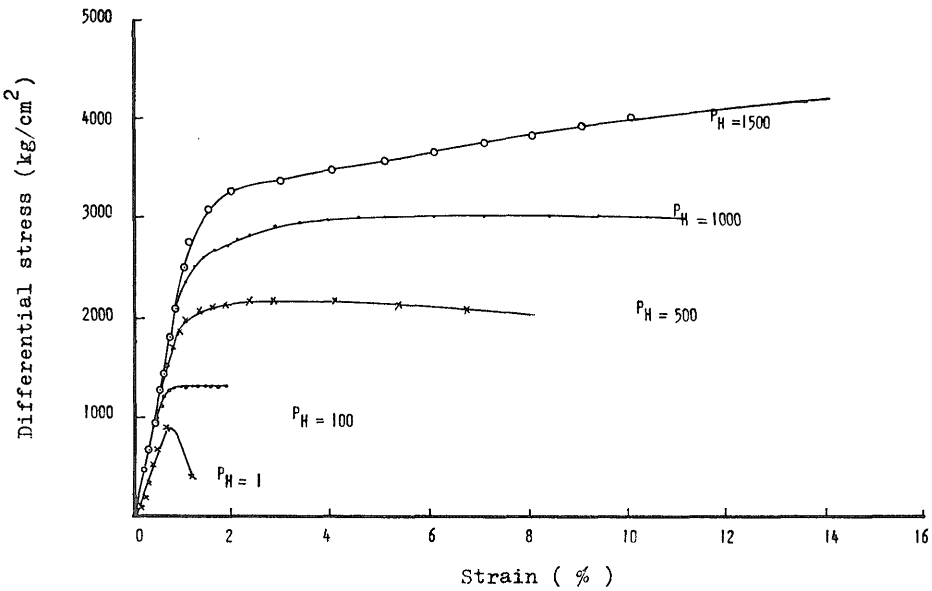

Fig. 2 Stress-strain curve for Yamaguchi marble (SKA-1), tested in compression at room temperature and under confining pressures given for each curve.

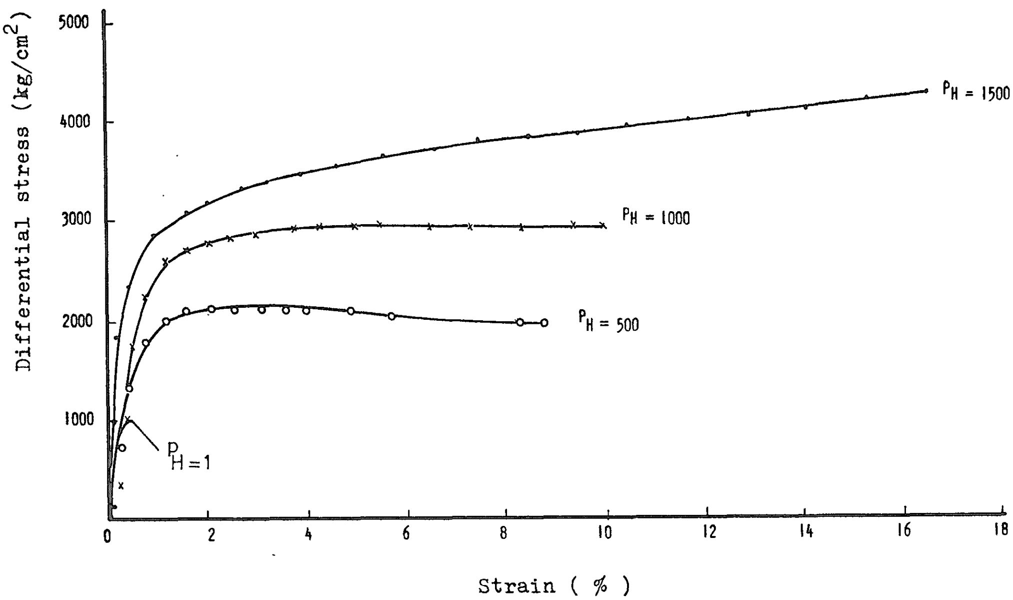

Fig. 3 Stress-strain curve for Yamaguchi marble (SKA-2), tested in compression at room temperature and confining pressures given for each curve.

SKA-2 and SKA-3 are taken from a single block of marble, the orientation of each cylinder axis in the original block is perpendicular with one another. The stress-strain curves of SKA-1 and SKA-2 are found to be very similar. The stress-strain curves of SKA-3 under confining pressures of 1,000 and 1,500 kg/cm^2 are also similar to those for SKA-1

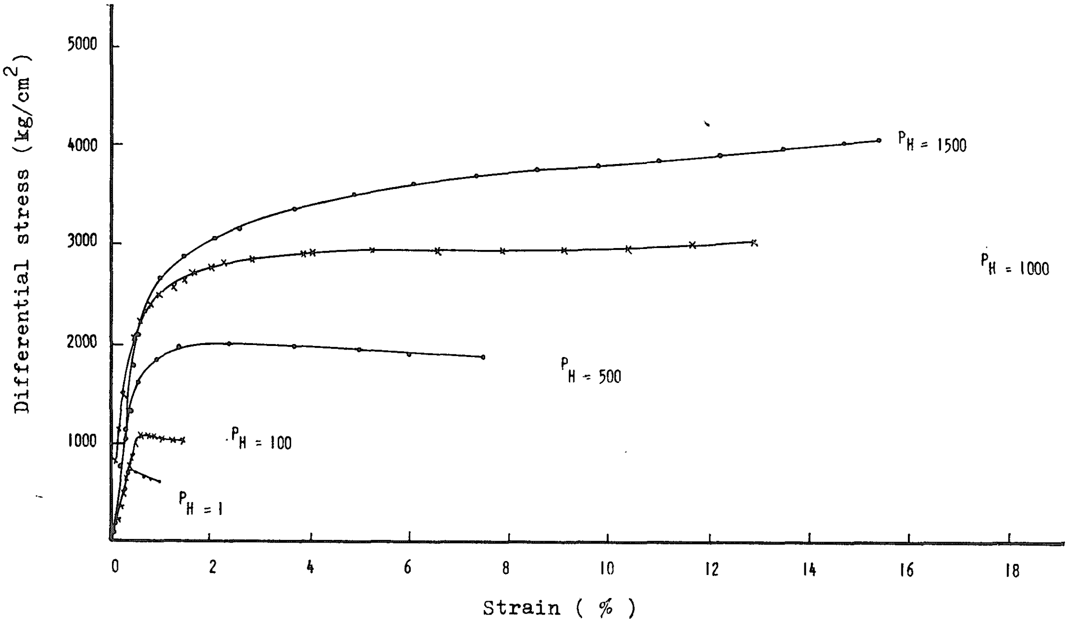

Fig. 4 Stress-strain curve for Yamaguchi marble (SKA-3), tested in compression at room temperature and under confining pressures given for each curve.

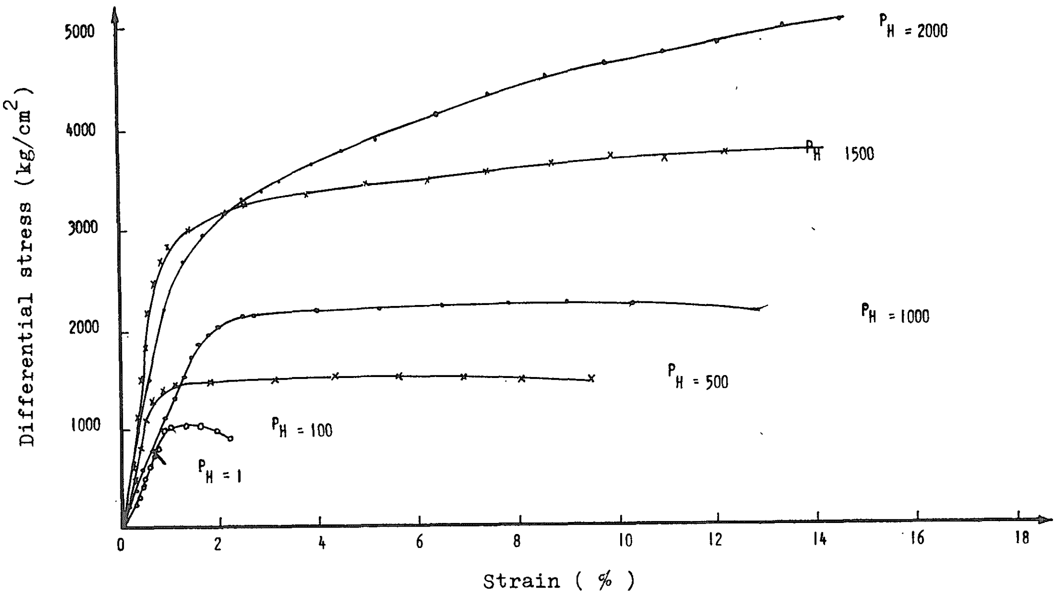

Fig. 5 Stress-strain curve for Kamioka marble (KK), tested in compression at room temperature and under confining pressures given for each curve.

and 2. The cylinder SKA-3, however, is weaker than the others under the confining pressure of 500 kg/cm^2 and the atmospheric pressure. The difference of strength is relatively larger under lower confining pressure. The Yamaguchi marble is, thus, mechanically anisotropic at lower confining pressure than 500 kg/cm^2 but almost isotropic under confining pressure above 1,000 kg/cm^2. DONATH (1961) and IMAM and SAYED AHMED (1972) showed that the strength and deformation mode are strongly affected by the presence of planar anisotropy. Closure of preexisting fractures would be the cause of the more isotropic behavior of marble under higher confining pressures.

Kamioka marble

The rock has been tested at 1, 100, 500, 1,000, 1,500 and 2,000 kg/cm^2 confining pressures. Stress-strain curves are shown in Fig. 5. Results obtained show that the rock is weak and brittle under the atmospheric pressure. The rock is remarkably ductile even at low confining pressures. The ultimate strength and ductility increase remarkably with the confining pressure. The ultimate strength at 2,000 kg/cm^2 confining pressure is about 7 times that at the atmospheric pressure.

Grain boundary fracturing, intragranular fracturing, translation sliding and twinning are observed microscopically in thin sections of the deformed marble (Plate 12). Fractures are extensive at 100 and 500 kg/cm^2, but twinning and translation sliding are prominent under high confining pressures. Undulatory extinction observed in the specimen tested under 1,000 kg/cm^2 indicates residual strain in calcite crystals.

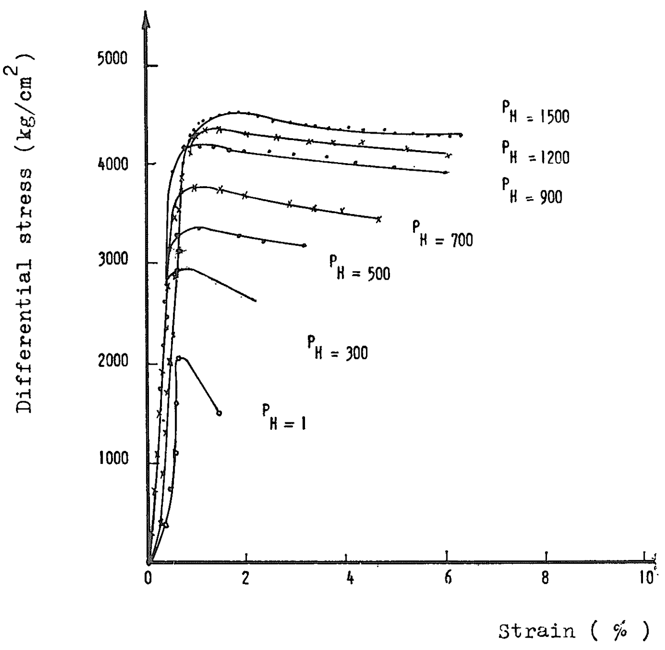

Fig. 6 Stress-strain curve for Egyptian micritic limestone (E), tested in compression at room temperature and under confining pressures given for each curve.

Egyptian limestone

The rock has been tested at 1, 300, 500, 700, 900, 1,200 and 1,500 kg/cm^2 confining pressures. The results are shown in stress-strain curves of Fig. 6. Their Mohr envelope can thus be drawn as Fig. 7. The rock is very brittle and strong under the atmospheric pressure. At 300 kg/cm^2 confining pressure, the rock is still brittle and shows a declining in differential stress. The stress-strain curves at 500 and 700 kg/cm^2 show slight decrease

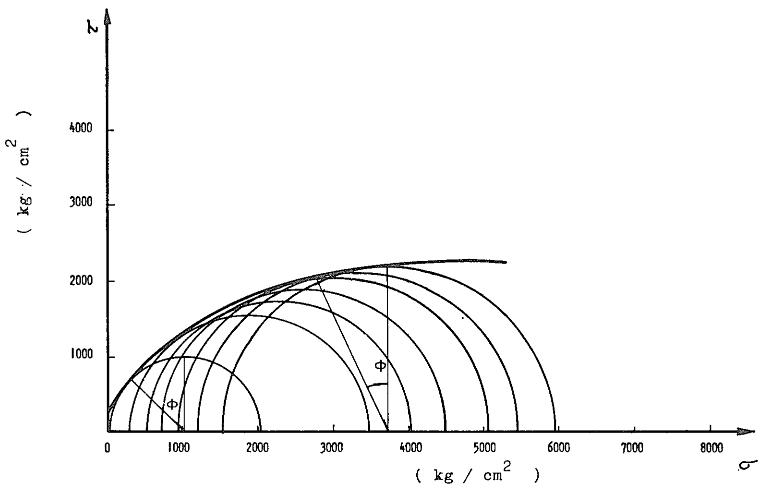

Fig. 7 Mohr envelope of Egyptian limestone (E)

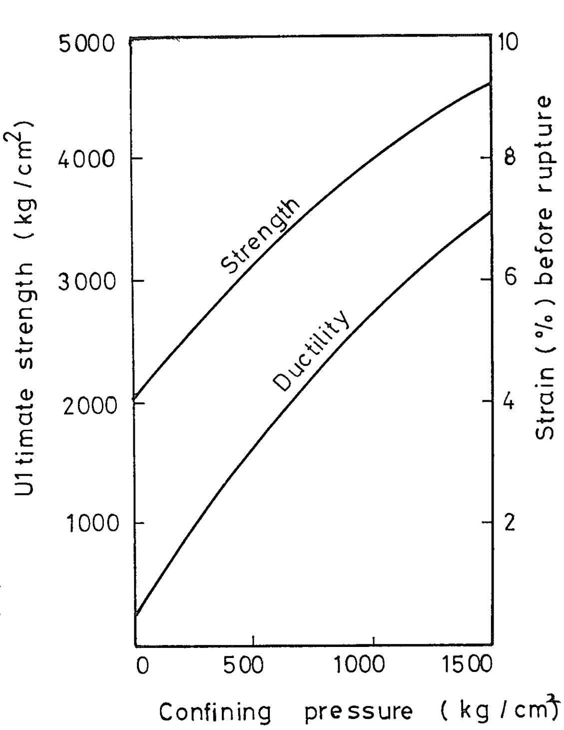

Fig. 8 Ultimate strength and ductility for Egyptian limestone (E) vs. confining pressure.

in differential stress after the yield points. The ultimate strength and ductility increase slowly with the increase in confining pressure. The ductility is defined as the strain at the ultimate stress (HANDIN, 1966). The relationships are slightly nonlinear (Fig. 8).

Mode of failure of this limestone under the atmospheric pressure is almost of brittle type, developing shear fractures with granulation in shear zone (Fig. 1 of Plate 10). At 300 kg/cm², brittle failure occurred on shear plane (Fig. 2 of Plate 10). Fine white Lüders bands are clearly observed in the specimens deformed under higher confining pressures. The Lüders band is a deformation zone in which numerous microcracks are concentrated (KOIDE and HOSHINO, 1967; HOSHINO and KOIDE, 1970; KOIDE, 1971). Some Lüders bands originate from defects in the specimens deformed at 700 and 900 kg/cm² confining pressures (Plate 10).

Maze sandstone:

The rock has been tested under the confining pressure ranging from 300 to 1,500 kg/cm². Stress-strain curves are shown in Fig. 9, and the Mohr envelope in Fig. 10. The rock fails in a brittle manner within this range of confining pressure. The breaking strenth increases remarkably with pressure. The ultimate strain increases slightly, not exceeding 3.5 percent. The strength-pressure curve is nonlinear (Fig. 11). Fracture occurs on the shear surface inclined at 8–31° to the major principal stress axis (Plate 11-a).

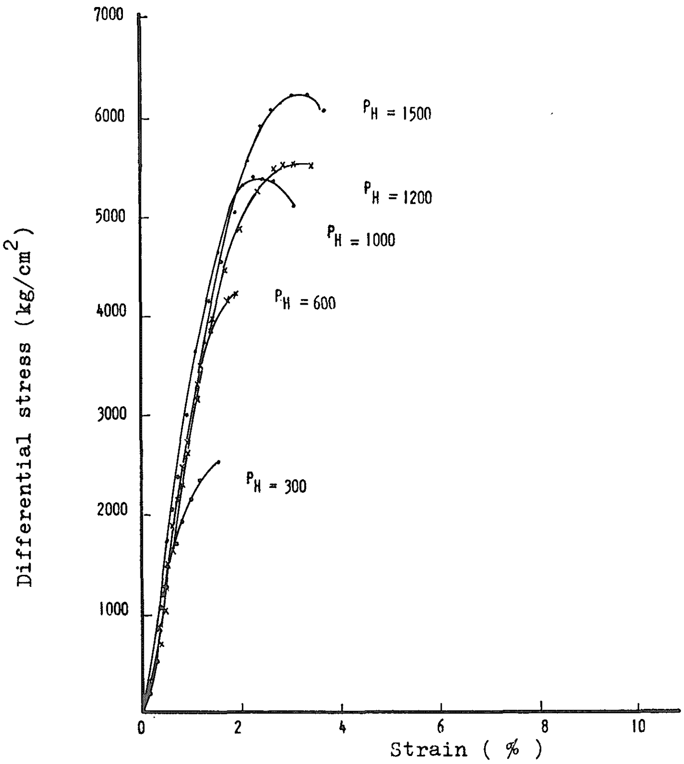

Fig. 9 Stress-strain curve for Maze sandstone (2K), tested in compression at room temperature and under confining pressures given for each curve.

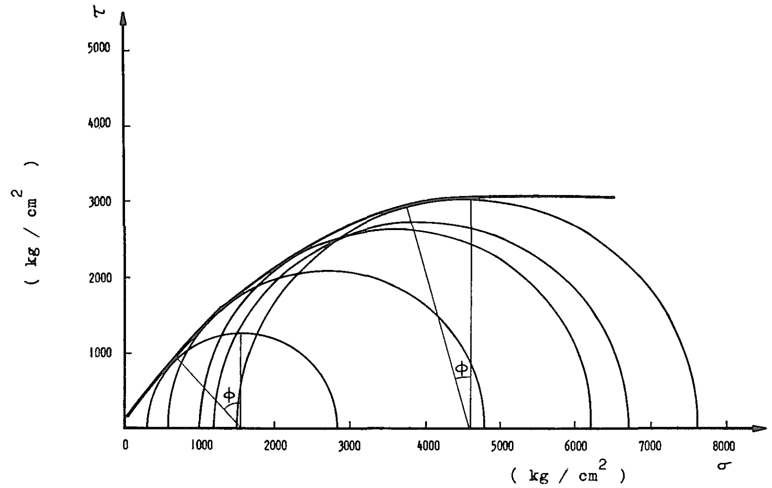

Fig. 10 Mohr envelope of Maze sandstone (2K).

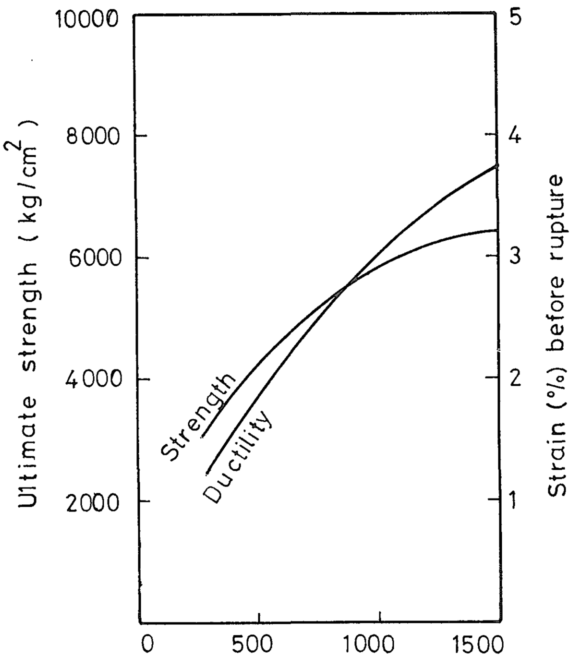

Fig. 11 Ultimate strength and ductility for Maze sandstone (2K) vs. confining pressure.

Tokuyama granite

The test has been made under the confining pressure ranging from the atmospheric to 1,500 kg/cm^2. The results are shown in Fig. 12 and 13. The rock is very brittle under these confining pressures and failure is followed by a drop of the differential stress to zero. The breaking strength increases remarkably with pressure. The increase in the ductility is very slight, not exceeding 1.5 percent. The ultimate strength at 1,500 kg/cm^2 is about five times that at the atmospheric pressure (Fig. 14).

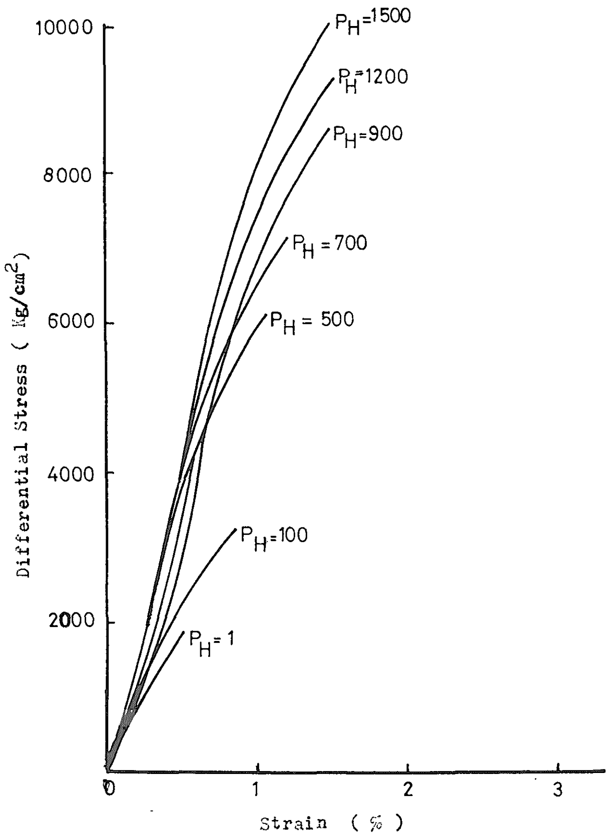

Fig. 12 Stress-strain curve for Tokuyama granite (SKB), tested in compression at room temperature and under confining pressures given for each curve.

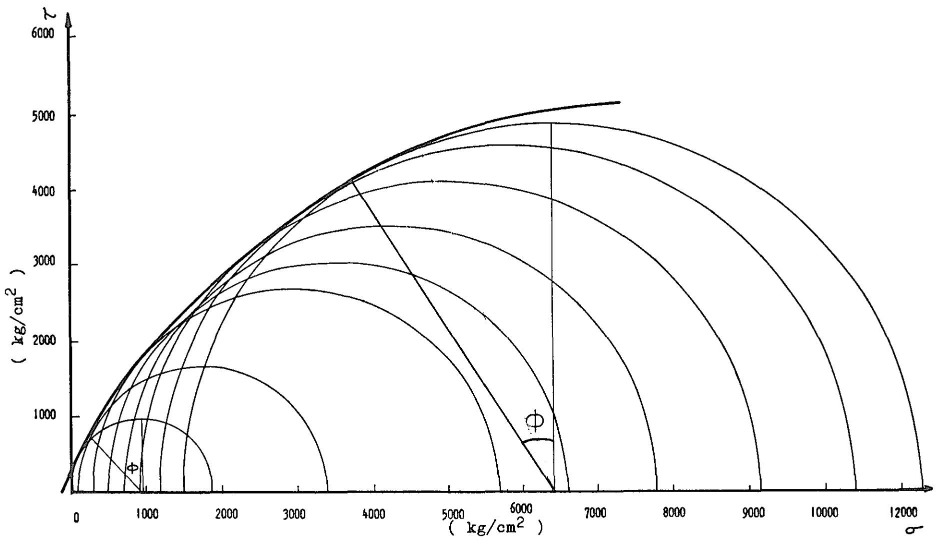

Fig. 13 Mohr envelope of Tokuyama granite (SKB)

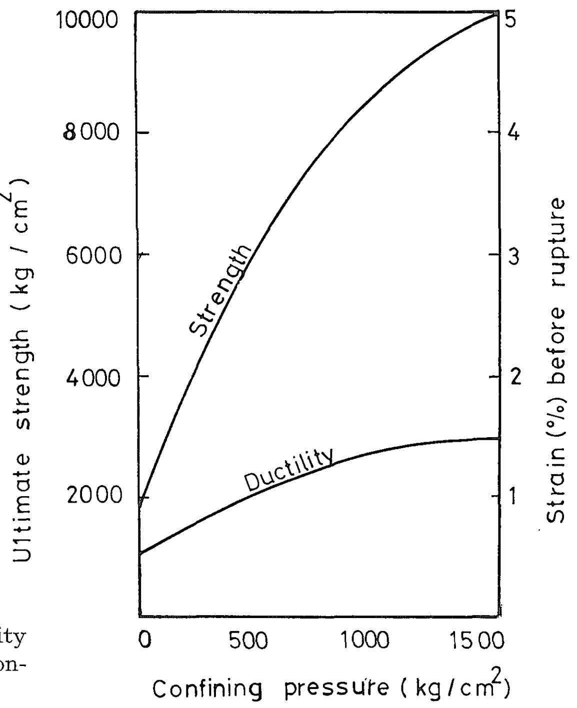

Fig. 14 Ultimate strength and ductility for Tokuyama granite (SKB) vs. confining pressure.

Under the atmospheric pressure, the fractured rock shows characteristic wedge type pattern. Under higher confining pressures the fracture occurs on the shear surface inclined at 27–25° to the major principal stress axis (Plate 11-b).

4. Discussion

The Egyptian micritic limestone, which consists of very fine micrite grains (mean diameter=0.005 mm), is very strong and brittle. On the other hand the Kamioka marble, which occurs near a contact metasomatic lead-zinc deposit of the Kamioka mine, Gifu prefecture, central Japan and is composed of very large grains (mean diameter =4 mm), is found to be very weak and ductile. The Yamaguchi marble (SKA), the grain size of which is much smaller (mean diameter=0.3 mm) than the Kamioka marble, shows an intermediate property. The relations between ultimate strength and grain size at the confining pressures of 1, 500 and 1,000 kg/cm^2 are shown in Fig. 15 on log-log coordinates. The ultimate strength is also plotted against the inverse square root of the mean grain size in Fig. 16. The data of three additional Yamaguchi marbles (YD, YE and YS), also plotted in Figs. 15 and 16, are taken from INAMI *et al.* (1969), in which the experiment has been made using the same apparatus in the Geological Survey of Japan as the present study. The ultimate strength cannot be defined for the marbles under confining pressures above 1,500 kg/cm^2.

The relation between strength and grain size can be generally described by the following equation (INAMI *et al.*, 1969; OLSSON, 1974).

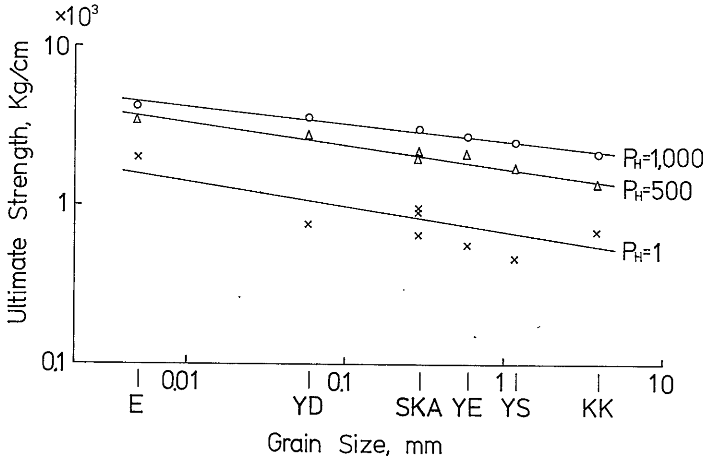

Fig. 15 Ultimate strength as a function of grain size in log-log coordinates. YD, YE and YS are Yamaguchi marbles tested with the same apparatus as in this experiment (INAMI *et al.*, 1969). Tested confining pressures are 1 kg/cm² (cross), 500 kg/cm²(triangle) and 1,000 kg/cm²(circle).

$$\sigma_u = K_0 + Kd^m \qquad \cdots\cdots\cdots(1)$$

where σ_u is the ultimate strength, d is the mean grain size, and K_0, K, m are constants.

The strength data under the atmospheric pressure are fluctuated. However, the strength decreases almost linearly with the increase of grain size under 500 and 1,000 kg/cm², confining pressures, although the points in Fig. 15 seem to follow lines slightly concaved downwards. The value of index under m in the equation (1) is estimated as -0.11–-0.15 from Fig. 15.

PETCH (1953) postulated that, in metal polycrystals, the tensile stress concentration ahead of a group of dislocation pile up against a grain boundary is relieved by the formation of microcrack. The theoretical value of m is $-1/2$ by Petch's simple model. In rocks, grain boundaries are the most important planes of weakeness rather than rigid obstacles of dislocation (Plate 12). The condition for the formation of microcracks ahead of planes of weakness such as grain boundary or lamella is obtained by the Griffith inclusion model (KOIDE, 1972).

$$\tau = \frac{2T_m}{b}\sqrt{1 - \frac{a}{T_m}\sigma}. \qquad \cdots\cdots\cdots(2)$$

where,

$$a = 8\Big/\left\{2\pi/s + 4(1-\nu)\frac{K'}{G} + \frac{16}{3}(1-\nu)\frac{G'}{G}\right\},$$
$$b = 8\Big/\left\{(2-\nu)\pi/s + 4(1-\nu)\frac{G'}{G}\right\} \qquad \cdots\cdots\cdots(3)$$

In this equation, τ is the critical shearing strength which forms microcracks ahead of the Griffith inclusion, σ is normal stress (compression being negative), s is the aspect ratio, $s=\sqrt{c/2\rho}$, where c is the diameter of the penny-shaped Griffith inclusion and ρ

is the radius of curvature of the inclusion tip, ν and G are Poisson's ratio and the rigidity of the host, respectively, G' and K' are the rigidity and the bulk modulus of the inclusion, respectively, and T_m is the ideal tensile strength of the host.

As the ratio K'/G for grain boundary is not very small, the coefficient a is relatively small in comparison with the conventional Griffith crack model. In this study, effect of normal pressure can be neglected. Thus, the ultimate strength is almost twice the critical shearing strength. If the radius of curvature of the inclusion tip is constant, the ultimate strength can be expressed as a function of the diameter of Griffith inclusion.

$$\sigma_u = K_0' + K' \times c^{-1/2} \qquad \cdots\cdots\cdots(4)$$

where K_0' and K' are constants and c is the diameter of Griffith inclusion. If the effective Griffith inclusion in marble is of the size of grain boundary, the equation (4) is similar to Petch's relation in metallic polycrystals (PETCH, 1953).

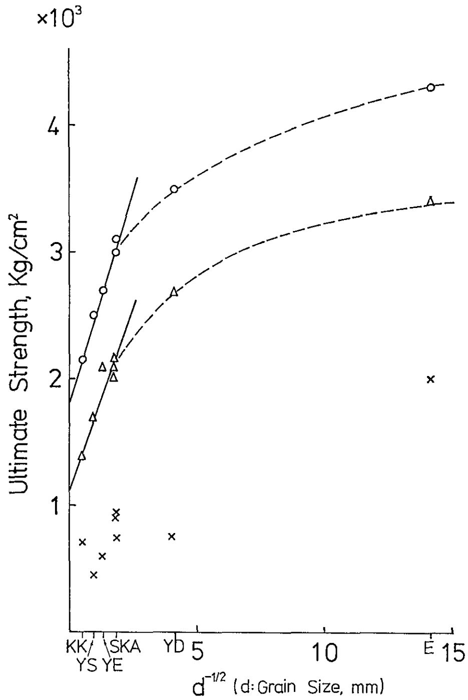

Fig. 16 Ultimate strength plotted against (mean grain size $d)^{-1/2}$. Symbols are the same as Fig. 15.

Under confining pressures of 500 and 1,000 kg/cm², the experimental relation of σ_u versus $d^{-1/2}$ is almost linear for four coarse-grained marbles which consist of larger calcite grains than 0.3 mm (Fig. 16). However, the measured strength of fine-grained marble and limestone is much weaker than the theoretically expected value (Fig. 16). This unexpected weakness suggests that the effective Griffith inclusion in fine-grained limestone is larger than the order of a single grain diameter. In fine-grained limestones, there is high possibility that the specimens contain intergranular Griffith inclusions which are effectively connected grain boundaries, pre-existing fractures, schistosity planes etc.

The ultimate strength-grain size relation of the four coarser marbles under 1,000 kg/cm² confining pressure is expressed in the following equation.

$$\sigma_u = 1{,}800 + 670 \times d^{-1/2} \qquad \cdots\cdots\cdots(5)$$

If the Griffith inclusion in coarse-grained marble is about the size of grain diameter, the approximate size of Griffith inclusion in fine-grained limestone can be estimated from the equation (5). The roughly estimated sizes of effective Griffith inclusions are 0.16 mm for Yamaguchi marble (YD) and 0.08 mm for Egyptian micritic limestone (E). If micrite grains within the interstices of quartz grains control the strength of the calcitecemented Maze sandstone (2K), the size of Griffith inclusion is estimated as 0.04 mm. However, detailed microscopic observation is necessary to clarify real feature of Griffith inclusion.

5. Conclusion

The relation between ultimate strength and grain size has been analyzed for five marbles and one limestone, which range from 4 mm to 0.005 mm in the mean grain size. The ultimate strength of coarse-grained marble, the mean grain size of which is larger than 0.3 mm, increases linearly with the inverse square root of the mean grain size under the confining pressures of 500 and 1,000 kg/cm^2, as it is suggested by the Griffith inclusion model of fracture. Fine-grained limestones, the mean grain size of which is smaller than 0.3 mm, are much weaker than the theoretical strength which is estimated from the grain size. The size of effective Griffith inclusion is about the size of a single grain diameter in coarse-grained marble, but the intergranular Griffith inclusion exists in the specimens of fine-grained marble and limestone.

The Yamaguchi marble is mechanically anisotropic under the atmospheric pressure but becomes less anisotropic under higher confining pressures.

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Appendix 1

Petrographic Description of Rocks

Yamaguchi marble (SKA): The rock was quarried from Carbo-Permian Akiyoshi limestone formation at 4 km NE from Shigeyasu-station, Miné City, Yamaguchi prefecture. The marble consists of uniform calcite grains of medium size (about 0.3 mm) with a characteristic mosaic texture. The cylinder axes of SKA-1, SKA-2 and SKA-3 are perpendicular with one another.

Kamioka marble (KK): The rock, a recrystallized marble in the Hida gneissic terrain, was sampled in an underground gallery in the neighborhood of the contact metasomatic. Tochibora lead-zinc deposit of the Kamioka mine, Gifu prefecture. It consists of coarse anhedral to subhedral calcite grains. The size of the calcite grains ranges from 4 mm to 8 mm.

Egyptian micritic limestone (E): (Assiut Quarry): The limestone consists mainly of fine micritic limestone with average grain size of 0.005 mm. Some patches and veinlets of microcrystalline calcite traverse the micritic groundmass.

Maze sandstone (2K): The rock was quarried from Maze formation in Oshima, Nagasaki prefecture. The middle Oligocene sandstone consists of fine-grained angular, subangular to subrounded quartz grains. Chlorite and carbonate fragments are abundant (about 10%) in interstices of quartz grains.
Tokuyama granite (SKB): The rock, a Hiroshima type granite, was obtained from a quarry at Kurokami Island in Tokuyama City, Yamaguchi prefecture. It is medium-grained, consisting of alkali feldspar and plagioclase (60%), quartz (30%), hornblende and biotite (10%).

Appendix 2

Dynamic physical properties of rocks

Rock type	ρ gm/cm³	η %	V_p km/sec	V_s km/sec	ν	E dyne/cm²	G dyne/cm²	K dyne/cm²
Yamaguchi marble	2.71	0.4	3.58	1.38	0.41	1.46×10^{11}	5.16×10^{10}	2.79×10^{11}
Kamioka marble	2.68	0.5	4.64	2.34	0.33	3.91×10^{11}	1.47×10^{11}	3.81×10^{11}
Egyptian limestone	2.65	0.2	6.17	3.21	0.31	7.15×10^{11}	2.73×10^{11}	6.45×10^{11}
Maze sandstone	2.57	8.3	4.03	2.61	0.31	4.59×10^{11}	1.75×10^{11}	1.84×10^{11}
Tokuyama granite	2.65	0.5	5.03	2.78	0.28	5.24×10^{11}	2.05×10^{11}	3.97×10^{11}

ρ: Bulk density η: Porosity V_p: P-wave velocity V_s: S-wave velocity E: Young's modulus
ν: Poisson's ratio

封圧下における石灰岩の最大強度の粒径依存性とグリフィス・インクルージョンの大きさ

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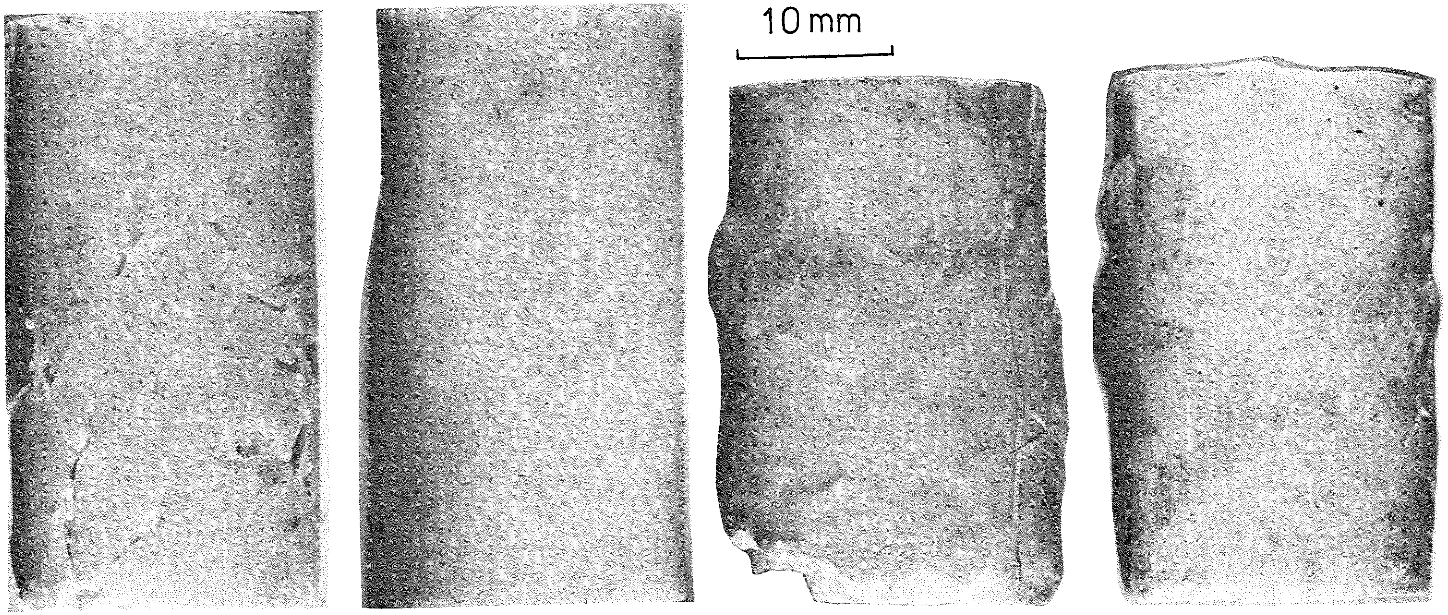
小出 仁・井波 和夫

要　旨

エジプト産細粒石灰岩と日本産結晶質石灰岩・砂岩・花崗岩の，室温・封圧 1-2000 kg/cm² における破壊実験を行った．粒径 0.3 mm 以上の結晶質石灰岩は，グリフィス・インクルージョン理論で推定されるように，粒径の平方根に反比例して，封圧 500 および 1000 kg/cm² における最大強度が低下する．しかしより細粒の石灰岩の強度は理論値よりずっと小さい．この結果は，破壊源となるグリフィス・インクルージョンが，粗粒石灰岩では粒径の大きさに近いが，細粒石灰岩では粒径より大きいとすると説明できる．山口県産の石灰岩に大気圧下で強度異方性が測定されたが，封圧が大きくなると異方性が小さくなった．

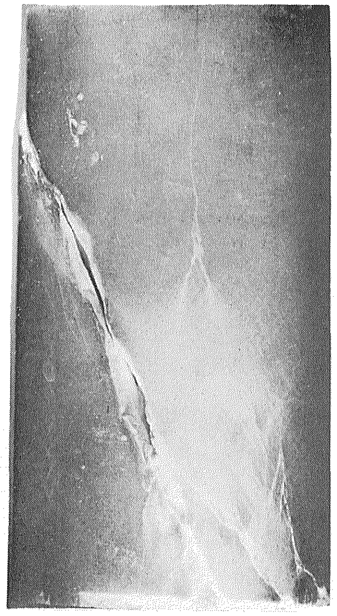
（受付：1976年9月25日；受理：1976年11月4日）



1. $P_H = 1$ kg/cm^2　　2. $P_H = 100$ kg/cm^2　　3. $P_H = 1{,}500$ kg/cm^2　　4. $P_H = 2{,}000$ kg/cm^2

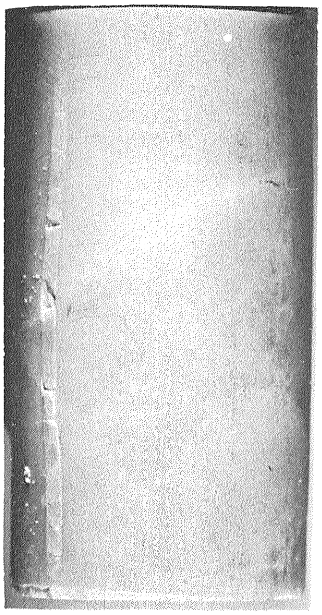
Kamioka marble (KK) cylinders compressed under confining pressures ranging from 1 to 2,000 kg/cm^2.

1. $P_H = 1$ kg/cm^2



2. $P_H = 300$ kg/cm^2

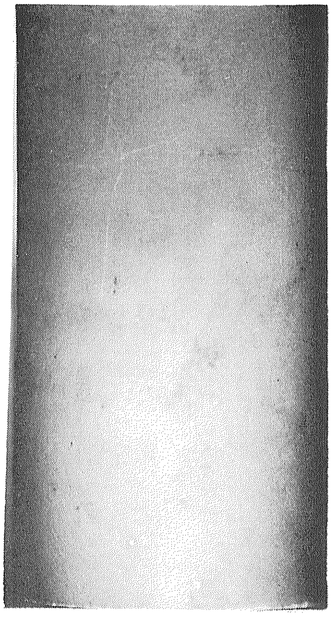
3. $P_H = 500$ kg/cm^2



4. $P_H = 700$ kg/cm^2

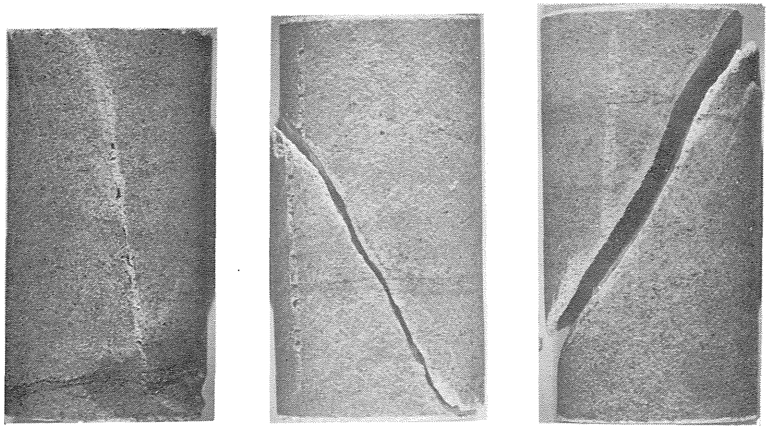
10 mm

5. $P_H = 900$ kg/cm^2

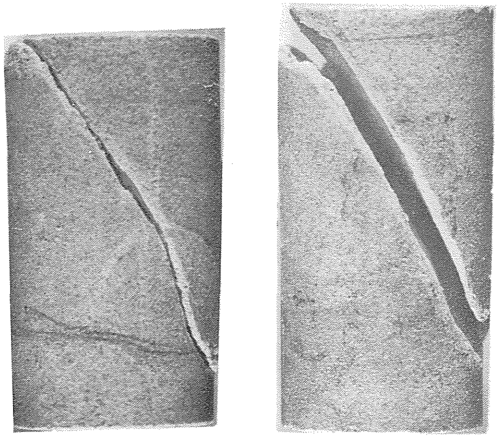


6. $P_H = 1{,}500$ kg/cm^2

Egyptian micritic limestone (E) cylinders compressed under confining pressures ranging from 1 to 1,500 kg/cm^2.



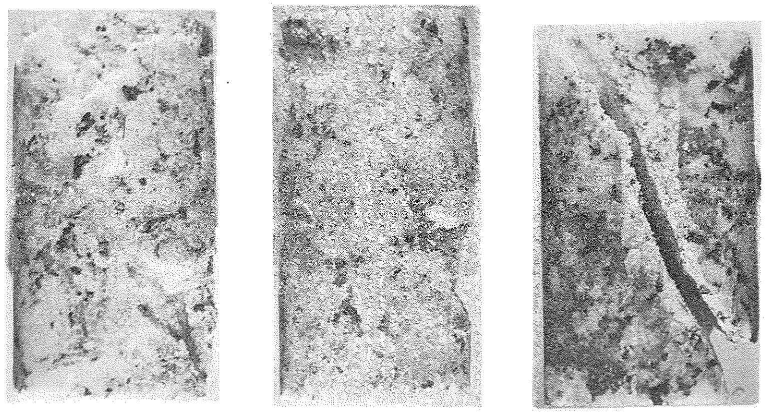
1. $P_H=300$ kg/cm² 2. $P_H=800$ kg/cm² 3. $P_H=1{,}000$ kg/cm²



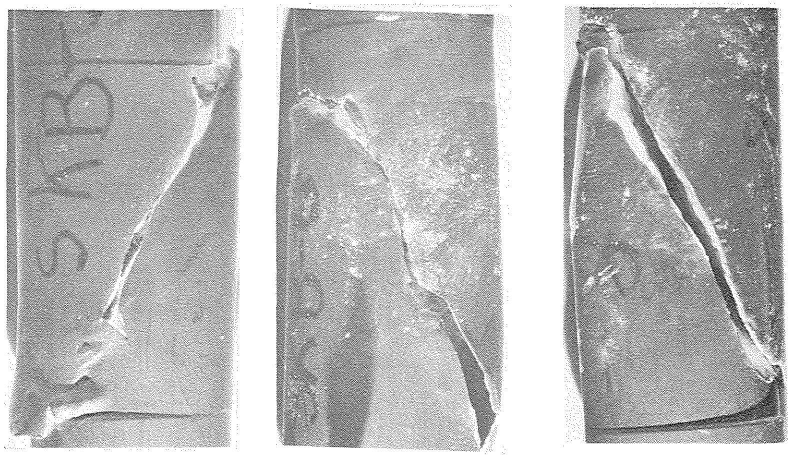
4. $P_H=1{,}200$ kg/cm² 5. $P_H=1{,}500$ kg/cm²

10 mm

a Maze sandstone (2K) cylinders compressed under confining pressures ranging from 300 to 1,500 kg/cm².

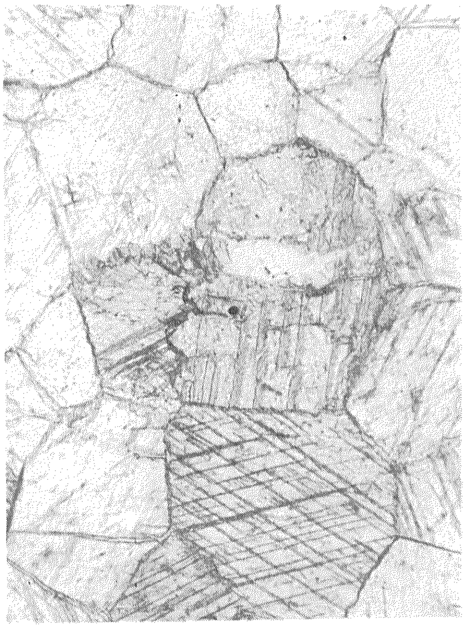


1. $P_H=1$ kg/cm² 2. $P_H=100$ kg/cm² 3. $P_H=300$ kg/cm²

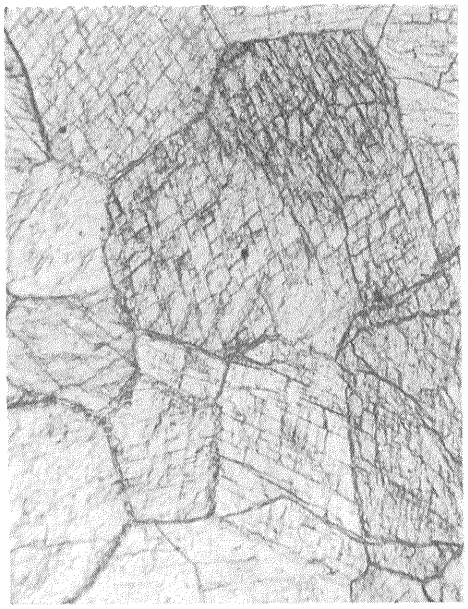


4. $P_H=700$ kg/cm² 5. $P_H=900$ kg/cm² 6. $P_H=1{,}500$ kg/cm²

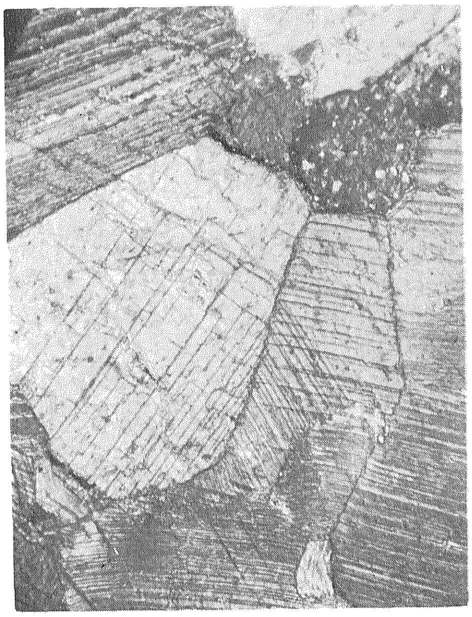
b Tokuyama granite (SKB) cylinders compressed under confining pressures ranging from 1 to 1,500 kg/cm². The specimens 4–6 are still jacketed.



1. $P_H = 100$ kg/cm^2



2. $P_H = 500$ kg/cm^2



3. $P_H = 1,000$ kg/cm^2

5 mm

Photomicrographs of thin sections of Yamaguchi marble (SKA) deformed under 100, 500 and 1,000 kg/cm^2 confining pressures.