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PHYSICAL PROPERTIES OF SOIL PARTICLES AND THEIR EFFECT ON HYDRAULIC CONDUCTIVITY OF UNSATURATED DECOMPOSED GRANITE SOIL

SHINICHIRO MATSUO*, KAZUHIKO NISHIDA** and SEIICHI SASAKI***

ABSTRACT

The purpose of this study was to establish the influences of physico-chemical properties of soil particles on the hydraulic conductivity of partially saturated decomposed granite soil. The influences of water content during permeation and specific surface area of soil particles on the hydraulic conductivity were examined in detail. Water content determinations were made by a gamma ray radiation method, and specific surface area was calculated from the pore size integral curve obtained using a mercury pressure porosimeter.

It was concluded that specific surface area can be correlated with specific gravity, apparent specific gravity, and the 50% size of the graduation curve. The water content measured during permeability tests can be estimated immediately by count ratio of gamma ray radiation. Hydraulic conductivity can be related to volumetric water content and specific surface area, both of which have a close relation to the physical properties of soil particles.

Key words: decomposed granite soil, isotope, measurement, partially saturated soil, permeability, water content, weathering
IGC: D 2/D 4

INTRODUCTION

Decomposed granite soil is composed of primary minerals such as quartz, feldspar, coloured minerals, and clay minerals. Compositions and physical properties vary to a considerable degree with the degree of weathering. The physical properties of soil particles depend on irregularities of particle shape, pores within the soil particles and crystal structure of the minerals.

The authors have already clarified the relationship between water molecules and soil particles by means of water adsorption tests. It was demonstrated that the degree of weathering of soil particle was closely related to the lowering of surface free energy during water adsorption (Nishida et al., 1975). Furthermore, soil water at pF value 3.3 is an index of the water retention capacity of the soil mass, which has a close connection with the degree of weathering. It gives an important factor to examine the permeability (Matsuo et al., 1979).

* Professor, Department of Civil Engineering, Kyoto University, Sakyo-ku, Kyoto.
** Professor, Department of Civil Engineering, Kansai University, Yamate-cho, Suita, Osaka.
*** Associate Professor, Department of Civil Engineering, Wakayama Technical College, Nada-cho, Gobo, Wakayama. Research Associate at University of California, Berkeley, U. S. A.
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Hence, it is assumed that the physical properties of soil particles also influence the hydraulic conductivity of unsaturated specimens. For the discussion of water flows, it is necessary to find how the degree of weathering of soil particles influences hydraulic conductivity.

Several researchers have investigated permeation of water through unsaturated soil (Yamasaki, 1974). These studies, however, deal mainly with idealized porous media such as clean sand. In the present study, the relationship between the physical properties of the soil particles and the degree of weathering was studied in order to find their influence on the hydraulic conductivity.

Changes in water content during permeation were determined a gamma ray radiation device which was attached to Richards permeability test apparatus.

The pore size distribution was determined by means of mercury pressure porosimeter, and the results were used for determination of specific surface area. The hydraulic conductivity of the soil was examined in relation to the specific surface area and the volumetric water content.

SAMPLES AND EXPERIMENTAL PROCEDURE

The samples tested were a river sand from the Hidaka River in Wakayama Prefecture and three weathered granite soils of different weathering degrees. The latter were collected at Mt. Ikoma in Nara Prefecture and at Mikkaichi in Osaka Prefecture. All the samples consist of natural compositions of minerals.

The samples were dried at room temperature and humidity, and then sieved into fractions smaller than 2 000 μm after breaking them up by hand without severe breaking of soil particles.

In the experiment, the apparent specific gravity and ignition loss were used as a measure of the degree of weathering (JSSMFE, 1972). The value of specific surface area was determined using a mercury pressure porosimeter. The principle of this apparatus is based on the fact that mercury cannot penetrate into the pore of soil particles without high pressure applied because of high value of surface tension of mercury and the negative contact angle with particle surface.

If it can be assumed that the pores are of ideal cylindrical shape, the pore radius can be calculated, and the specific surface area is given by Eq. (1) (Keii, 1971).

$$S_p=\frac{2\sum \Delta V_p}{R_p}\times 10^4 \tag{1}$$

where, S_p : Specific surface area (m^2/g)
ΔV_p : Change of pore volume (ml/g)
R_p : Pore radius (Å)

The pore size distribution was measured by varying the mercury pressure from 1 kg/cm^2 (98 kN/m^2) to 1000 kg/cm^2 (98 MN/m^2) (equivalent pore radius range of 75 000 Å$\sim$75 Å).

Richards permeability test apparatus has been used for determining the hydraulic conductivity of unsaturated soil specimens. It is, however, impossible to examine the relationship between hydraulic conductivity and water content of the sample during the permeability test (Yahata, 1979).

To investigate the relationship between hydraulic conductivity and water content, the apparatus was improved to provide a dummy pressure cell by which water content can be determined (Hasegawa, 1975). Even with this modification, however, a discrepacy between the dummy sample and the main sample in a holder remained.

The authors improved the Richards apparatus by using gamma ray radiation to obtain more accurate values of water content. These characteristics of the method are explained

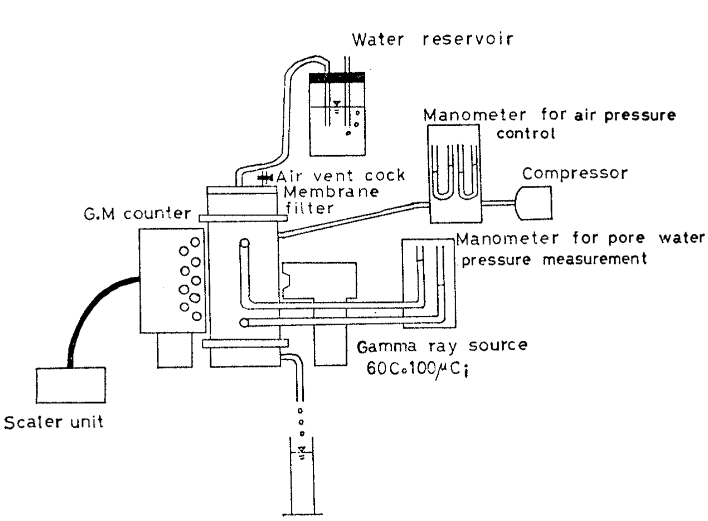

Fig. 1. Layout of experimental apparatus

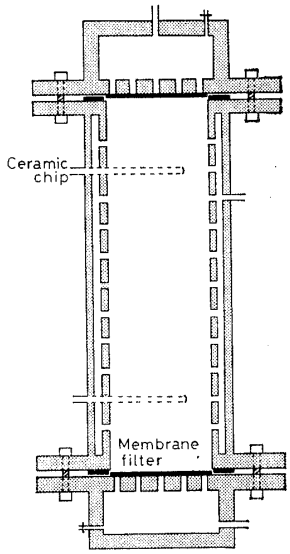

Fig. 2. Details of sample holder used

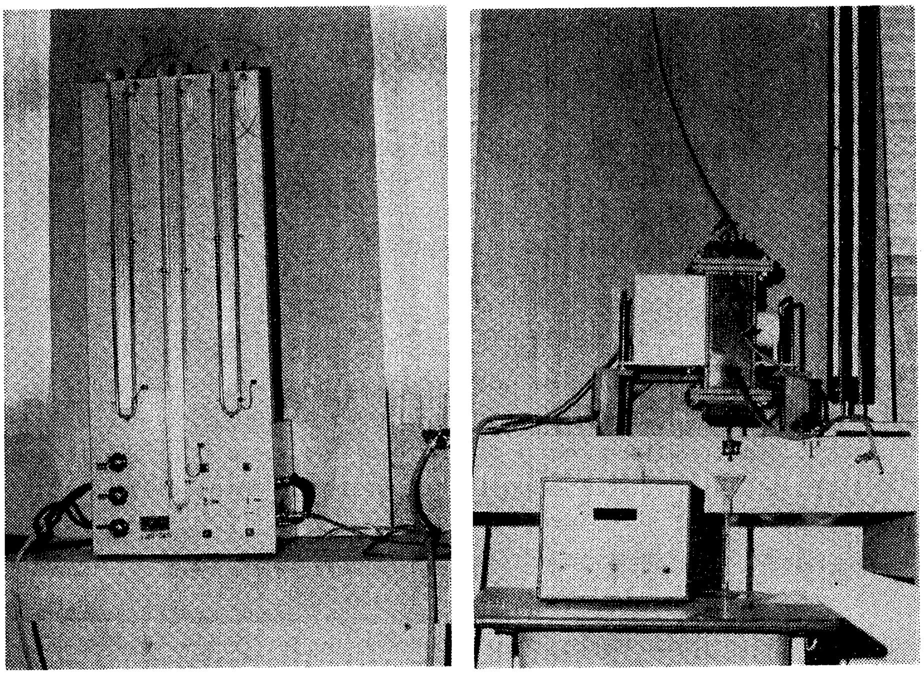

Photo. 1. Potograph of experimental apparatus

as follows ; the experimental apparatus is composed mainly of the sample holder made of lucite, the measurement system for gamma ray radiation and the apparatus for automatic control of air pressure shown in Fig. 1 and Photo. 1. The details of the sample holder are given in Fig. 2. In the experiment, it is essential to keep samples in the holder in an unsaturated state by air pressure control through the porous plates, and it results in developing of negative pore water pressure.

The negative pore water pressure in the samples was determined through the cylindrical ceramic chips attached to the wall of the holder. The surface tension between water molecules and wall of pores in the ceramic chip prevents air from introducing into them. The pressure at which air can pass through the pore into the ceramics is termed the air entry value, and it depends on the pore size. In this experiment, the chips used had an entry value of 2 kg/cm^2 (196 kN/m^2). The negative pore water pressure in the soil is equal to the measured water pressure at the ceramic chips minus air pressure in the cell.

Changes in water content of the sample during a permeability test could be determined by gamma ray radiation. The principle is based on the fact that the gamma ray can pass through material, and the amount of radiation transmitted depends on the density of soils. As water is gradually introduced into the sample, the bulk density of the sample increases, and the transmission of the ray decreases (Kōno et al., 1981).

The intensity of the radio-isotope used in the experiment was low, i.e., down to 100 μC_i. The frequency of measurement was 10 times per 30 seconds.

Air pressure was carefully controlled by a mercury manometer with relay circuit. The precision of the manometer was ± 1 mmHg. The hydraulic conductivity was determined as follows ; the samples were molded in a sample holder and then immersed in water to make them saturated. After the water permeated through the sample from the water reservoir for several hours, the pore water pressure was recorded. Throughout the experiment, the air pressure was kept constant, and then discharge, pore water pressure and the count of gamma rays were measured simultaneously. From the experimental data, the hydraulic conductivity was calculated by Eq. (2) (Yahata, 1977).

$$K=\frac{Ql}{(S_l+l-S_u)tA} \tag{2}$$

where ; K : hydraulic conductivity (cm/s)

Q : discharge of water (ml)

l : distance between two ceramic chips (cm)

S_u, S_l : negative pressure at upper and lower chips (cm)

t : time (s)

A : cross sectional area of sample (cm^2)

PHYSICAL PROPERTIES OF SOIL PARTICLES

The engineering properties of the decomposed granite soil are affected to a condsiderable degree by the physical properties of the surface of soil particles. These properties are dependent on irregularities of the particle shape and the pores within and around the soil particles. It is most important for evaluating the permeability to examine the pore texture (Nishida et al., 1979).

Fig. 3 shows the pore size distribution curves of the samples determined by the mer-

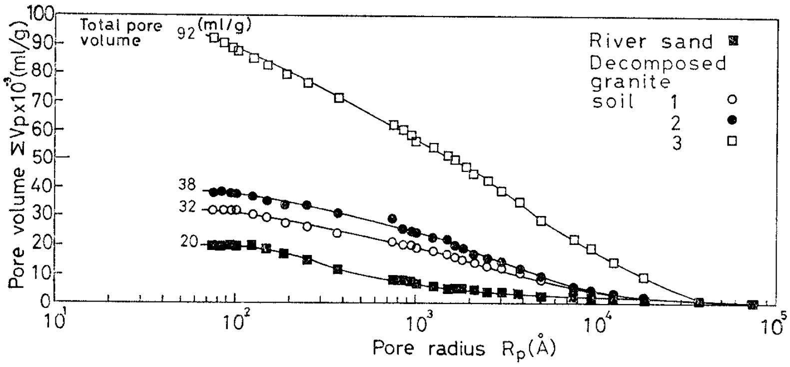

Fig. 3. Pore size distribution curves of samples

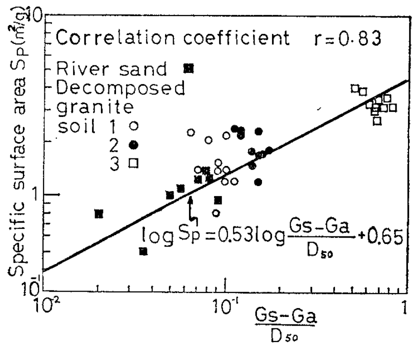

Fig. 4. Relationship between specific surface area and G_s-G_a/D_{50}

Table 1. Physical properties of samples

Physical properties / Sample	Specific gravity G_s	Apparent specific gravity G_a	Grain size at 50% of accumulation curve D_{50}(mm)	Specific surface area S_p (m²/g)	Ignition loss (%)	Degree of weathering
River sand	2.672	2.637	0.540	1.022±0.233	2.13	Slightly weathered
Decomposed granite soil 1	2.591	2.503	0.990	1.544±0.157	2.58	↕
Decomposed granite soil 2	2.595	2.424	1.080	1.952±0.129	2.66	
Decomposed granite soil 3	2.648	2.395	0.420	3.427±0.123	6.23	Severely weathered

cury pressure prosimeter. It is evident that a significant amount of mercury penetrates into the soil samples over the applied pressure range. The more weathered are the samples, the steeper is the pore size distribution curve. The pore volume also increases with an increasing degree of weathering. For these tests, the values did not depend on intergranular voids, because the sample was kept loose, and intergranular voids were too large to take into consideration. Accordingly, the results suggest the existence of intragranular voids within the soil particles.

The properties of the samples and the specific surface areas calculated from the data using Eq. (1) and Fig. 3 are given in Table 1. As stated earlier, the apparent specific gravity and ignition loss were taken as measure of the degree of weathering. The results imply that the apparent specific gravity decreases, and inversely ignition loss increases with an increasing degree of weathering. The results shown in Table 1 indicate that the values of specific surface area increase with the degree of weathering.

Fig. 4 shows the relationship between G_a, G_s, D_{50} and S_p from Table 1. Accordingly, the relation between S_p and G_s-G_a/D_{50} can be formulated as Eq. (3) taking advantage of the least squares method. The coefficient of correlation r between them is equal to 0.83.

$$S_p=b\left(\frac{G_s-G_a}{D_{50}}\right)^a \qquad (3)$$

As far as the present experiment is concerned, a and b are experimental constants equal to 0.53 and 4.47, respectively. Using Ep. (3), a value of S_p can simply be assumed from the parameters G_s, G_a and D_{50}.

PROCEDURE OF DETERMINATION OF WATER CONTENT BY MEANS OF GAMMA RAY RADIATION

Calibration Curve of Samples

To relate the intensity of gamma ray to the density and the water content of soil samples, a calibration curve must be prepared. The calibration curve is represented in the relationship between the count ratio and the water content. The count ratio defined here means the ratio of the gamma ray count of the apparatus with sample to that without sample. The reason why the ratio is adopted is that the radiation of $^{60}C_0$ varies even in the period of time of reading.

Experimental data in Figs. 5, 6, 7 and 8 are expressed by relationships between the count ratio R and dry density ρ_d for different values of water content w. By making use of these characteristics, it is possible to estimate indirectly the water content of the sample during the permeability test for each sample. It has been stated that the curves obtained in this way are not influenced by the physical properties of soil (JSSMFE, 1974). For the decomposed granite soil with complicated physical properties, it is doubtful if the same conclusion is valid. In Figs. 5~8, it is evident that R value decreases with increasing ρ_d. But at the same dry density and water content, the count ratio is different from sample to sample.

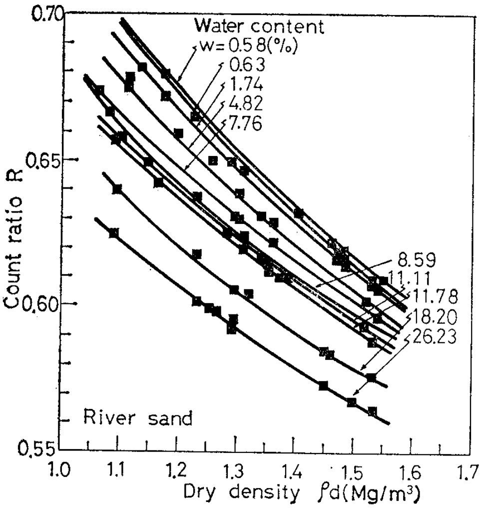

Fig. 5. Relationship between count ratio and dry density for different values of water content (River sand)

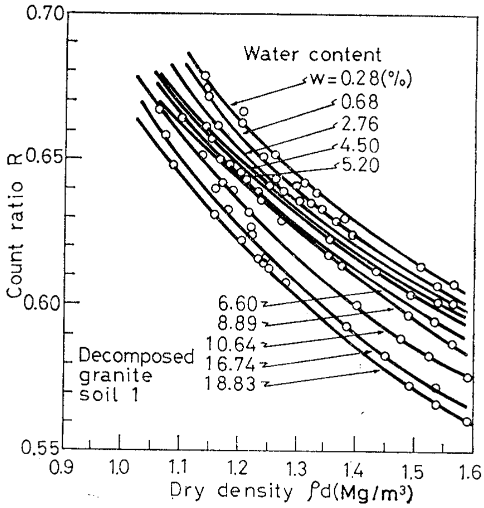

Fig. 6. Relationship between count ratio and dry density for different values of water content (Decomposed granite soil-1)

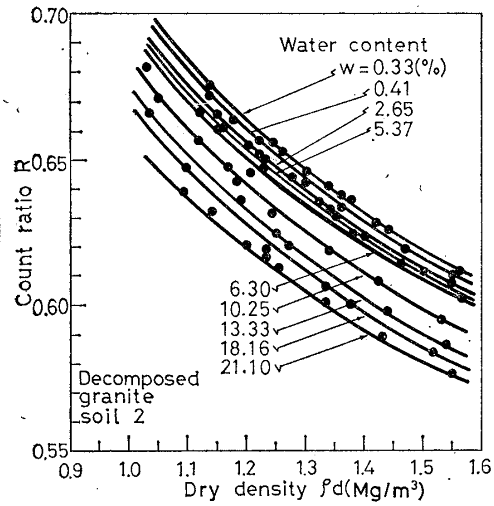

Fig. 7. Relationship between count ratio and dry density for different values of water content (Decomposed granite soil-2)

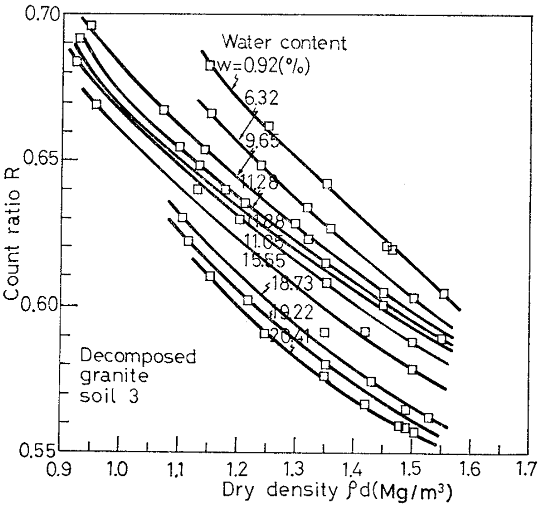

Fig. 8. Relationship between count ratio and dry density for different values of water content (Decomposed granite soil-3)

The Experimental Equation For Water Content

Figs. 9, 10, 11 and 12 are rearranged experimental results from Figs. 5~8 for the relationship between R and w for different values of ρ_d. From the figures, it becomes clear that R values decrease with an increase in w. Accordingly, the relation between R and w can be formulated taking advantage of the least square method. If the gradient of these curves is assumed constant and independent of dry density, the R value is expressed as follows ;

$$R=\alpha w+R_0 \tag{4}$$

where, R : count ratio of gamma ray
α : average value of gradient

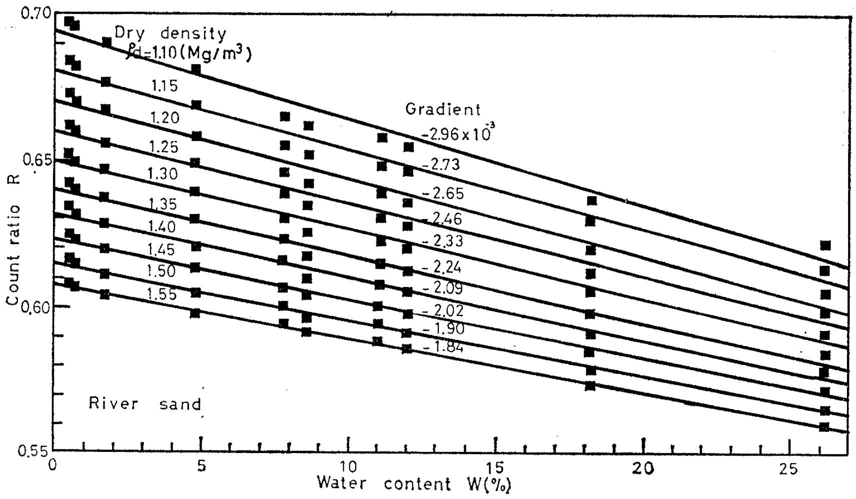

Fig. 9. Relationship between count ratio and water content for different values of dry density (River sand)

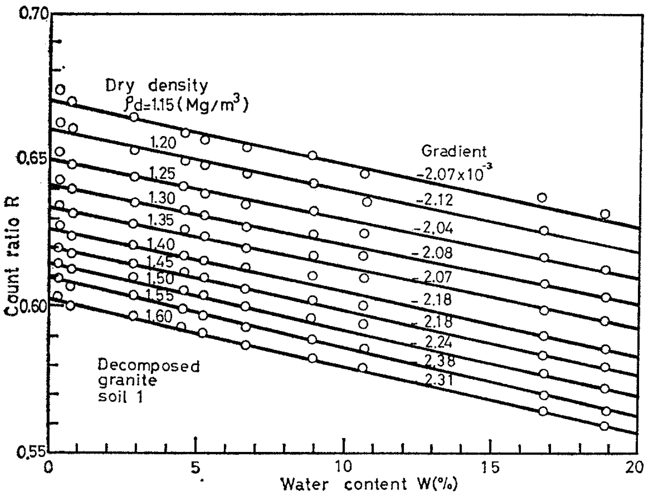

Fig. 10. Relationship between count ratio and water content for different values of dry density (Decomposed granite soil-1)

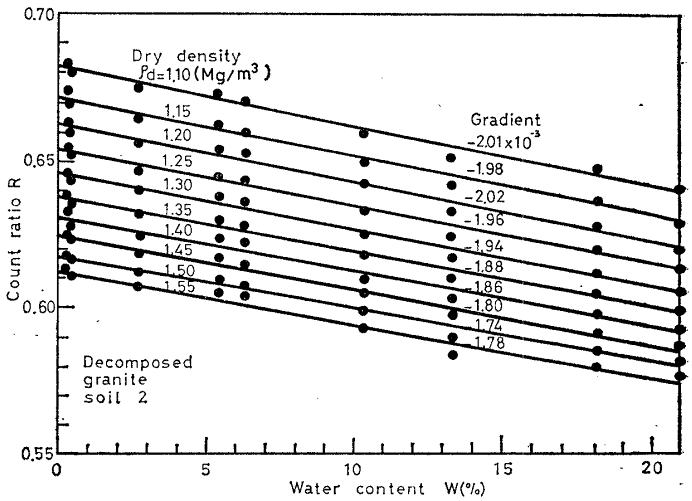

Fig. 11. Relationship between count ratio and water content for different values of dry density (Decomposed granite soil-2)

w : water content

R_0 : count ratio at which water content equals zero

In this experiment, the average values of gradients α were $(-2.32\pm0.12)\cdot10^{-3}$, $(-2.17\pm0.14)\cdot10^{-3}$, $(-1.89\pm0.04)\cdot10^{-3}$ and $(-3.28\pm0.10)\cdot10^{-3}$, for river sand and decomposed granite soils 1, 2, 3 respectively.

The experimental relationship between R_0 and ρ_d is given in Fig. 13. Samples were dried in an oven at 110°C for 24 hours to obtain these values. The coefficient of correlation r is equal to 0.99. Accordingly, the relation between R_0 and ρ_d can be formulated as Eq. (5).

$$R_0=-0.163\,\rho_d+0.856 \tag{5}$$

Eq. (6) can be derived from Eqs. (4) and (5).

$$w=\frac{R+0.163\,\rho_d-0.856}{\alpha} \tag{6}$$

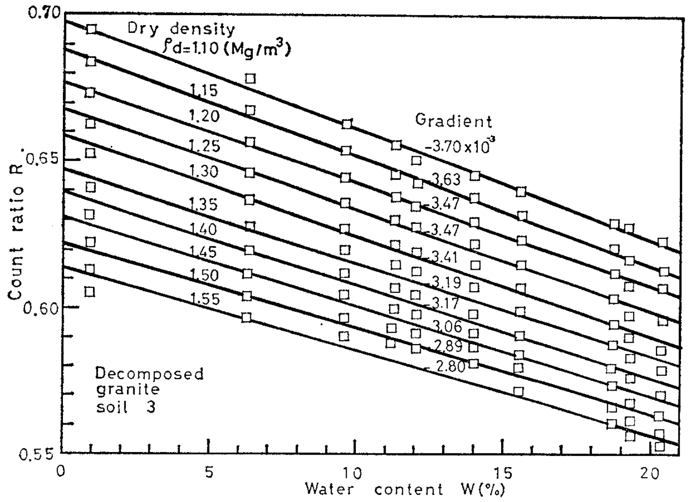

Fig. 12. Relationship between count ratio and water content for different values of dry density (Decomposed granite soil-3)

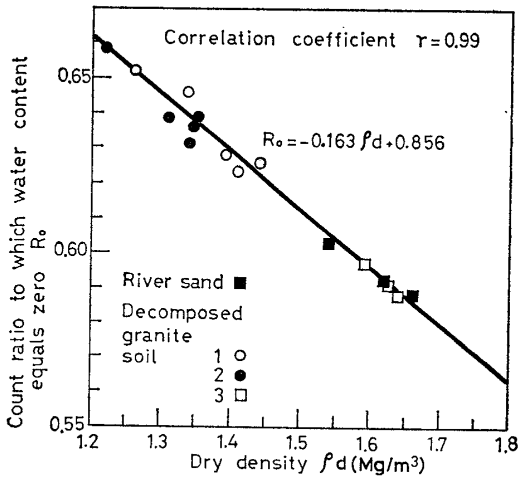

Fig. 13. Variation in R_0 at various dry densities

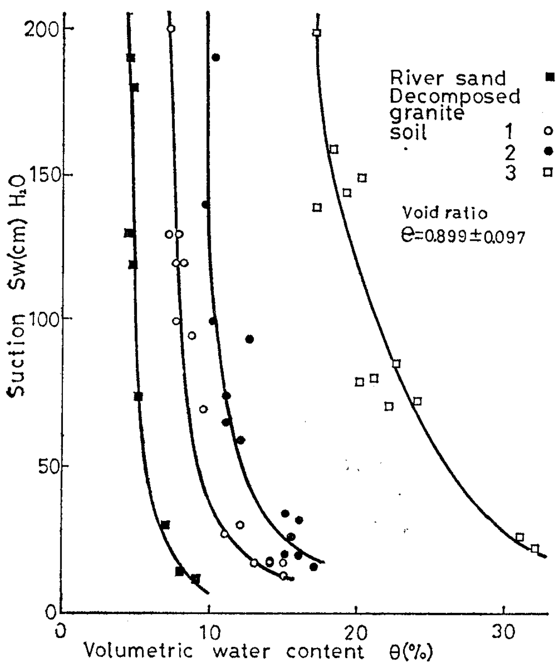

Fig. 14. Soil moisture characteristic curves of samples

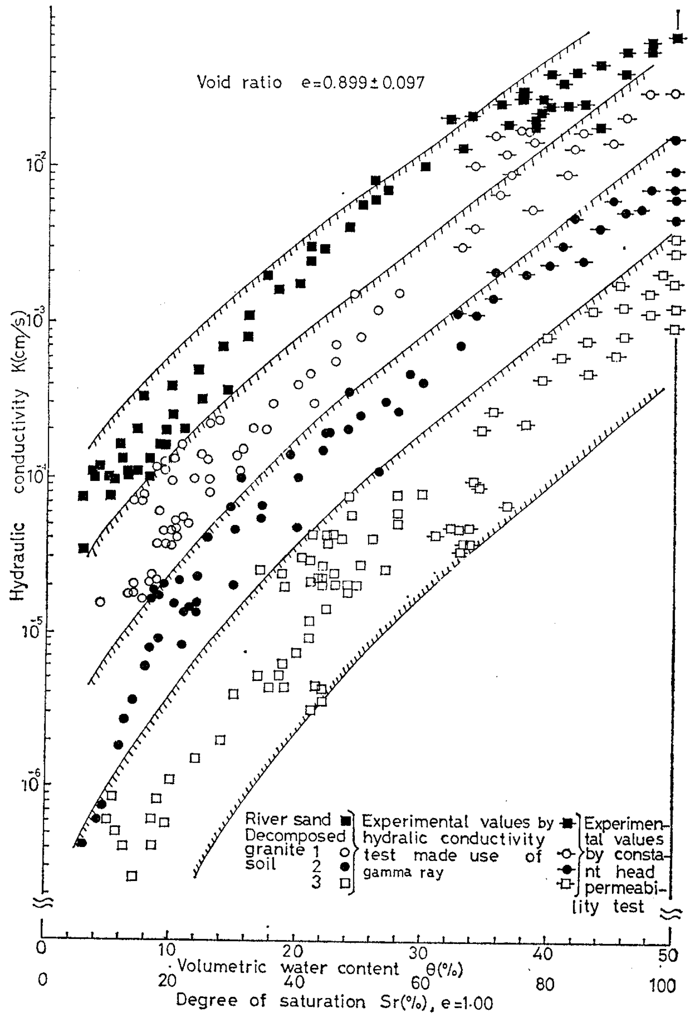

Fig. 15. Relationship between hydraulic conductivity and volumetric water content of samples

Using Eq. (6), w value of samples can be simply assumed from the count ratio, if the value of dry density is known in advance. By using Eq. (6), the water content can be determined easily for any value of dry density.

THE FACTORS CONTROLLING HYDRAULIC CONDUCTIVITY OF THE SOIL

Suction versus volumetric water content curves for the samples of different degrees of weathering are given in Fig. 14. The volumetric water contents in this figure were calculated by Eq. (6). It is seen that the volumetric water content decreases with an increment of suction, as is generally reported for sandy soil ; at the same suction, the water contents increase with degree of weathering.

Experimental results showing the relationship between hydraulic conductivity and volumetric water content are given in Fig. 15. It is clear that the hydraulic conductivities depend strongly on the volumetric water content, with the hydraulic conductivity decreasing with the decrease of the volumetric water content.

In examing the results in detail, the difference in the degree of weathering of the samples is clearly reflected by the hydraulic conductivity. For a constant volumetric water content, the hydraulic conductivity decrese with increasing of degree of weathering.

According to the experimental data, the difference in the hydraulic conductivity among the samples is dependent on complicated interactions between physical properties of soil particles and water molecules. Weathered soil particles can retain more moisture around or in internal cracks of the soil particles (Nishida et al., 1979).

It can be concluded that the hydraulic conductivity decreases and inversely the volumetric water content increases with the degree of weathering. This suggests that the reduced hydraulic conductivity has a close connection to irregular surfaces of soil particles or intragranular voids measured by mercury pressure porosimeter and the water retained within or around the soil particles which prevent water from flowing. The hydraulic conductivity of the decomposed granite soil is related to such factors as volumetric water content and specific surface area.

DISCUSSION ON HYDRAULIC CONDUCTIVITY

It is clearly shown that the factors controlling the hydraulic conductivity are void ratio, volumetric water content and specific surface area which, in turn, are dependent on the characteristics of soil particles.

The relationship between them is expressed as Eq. (7).

$$K=f(e, \theta, S_p) \quad (7)$$

Of these parameters, e can be thought as a constant value in the experiment. By introducing the concept of an average water film thickness M defined by Eq. (8), the experimental data plotted in relation between K and M are shown in Fig. 16.

$$M=\frac{\theta}{S_v} \quad (8)$$

where, M : average thickness of water film (μm)

θ : volumetric water content (cm^3/cm^3)

S_v : surface area per unit volume of soil particles (cm^2/cm^3)

S_v in Eq. (8) is also given by $S_p \cdot \rho_d$ and S_p can be estimated practically by Eq. (3). Thus, M is given by Eq. (9).

$$M=\frac{\theta}{b\left(\frac{G_s-G_a}{D_{50}}\right)^a \rho_d} \quad (9)$$

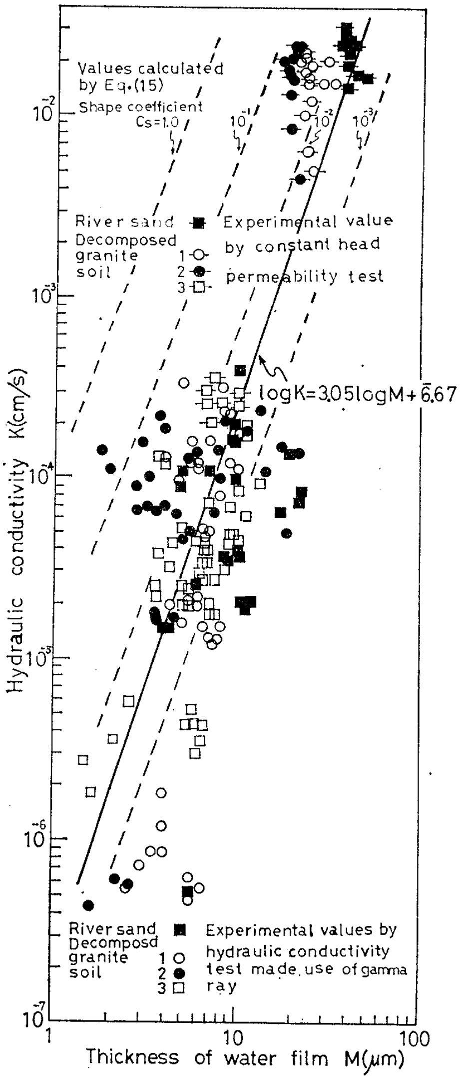

Fig. 16. Relationship between hydraulic conductivity and average thickness of water film of samples

In this experiment, the coefficient of correlation r between them equals 0.873. Experimental Eq. (10) is derived using the least squares method to obtain the relationships between K and M.

$$K=\psi M^{\omega} \tag{10}$$

In this experiment, ψ and ω equal 2.14×10^{-7} and 3.05, respectively.

Thus, Eq. (10) becomes

$$K=\psi\left\{\frac{\theta}{b\left(\dfrac{G_s-G_a}{D_{50}}\right)^{a}\rho_d}\right\}^{\omega} \tag{11}$$

Eq. (11) includes the parameters G_s, G_a, D_{50}, θ and ρ_d. These parameters are fundamental properties of soil particles and they can be measured easily in the laboratory. In Eq. (11), the term G_s-G_a/D_{50} is an index of the degree of weathering.

The value of $\theta/G_s-G_a/D_{50}$ is considered to be another expression of the average thickness of water film, which is very important for the analysis of the permeability of unsaturated soil.

Mitchell derived Eq. (12) by extending the Kozeny-Carman equation to the hydraulic conductivity of unsaturated soil (Mitchell, 1976).

$$K=C_sV_s^2\left(\frac{\gamma_p}{\mu}\right)\frac{1}{S_v^2}\left(\frac{e^3}{1+e}\right)S_r^3 \tag{12}$$

where, K : hydraulic conductivity
C_s : shape coefficient
V_s : volume of solids (1)
γ_p : unit weight of water (980 dyn/cm) (9.81 kN/m³)
μ : viscosity of water (1×10^{-2} dyn·sec/cm) (0.1 NS/m²)
S_v : surface area per unit volume of soil (cm²/cm³)
e : void ratio
S_r : degree of saturation

The degree of saturation is given by Eq. (13).

$$S_r=\frac{1+e}{e}\theta \tag{13}$$

Thus, Eq. (12) becomes

$$K=C_sV_s^2\left(\frac{\gamma_p}{\mu}\right)\frac{1}{S_v^2}(1+e)^2\theta^3 \tag{14}$$

Using the average thickness of water film estimated in Eq. (8), Eq. (14) can be represented as follows.

$$K=3.92\,C_sS_vM^3\cdot10^{-5} \tag{15}$$

As far as the present experiment is concerned, the void ratio in Eq. (15) can be taken as a constant value (1).

The broken lines among the plots in Fig. 16 are calculated values using Eq. (15) in which C_s values are assumed arbitrarily. As shown from the experimental data, the difference between Eqs. (10) and (15) is dependent essentially on the value of C_s. Thus, it is important to estimate C_s value accurately in Eq. (15).

In this experiment, however, a suitable value of C_s falls in the range between 10^{-2} and 10^{-3}. The values differ largely from those calculated theoretically for the particles of ideal sphere in shape. Therefore, a contribution of specific surface area to the C_s value should be taken into consideration.

CONCLUSION

To examine the factors responsible for the hydraulic conductivity of a soil, experiments were done using an apparatus modified from that developed by Richards.

The results lead to the following conclusions ;

1) The water content during permeation can be measured easily and accurately by using gamma ray tool attached to the permeability test apparatus.
2) The pore volume of soil particles, which is dependent on the degree of weathering, can be determined by mercury pressure porosimeter.
3) Specific surface area calculated from Eq. (1) can be expressed successfully by the parameters $G_s - G_a$ and D_{50}.
4) It is important to evaluate C_s value properly, when Eq. (12) is used for estimation of the permeability of unsaturated decomposed granite soil.
5) Hydraulic conductivity of unsaturated samples is controlled primarily by two factors: volumetric water content and specifiic surface area.

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NOTATION

A = cross sectional area of sample
a, b = experimental constant at Eq. (3)
C_s = shape coefficient
D_{50} = grain size at 50% of accumulation curve
e = void ratio
G_a = apparent specific gravity
G_s = specific gravity
K = hydraulic conductivity
l = distance between upper chip and lower chip
M = average thickness of water film
Q = discharge of water
R = count ratio of gamma ray
R_0 = count ratio at which water content equals zero
R_p = pore radius
r = coefficient of correlation
S_p = specific surface area of soil particles calculated from pore size distribution curve
S_r = degree of saturation
S_u, S_l = suction at upper chip and lower chip
S_v = surface area per unit volume of soil particles
S_w = suction of soil water
t = time
V_p = pore volume

V_s=volume of solids
w=water content
α=experimental constant at Eq. (4), (6)
γ_p=unit weight of water
θ=volumetric water content
μ=viscosity of water
ρ_d=dry density
ϕ, ω=experimental constant at Eq. (10)

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