Zhang, M., Takeda, M., Physical, mechanical and hydraulic properties of Inada granite and Shirahama sandstone in Japan.
International Symposium on the Fusion Technology of Geosystem Engineering, Rock Engineering and Geophysical Exploration
Seoul, Korea, Nov. 18-19, 2003

Physical, mechanical and hydraulic properties of Inada granite and Shirahama sandstone in Japan

Ming Zhang, Mikio Takeda
Research Centre for Deep Geological Environments, AIST, Tsukuba, Ibaraki 305-8567, Japan

Abstract: Laboratory testing of representative rock specimens is of fundamental necessity for the successful design and/or assessment of facilities associated with many kinds of underground exploitation, including the geological disposal of radioactive nuclear waste. As a fundamental and systematic study, a series of measurements of the physical, mechanical and hydraulic properties of Inada granite and Shirahama sandstone, two rock types that are widely available in Japan, have been performed. This paper presents the results of a study of the effective porosity, density, compressive and shear wave velocity, unconfined compressive strength and permeability of the two rocks. The anisotropy and the effects of confining pressure on the permeability of the rocks, as well as the relationships among the physical, mechanical and hydraulic properties, are also investigated and discussed.

1. Introduction

Laboratory testing of representative rock specimens is of fundamental necessity for the successful design and/or assessment of facilities associated with many kinds of underground exploitation, including the geological disposal of radioactive nuclear waste. Knowledge of the mechanical properties of the rock, in particular the compressive strength, is generally required for an analysis of structural stability, and knowledge of the hydraulic properties, typically the permeability or hydraulic conductivity, is crucially important for the assessment of retardation capability of a rock stratum to fluid and/or contaminant transportation. Measurements of physical properties of rock specimens, especially the wave velocities, are useful because they may provide correlations with properties routinely measured in the field. In addition, measurements of other physical properties, such as effective porosity and density are also of fundamental importance because effective porosity is a basic parameter that controls fluid flow within the rock, and density is required for calculating ultrasonic elastic constants of rock from wave velocities.

As a fundamental and systematic study, we performed a series of tests on some physical, mechanical and hydraulic properties of Inada granite and Shirahama sandstone, two rock types widely available in Japan. The tests covered the measurements of effective porosity, density, velocities of both compression and shear waves, unconfined compressive strength and permeability of the two rocks. To investigate the effects of anisotropy on individual properties, specimens cored in different directions for each kind of rock were tested. In addition, permeability tests were performed under high confining and pore pressure conditions that simulate ground pressures at depths.

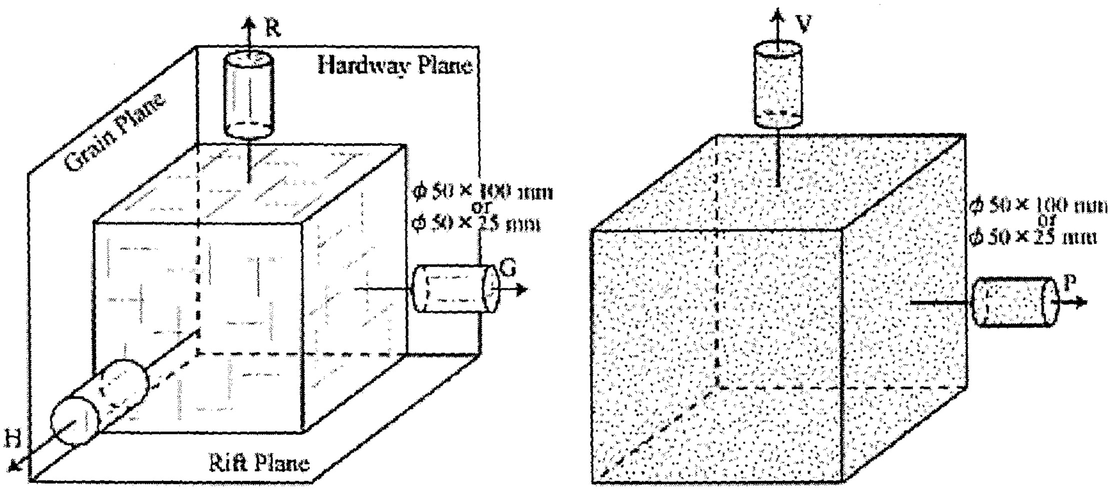
In the following sections, we present the experimental program including the description of specimens, test methods and apparatus, test results and major conclusions drawn from this study.

2. Experimental program

Specimens

Two types of rock that are commonly available in Japan were used for the experiments. Inada granite and Shirahama sandstone were used as typical examples of igneous and sedimentary rocks, respectively.

In general, granite contains many small defects that are preferentially oriented along three mutually perpendicular planes, defined as Rift, Grain and Hardway Planes (Osborne, 1935; Kudo et al. 1986). The properties of sedimentary rocks are also known to vary relative to orientations perpendicular and parallel to bedding (e.g., Morin et al., 1997). To investigate the effects of such anisotropy on the individual properties of rock, specimens cored in the directions perpendicular to the Rift, Grain and Hardway Planes for granite, and specimens cored both perpendicular and parallel to bedding for sandstone were used, as shown in Fig. 1 a) and b), respectively. Cylindrical specimens, 50 mm in diameter and 100 mm in length, were used in physical and mechanical property measurements. To shorten the times required for hydraulic property measurements, i.e., the permeability tests, disc shaped cylindrical specimens 50 mm in diameter by 25 mm in length were used.



a) Inada granite b) Shirahama sandstone

Fig. 1. Specimens cored perpendicular to Rift, Grain and Hardway Planes for granite, and specimens cored parallel and perpendicular to bedding for sand stone.

Test methods and apparatuses

Effective porosity is defined as the ratio of the part of the pore volume where water can circulate to the total volume of a representative sample. It is a basic but important physical property that contributes to fluid flow. The effective porosity was determined from the difference in weight between an oven-dried and water-saturated rock specimen. One specimen of each rock type was tested. For the determination of density, the mass of the specimen was measured by an electronic balance and the volume of the specimen was determined from specimen dimensions. For each rock type, three specimens were tested in each direction.

Velocity measurements were performed in accordance with the standard test method for laboratory determination of pulse velocities and ultrasonic elastic constants of rock (ASTM Standard D2845). Fig. 2 shows a photograph of the apparatus used for the velocity measurements. The resonance frequencies of the compression and shear wave transducers were 200 kHz and 100 kHz, respectively. Three specimens in each direction for each rock type were tested.

Compression tests were performed in accordance with the standard test method for elastic moduli of intact rock core specimens in uniaxial compression (JIS M0302; ASTM standard D3148). Loading was controlled at a constant strain rate of 0.01%/min. Axial and lateral strains were simultaneously measured with strain gauges at the same point and two points for each specimen were measured. Three specimens in each direction for each rock type were tested. A photograph of the apparatus for the compression test is shown in Fig. 3.

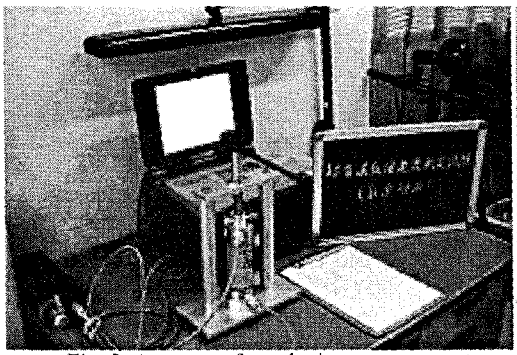


Fig. 2. Apparatus for velocity measurements.

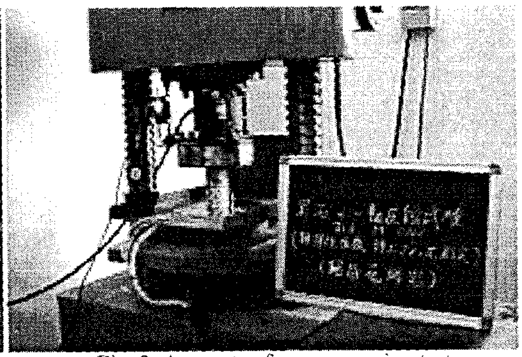


Fig. 3. Apparatus for compression test.

A recently-developed versatile laboratory permeability system, shown in Fig. 4, was adopted to conduct the permeability tests. It consists primarily of a pressure vessel for hydrostatic testing, three syringe pumps with a controlling unit, a data logger and personal computer (PC) connected to several sensors (a differential-pressure transducer (DPT) and thermocouples) for data acquisition and monitoring, the necessary plumbing (valves and stainless-steel tubing), and heat insulated chambers. This system can implement three different kinds of permeability tests (constant-head, constant flow-rate and transient-pulse permeability tests) while simultaneously subjecting a specimen to high confining and pore pressures (up to 69 MPa), thereby simulating *in situ* conditions at great depths. The precision and versatility of this system have been verified by Zhang et al. (2002). In this study, only the transient-pulse method was used for the permeability tests, since this technique can measure the permeability of low permeability geological materials in a relatively short time (Brace et al. 1968). In this case, the cylinders of syringe pumps A and B are used as upstream and downstream reservoirs, respectively. A series of permeability tests under different levels of effective confining pressure were conducted for each direction of the cored specimens. The effective confining pressure defined herein is the difference between the confining and pore pressures. In this study, the confining pressure for each specimen was increased stepwise from 2 to 60 MPa and the pore pressure was kept constant at 1 MPa.

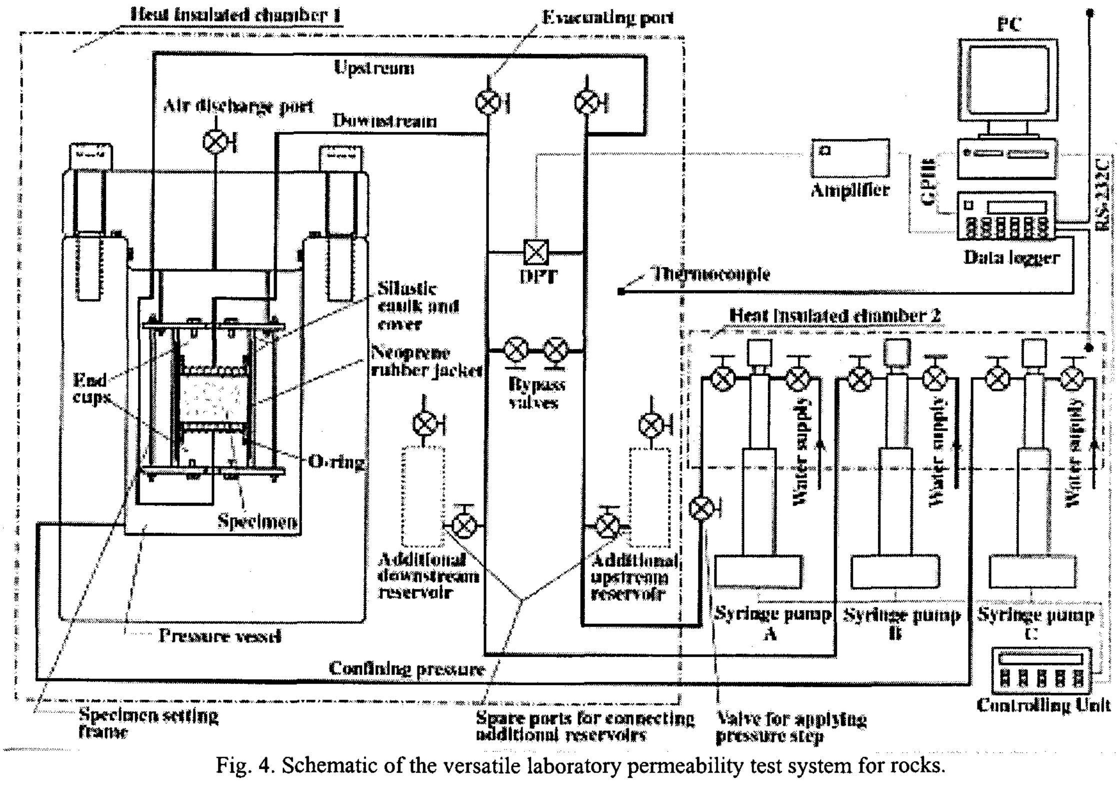


Fig. 4. Schematic of the versatile laboratory permeability test system for rocks.

3. Test results

The results of physical and mechanical measurements of the two rocks are summarised in Table 1. The effective porosity of Inada granite and Shirahama sandstone were 0.70 and 11.18%, respectively. The density of oven-dried Inada granite and Shirahama sandstone were about 2.68 and 2.35 g/cm^3, respectively.

The average velocities of the compression wave (P wave) in the directions perpendicular to Rift, Grain and Hardway Planes for Inada granite were 3.66, 4.38 and 3.80 km/s, respectively, and the average velocities of the shear wave (S wave) in the same directions were 2.33, 2.48 and 2.47 km/s, respectively. For Shirahama sandstone, the average velocities of the compression wave in the directions perpendicular and parallel to bedding were 2.33 and 2.40 km/s, respectively, and the average velocities of the shear wave in the same directions were 1.54 and 1.55 km/s, respectively. The ultrasonic elastic constants for individual specimens were calculated using the following equations and are tabulated in Table 1:

Table 1. Results of physical and mechanical measurements of Inada granite and Shirahama sandstone.

	Rock type	Inada granite									Shirahama sandstone					
	Orientation	Perpendicular to Rift Plane			Perpendicular to Grain Plane			Perpendicular to Hardway Plane			Perpendicular to bedding			Perpendicular to bedding		
	Specimen No.	R-1	R-2	R-3	G-1	G-2	G-3	H-1	H-2	H-3	SV-1	SV-2	SV-3	SP-1	SP-2	SP-3
	Effective porosity (%)	0.70									11.18					
	Dried density (g/cm^3)	2.67	2.67	2.67	2.67	2.68	2.68	2.67	2.68	2.67	2.11	2.35	2.35	2.35	2.34	2.34
		2.67			**2.68**			**2.68**			**2.35**			**2.35**		
Velocity measurements	Velocity of P wave (km/s)	3.61	3.69	3.67	4.43	4.52	4.18	3.87	3.73	3.80	2.31	2.31	2.37	2.43	2.37	2.40
		3.66			**4.38**			**3.80**			**2.33**			**2.40**		
	Velocity of S wave (km/s)	2.38	2.28	2.32	2.49	2.57	2.39	2.52	2.49	2.40	1.50	1.53	1.58	1.57	1.53	1.550
		2.33			**2.48**			**2.47**			**1.54**			**1.55**		
	Dynamic modulus of elastisity (kN/m^2)	3.38E+7	3.31E+7	3.36E+7	4.20E+7	4.47E+7	3.85E+7	3.84E+7	3.66E+7	3.60E+7	1.20E+7	1.23E+7	1.29E+7	1.32E+7	1.26E+7	1.28E+7
		3.35E+7			**4.17E+7**			**3.70E+7**			**1.24E+7**			**1.29E+7**		
	Dynamic Poisson's ratio	0.12	0.19	0.17	0.27	0.26	0.26	0.13	0.10	0.170	0.14	0.11	0.09	0.14	0.15	0.14
		0.16			**0.26**			**0.13**			**0.11**			**0.14**		
Uniaxial compression test	Compressive strength (kN/m^2)	125685	155960	168469	167117	162045	180194	157474	165047	169894	53094	52922	52927	44974	43281	4366
		150038			**169785**			**164138**			**52981**			**43974**		
	Young's modulus (MN/cm^2)	52501	90644	74864	58916	67984	60588	61392	62175	59150	11274	11313	11379	8741	7846	7887
		72670			**61796**			**60906**			**11322**			**8158**		
	Poisson's ratio	0.39	0.34	0.31	0.20	0.21	0.22	0.22	0.22	0.21	0.28	0.29	0.28	0.28	0.45	0.38
		0.35			**0.21**			**0.22**			**0.28**			**0.37**		

$$\mu_d = \frac{\left(V_P^2 / V_S^2\right) - 2}{2\left(V_P^2 / V_S^2 - 1\right)} \tag{1}$$

$$G_d = \rho \times V_S^2 \tag{2}$$

$$E_d = 2\left(1 + \mu_d\right) \times G_d \tag{3}$$

where:

V_P = velocity of compression wave; V_S = velocity of shear wave; μ_d = dynamic Poisson's ratio; G_d = modulus of rigidity or shear modulus; ρ = density; and E_d = dynamic modulus of elasticity, respectively.

The uniaxial, or unconfined, compressive strengths of Inada granite were 150038, 169785 and 164138 kN/m^2, respectively for specimens cored in the directions perpendicular to the Rift, Grain and Hardway Planes respectively. The uniaxial compressive strengths for Shirahama sandstone cored in the directions perpendicular and parallel to bedding were 52981 and 43974 kN/m^2, respectively. Young's modulus, E, of each specimen was determined with secant modulus measured up to 50% of ultimate/maximum strength from the axial stress-axial strain curve obtained during the compression test, and Poisson's ratio, v_S, for each specimen was determined using the average of the ratios of lateral strains to axial strains from the stress level of 0 to 50% of the ultimate strength (Table 1).

Fig. 5 shows examples of the data obtained from the transient-pulse permeability tests. The curves illustrate the normalized differential hydraulic head, defined as the ratio of hydraulic head to the pulse pressure instantaneously applied to the upstream reservoir at the beginning of a test, versus time. The permeabilities of test specimens were calculated from these data by using the exact solutions to transient-pulse test derived by Hsieh et al. (1981), shown in equations (4) to (6) below, and the parameter identification technique recently proposed by Zhang et al. (2000). For comparison, simulated curves for individual tests are also shown in the same figure.

$$\frac{h(x,t)}{H} = \frac{1}{1+\beta+\gamma} + 2\sum_{m=0}^{\infty} \frac{\exp\left(-\alpha\phi_m^2\right)\left[\cos\phi_m\xi - \left(\gamma\phi_m / \beta\right)\sin\phi_m\xi\right]}{\left(1+\beta+\gamma-\gamma\phi_m^2/\beta\right)\cos\phi_m - \phi_m\left(1+\gamma+2\gamma/\beta\right)\sin\phi_m} \tag{4}$$

where

$$\xi = \frac{x}{l},\ \alpha = \frac{Kt}{l^2 S_s},\ \beta = \frac{S_s A l}{S_u},\ \gamma = \frac{S_d}{S_u} \tag{5}$$

and ϕ_m are the roots of the following equation:

$$\tan\phi = \frac{\left(\gamma+1\right)\phi}{\gamma\phi^2/\beta - \beta} \tag{6}$$

where: $h(x,t)$ = the hydraulic head in the specimen; x = the distance along the specimen axis referenced from the downstream end; t = time; H = pulse pressure; S_d and S_u = the compressive storage of the downstream and upstream reservoirs, respectively, defined as the change in fluid volume in the reservoirs per unit change in hydraulic head in the reservoirs.

Under the tested conditions, the permeabilities of Inada granite ranged from 17.7 to 0.6 ($\times 10^{-12}$ m/s), 160.1 to 5.9 ($\times 10^{-12}$ m/s) and 82.3 to 5.5 ($\times 10^{-12}$ m/s) for the specimens cored perpendicular to the Rift, Grain and Hardway Planes, respectively. The permeabilities of Shirahama sandstone ranged from 7.2 to 1.0 ($\times 10^{-9}$ m/s) and 5.5 to 1.1 ($\times 10^{-9}$ m/s) for the specimens cored perpendicular and parallel to bedding. Variations of permeability due to the increase of effective confining pressure, and the effects of isotropy on permeability of each specimen are shown in Fig. 6.

4. Discussion

Although there were small differences among the values of velocities obtained from the three specimens cored in the same direction, both individual and average values showed that the velocities of both compression and shear waves in Inada granite have the following relationship (Table 1, left and middle part):

For the directions perpendicular to the three planes, the velocities increased in the order Rift Plane, Hardway Plane, Grain Plane.

Compared with the velocity test results, the compressive strengths of the three specimens cored in the same direction showed relatively large variations. However, the average compressive strength in each direction showed a

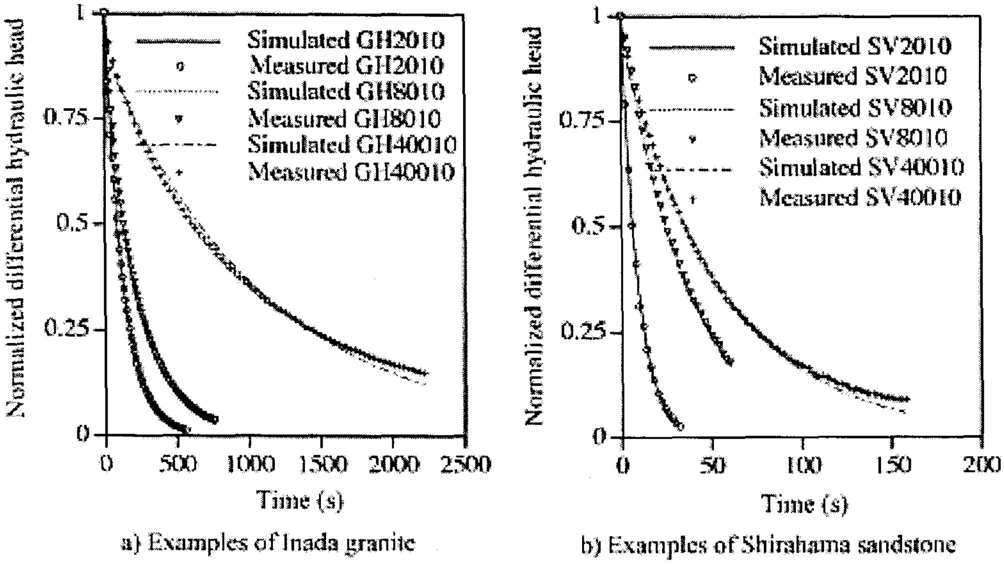
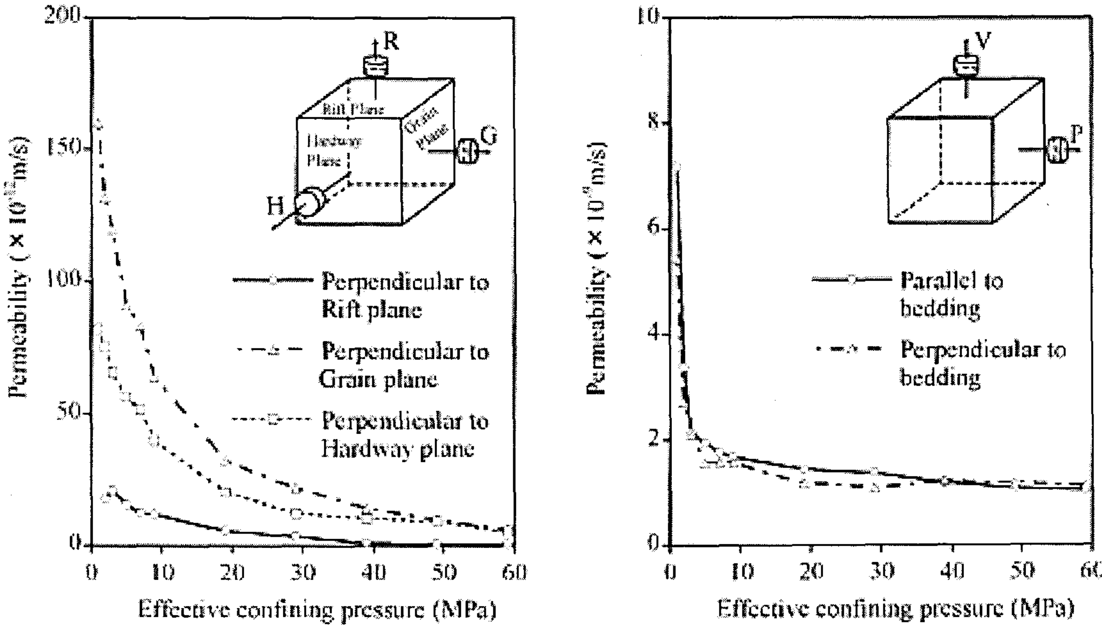


Fig. 5. Curves of normalized differential hydraulic head versus time obtained from the transient-pulse tests.



a) Inada granite

b) Shirahama sandstone

Fig. 6. Effects of effective confining pressure and anisotropy on permeability of rocks.

similar relationship to that of the velocities, again increasing in the directions perpendicular to the Rift, Hardway and Grain Planes (Table 1, left and lower part):

The simulated curves for normalized differential hydraulic head across the specimen are in close agreement with the experimental results (Fig. 5). This demonstrates the accuracy of the results obtained from the transient-pulse tests. The permeabilities in the three directions for the granite illustrate the same trend, with permeability increasing in the order Rift, Hardway and Grain Planes. The variations were also of the same order as those of the ultrasonic velocity and compressive strength (Fig. 6 a)):

The above observations illustrate that Inada granite is an anisotropic material, and the anisotropy is more significant in the Rift Plane than in the Hardway and Grain Planes.

In addition, the permeabilities of Inada granite decreased monotonically with increasing effective confining pressure for all directions, but the rate of decrease diminished at higher confining pressures (Fig. 6 a)). This reduction in permeability is attributed to the closure, at low confining pressure, of micro-cracks that control fluid flow in rock (Walsh and Brace 1984).

In contrast to Inada granite, the physical, mechanical and hydraulic properties of the Shirahama sandstone obtained from specimens cored perpendicular and parallel to bedding were almost the same (Table 1, right part; Fig. 6 b)). This illustrates that Shirahama sandstone is a relatively isotropic material. Similar to Inada granite, the permeabilities of Shirahama sandstone also decreased monotonically with increasing confining pressure, but the rate of decrease was much larger than that of Inada granite at low confining pressures. This is because the strength of sandstone is relatively lower than the strength of granite.

Although the mechanism of fluid flow, and the properties of igneous and sedimentary rocks may be different, the results of this study illustrate that the interrelationships between the physical, mechanical and hydraulic properties of rock are relatively clear. As the effective porosity increases, the density and ultrasonic velocity are reduced, strength is lowered and permeability is increased. These observations may provide some useful points to take into consideration when designing laboratory engineering tests. For example, the maximum permeability and its direction are the two most important factors that should be evaluated in a safety assessment of a facility for geological disposal of hazardous materials, such as radioactive nuclear wastes. Since physical properties such as the effective porosity and the ultrasonic wave velocity are easier to measure than hydraulic properties such as the permeability, it is advisable to initially measure the physical properties of representative samples, and perform the hydraulic tests on specimens having relatively large effective porosity and in the direction perpendicular to the plane through which the minimum ultrasonic velocities are measured.

5. Conclusions

Laboratory testing of representative specimens has been a very useful and widely adopted approach for characterizing the engineering properties of geological materials. In this study, physical, mechanical and hydraulic properties of Inada granite and Shirahama sandstone, two rock types widely available in Japan, have been assessed. This paper presents the results of effective porosity, density, compressive and shear wave velocities, unconfined compressive strength and permeability of the two rocks. In addition, the anisotropy and the effects of confining pressure on the permeability of the rocks, as well as the relationships among these properties, were also investigated and discussed. Major conclusions drawn from the present study are as follows:

1) The interrelationships between the physical, mechanical and hydraulic properties of rocks are relatively clear. Increasing the effective porosity results in lower density, slower ultrasonic wave velocities, reduced strength and increased permeability.

2) Inada granite exhibits significant anisotropy in all the physical, mechanical and hydraulic properties.The ultrasonic velocity, unconfined compressive strength and permeability of Inada granite increases in the order of the directions perpendicular to the Rift, Hardway and Grain planes.

3) Compared to Inada granite, Shirahama sandstone is a relatively isotropic geological material.

4) Under the tested conditions where the effective confining pressure was increased up to about 59 MPa, the permeabilities of Inada granite and Shirahama sandstone ranged from about $1.6X10^{-10}$ to $0.2X10^{-12}$ m/s and from $7.2X10^{-9}$ to $1.0X10^{-9}$ m/s, respectively. Although the permeability decreased monotonically with increasing confining pressure, the rate of decrease was dependent on the strength of the rock specimen.

Since the engineering properties of rock specimens may be sensitive to the stress conditions, further studies on simultaneous measurements of the wave velocity, compressive strength and permeability of rocks under high confining and/or tri-axial conditions are being performed.

References

Brace, W. F., Walsh, J. B., Frangos, W. T., 1968, Permeability of granite under high pressure, Journal of Geophysical Research, Vol. 73, No. 6, pp. 2225-2236.

Hsieh, P. A., Tracy, J. V., Neuzil, C. E., Bredehoeft, J. D., Silliman, S. E., 1981, A transient laboratory method for determining the hydraulic properties of tight rocks-I. theory, International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, Vol. 18, No. 3, pp. 245-252.
Kudo, Y., Hashimoto, K., Sano, O., Nakagawa, K., 1986, Relation between physical anisotropy and microstructure of granite, Proceedings, Japan Society of Civil Engineers, No.370/III-5, pp.189-199.
Morin, R. H., Carleton, G. B., Poirier, S., 1997, Fractured-aquifer hydrogeology from geophysical logs; the Passaic formation, New Jersey, Ground Water, Vol. 35, No. 2, pp. 328-338.
Osborne, F. F., 1935, Rift, Grain and Hardway in some pre-Cambrian granites, Quebec, Economic Geology, Vol. 30, No. 5, pp. 540-551.
Walsh, J. B., Brace, W. F., 1984, The effects of pressure on porosity and the transient transport properties of rock, Journal of Geophysical Research, Vol. 89, No. B11, pp. 9425-9431.
Zhang, M., Takahashi, M., Morin, R. H., Esaki, T., 2000, Evaluation and application of the transient-pulse technique for determining the hydraulic properties of low-permeability rocks - part 2: experimental application, Geotechnical Testing Journal, Vol. 23, No.1, pp. 91-99.
Zhang, M., Takahashi, M., Morin, R. H., Endo, H., Esaki, T., 2002, Determining the hydraulic properties of saturated, low-permeability geological materials in the laboratory: advances in theory and practice, Evaluation and Remediation of Low Permeability and Dual Porosity Environments, ASTM STP 1415, M. N. Sara and L. G. Everett, Eds., ASTM International, West Conshohocken, PA, pp. 83-98.