〔報文〕Moisture Characteristic Curves of Tuff Breccia Stone

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Abstract

The moisture characteristic curves of tuff breccia were obtained by three separate experiments - hanging water experiment, plate pressure experiment and chemical solution experiment - in order to clarify the moisture environment in the stone chamber of Takamatsuzuka Tumulus. Since the stone chamber is made of tuff breccia obtained from Mt. Nijozan, stone samples of tuff breccia obtained from Mt. Nijozan were used for the experiments. Experimental results showed that the equilibrium relative humidity was about 100% when the volumetric water content of the stone is higher than 10%. This result corresponded well with the relative humidity measurements in the stone chamber which was almost 100%. Therefore, the moisture characteristic curve of the stone of the chamber is an important physical parameter for the analysis of the inside moisture condition of the stone chamber of Takamatsuzuka Tumulus.

1. INTRODUCTION

Takamatsuzuka Tumulus was built in the seventh to eighth centuries. It is well known for its beautiful mural paintings directly painted onto thin plaster walls in the stone chamber. Takamatsuzuka Tumulus was discovered and excavated in 1972. At that time, the policy for the conservation of its mural paintings was discussed intensively. There was great concern about the stability of the plaster, which had been kept in high relative humidity (RH), about 100%, for more than a thousand years. It is believed that high humidity of the stone chamber of Takamatsuzuka Tumulus and high water content of its lime plaster walls caused fungi to appear on the walls inside the stone chamber. In order to clarify the real cause of the fungi and to find a suitable protective measure, it was necessary to know the moisture and temperature conditions and other necessary physical properties of the mound soil and stone chamber. In order to investigate the moisture transfer in the stone chamber of Takamatsuzuka Tumulus, moisture characteristic curves of tuff breccia were obtained. Three separate experiments were implemented to establish the moisture characteristic curves: hanging water experiment, plate pressure experiment and chemical solution experiment.

2. STONE SAMPLES

The stone samples of tuff breccia were obtained from Mt. Nijozan in Nara prefecture. Six disk-shaped samples were prepared for the experiments. The samples are shown in Figure 1. The diameter of a sample is 5 cm and its thickness is 2 cm. The wet density at water saturated condition, dry density and porosity are shown in Table 1. The average wet density, dry density and porosity are 1.67 g/cm^3, 1.27 g/cm^3 and 0.40, respectively.

Table1 Physical properties of the stone samples

Sample number	Wet density (g/cm^3)	Dry density (g/cm^3)	Porosity
1	1.70	1.31	0.39
2	1.68	1.28	0.40
3	1.66	1.24	0.42
4	1.69	1.26	0.42
5	1.62	1.20	0.41
6	1.69	1.31	0.38

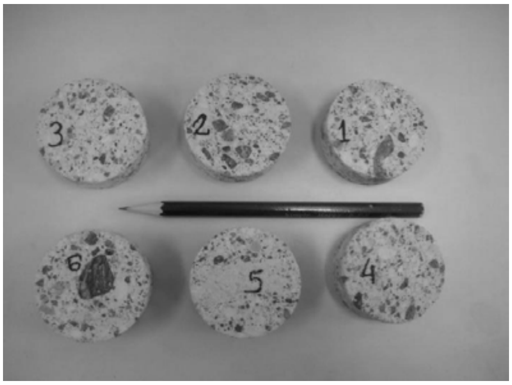

Fig.1 Stone samples of tuff breccia

3. RELATIVE HUMIDITY AND VOLUMETRIC WATER CONTENT

The moisture characteristic curve, which relates suction (matric, total, or both) to water content or saturation, is essential for characterizing the hydraulic and mechanical behavior of unsaturated porous materials. The method used to measure the moisture characteristic curve depends on the texture of the stone (coarse versus fine) and the magnitude of the suctions that must be established. Relative humidity is a term used to describe the amount of water vapor that exists in a gaseous mixture of air and water. Tuff breccia samples were obtained to be examined and analyzed experimentally by water hanging method, plate pressure apparatus method and chemical solution method in order to establish the relation between relative humidity and volumetric water content.

3-1 Hanging water column experiment

The method of hanging water column is suitable for making determinations for suctions in the range of 0 to 100 kPa. It is used to define the moisture characteristic curve at lower suctions near saturation. In this experiment (Fig. 2) water saturated, highly permeable porous ceramic plate is connected on its underside to a water column, terminating at a reservoir open to atmosphere. Water-saturated samples of tuff breccia held in rings are placed in contact with the flat plates when the water reservoir height is even with the top of the plate. Then the reservoir is lowered to a new height distance H below the top of the plate. By the equilibrium principle, water will flow from the stone samples through the ceramic plate to the reservoir until the total water potential of the system is constant. At this time the potential of the free reservoir may be set equal to zero, and at the stone sample height H we may write (assuming that $z - 0$; $P = P_{atm}$; neglecting solutes) (William A. Jury and Robert Horton, 2004)

$$\Psi_m + \Psi_z = 0 = \Psi_m + \rho_w g H \rightarrow \Psi_m = -\rho_w g H \quad (1)$$

Where

Ψ_m is the matric potential

Ψ_z is the gravimetric potential

ρ_w is the density of liquid water

g is acceleration of gravity

H is the hydraulic head

When the equilibrium has been stored, some of the samples may be removed and their gravimetric or volumetric water content measured. The tube may then be lowered further and a new set of samples measured. If there is good contact between the samples and ceramic, equilibrium will be reached rapidly (i.e., several hours) since the samples are quite moist.

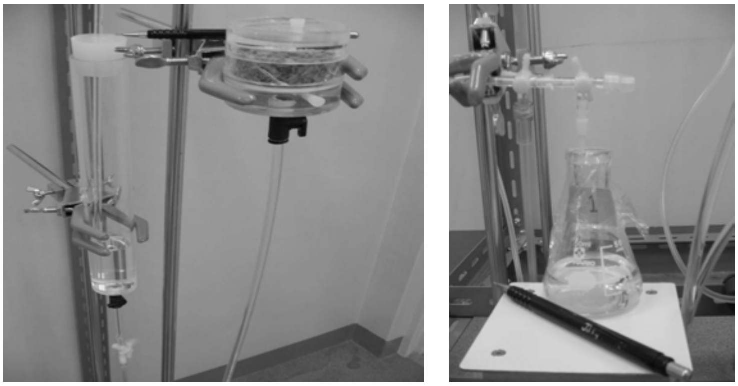

Fig.2 Water hanging column experiment

3-2 Pressure plate experiment

Pressure plate experiment (Fig. 3) is commonly used for applications where lower suctions (<10 kPa or 100 cm of water) are to be applied. For higher matric suctions, pressure plate extractors are used that have robust pressure cells, which can withstand higher air pressures (typically 1500 kPa). A pressure plate extractor has two main components: a porous plate with an air-entry pressure higher than the maximum matric suction to be applied during the test and a sealed pressure cell (Fredlund and Rahardjo 1993). Usually the porous plate is made of ceramic, although polymeric membranes are used when very high suctions (>1500 kPa or 150 m of water) are being applied (Fredlund and Rahardjo, 1993).

Pore water pressure (u_w) in the specimen is maintained at zero because it is exposed to atmospheric pressure at the outflow end of the specimen. Air pressure (u_a) inside the pressure cell is elevated to induce the desired matric suction (Ψ) by axis translation (i.e., $\Psi = u_a - u_w$). A description of the axis translation principle can be found in Fredlund and Rahardjo (1993). The desorption (drying) moisture characteristic curve is measured by first saturating the specimen and then applying u_a in a series of increments to achieve different Ψ. Each increment in u_a causes water to be expelled from the specimen until an equilibrium state is reached for the Ψ that has been established. Additional increments in u_a are applied only after outflow from the specimen has ceased. The volume of water expelled during each increment is measured (gravimetrically or volumetrically) to define the water content corresponding to each suction. After equilibrium has been reached at the maximum suction for the problem being considered, the sorption (wetting) moisture characteristic curve can be measured using the same procedure, except u_a is incrementally decreased. When measuring the sorption moisture characteristic curve, care must be employed to flush diffused gas from beneath the ceramic plate. (Xiaodong Wang and Craig H. Benson, 2004)

Fig.3 Pressure plate experiment set for tuff breccia

3-3 Saturated salt solution experiment

The energy level of a reservoir of pure water may be lowered to any specified level by adding pre-calibrated amount of certain salts. If this reservoir is brought into contact with a moist stone sample, water will flow from the sample to the reservoir. If the sample and reservoir are placed adjacent to each other in a closed chamber at constant temperature, water will be exchanged through the vapor phase by evaporation from the porous material and by condensation in the reservoir until equilibrium is reached. The experiment set up is shown in Figure 4. Six desiccators of constant temperature equal to 20 ℃ were used. The saturation salt solutions of potassium nitrate, potassium chloride, sodium chloride, sodium bromide, magnesium chloride (KNO_3, KCl, NaCl, NaBr and $MgCl_2 \cdot 6H_2O$) were poured inside desiccators smoothly. The six stone samples of the tuff breccia within six acrylic cups were inserted into each desiccator.

Fig.4 Saturated salt solutions experiment set for tuff breccia

Among the six samples, the measurement of initial water content of samples No.1 - 3 started in air-drying state, while the measurement of initial water content of samples No. 4 – 6 started when they were fully saturated with distilled water. The weight of the samples inside each desiccator was measured once a week. When the measurement of sample weights became fixed, the samples were removed from the desiccators and dried in an oven (105 ℃, 24 hours) to measure moisture content. The type of each salt used in the experiment and equilibrium relative humidity percentage at saturation level is shown in Table 2.

Table2 The type of each salt used in the experiment and equilibrium relative humidity

Salt type	Equilibrium relative humidity (%)
KNO_3	94
KCl	85
NaCl	75
NaBr	54
$MgCl_2 \cdot 6H_2O$	33

4. EXPERIMENTAL RESULTS

As both hanging water column and plate pressure methods are suitable for measuring suction in lower range whereas saturated salt solution method is implemented to determine suction in higher range, the experimental results were divided into two sections to analyze the results during these ranges.

4-1 Saturated salt solution experiment

The relative humidity of each salt solution, the measurement of gravimetric water content and volumetric water content of stone samples are shown in Table 3. The relation between suction of stone samples and volumetric water content is shown in Figure 5 where suction was plotted in logarithm scale. The latest measurement was maintained inside the desiccators with fixed relative humidity till the samples reached equilibrium condition. The relation between the relative humidity of stone samples and volumetric water content is shown in Figure 6. The gravimetric water content showed almost the same value, about 0.18, up to 70% relative humidity, but, when it exceeded 70%, the gravimetric water content increased gradually. Water potentials of the samples were calculated from the relative humidity of salt solutions at equilibrium condition, using the formula below.

$$h_r = exp\ (\ \phi_w\ M / RT) \qquad (2)$$

Where

h_r is relative humidity

ϕ_w is water potential (J kg^{-1})

M is mol mass of water (0.018 kg mol^{-1})

R is gas constant (8.3143 J mol^{-1} K^{-1})

T is temperature (K)

Then the calculated water potential was converted to the suction (Nakano, The University of Tokyo, 1995). It could be noticed that with increasing suction, the volumetric water content decreased almost linearly. The relative humidity, gravimetric water content and volumetric water content of stone samples are shown in Table 3.

Table3 The relative humidity, gravimetric water content and volumetric water content of stone samples

Relative humidity (%)	Gravimetric water content (kg/kg)	Volumetric water content (cm^3/cm^3)
33	0.016	0.029
54	0.018	0.033
75	0.021	0.038
85	0.028	0.051
94	0.033	0.059

4-2 Hanging water column and pressure plate experiments

The relation between the volumetric water content and the suction of stone samples is shown in Figure 5 based on the experiments of hanging water column, pressure plate extractors and saturated salt solutions. The suction value is plotted in logarithmic scale. The measured volumetric water content decreased gradually with increasing suction pressure. The corresponding relative humidity with the suction pressure was calculated by equation (2).

The relation between the volumetric water content and the calculated relative humidity is shown in Figure 6. These graphs show that the equivalent relative humidity is almost 100% when the volumetric water content is above 10%. Since the volumetric water content of the stone chamber was approximately 20% according to data of the size and weight of the stone wall at the time of the dismantlement of the stone chamber and the average dry density of the tuff breccia (Table 1), as shown in Figure 6, the equilibrium relative humidity of the stone chamber is about 100%.

This corresponded well with the measured high relative humidity inside the stone chamber which is considered to be a main cause of biological activities such as fungal and bacterial growth. This graph also shows that in order to reduce the equivalent relative humidity inside the stone chamber it is necessary to reduce the volumetric water content of the surrounding stone walls lower than 10%. Thus moisture characteristic curve of the stone of the chamber is an important physical parameter for the analysis of the inside moisture condition of the stone chamber.

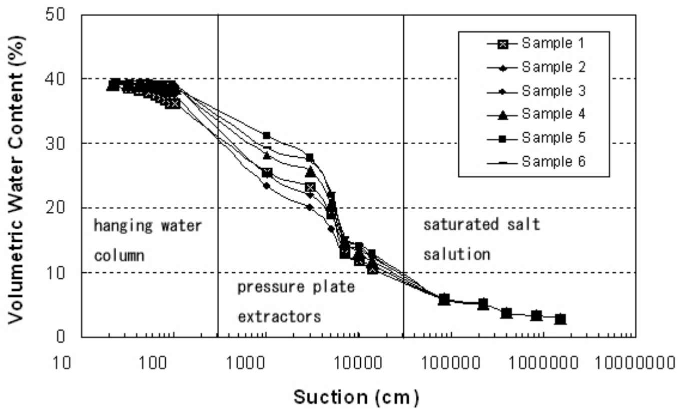

Fig.5 Suction of stone samples versus volumetric water content

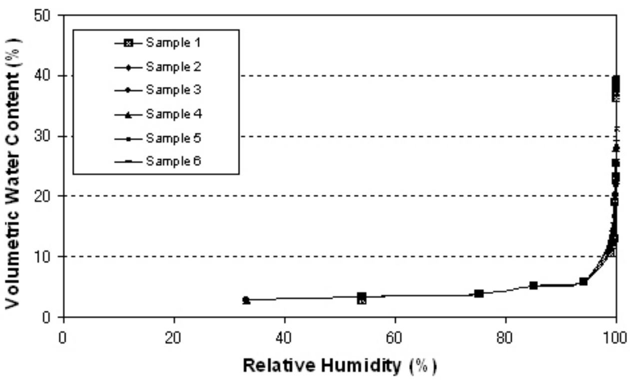

Fig.6 Relative humidity of stone samples verses volumetric water content

5. CONCLUSION

From the results of the three experiments - hanging water column, pressure plate and chemical solution - it was noticed that with increasing suction, the volumetric water content decreases almost linearly. It was also concluded that when the volumetric water content of tuff breccia stone exceeded the limit of 10%, the equivalent relative humidity was almost 100%. Since the volumetric water content of the stone chamber was approximately 20% according to the data of the size and weight of the stone wall and the average dry density of the tuff breccia obtained when the stone chamber was dismantled as well as from our experiment results, the equilibrium relative humidity of the stone chamber is about 100%.

These results corresponded well with the measured high relative humidity inside the stone chamber which is considered to be a main cause of biological activities such as fungal and bacterial growth. These results also showed that in order to reduce the equivalent relative humidity inside the stone chamber it is necessary to reduce the volumetric water content of the surrounding stone walls to lower than 10%.

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凝灰角礫岩の水分特性の測定

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高松塚古墳墳丘部の版築土の水分特性曲線をボーリング試料を用いて，つり下げ法，加圧版法，飽和塩法の３つの方法で求めた結果は，保存科学第46号に示した。この結果から，体積含水率が約10％以上の場合は，これと平衡する相対湿度がほぼ100％になることが分かった。今回は，高松塚古墳石室に使われた凝灰角礫岩と同じ二上山から得られた凝灰角礫岩の水分特性曲線を，つり下げ法，加圧版法，飽和塩法の３つの方法で測定した。測定結果から，版築に用いられた土試料と同じように，体積含水率が10％以上の時は，これと平衡する相対湿度は，ほぼ100％になることが分かった。石室解体時に測定した側壁の重量から壁石の湿潤密度を測定し，今回試験に用いた凝灰角礫岩の乾燥密度の平均値を用いて計算すると，体積含水率は，ほぼ20％となった。これと平衡する相対湿度は，100％となる。この結果は，石室内の相対湿度の測定値が，ほぼ100％であることと対応している。この石室を構成する石材の水分特性曲線は，墳丘部版築土の物理的特性と同様に石室内の環境変化を考える上で，基礎的なデータになると考えられる。

キーワード：高松塚古墳（Takamatsuzuka Tumulus）；凝灰角礫岩（tuff breccia）；
水分特性曲線（moisture characteristic curve）；サクション圧（suction pressure）