〔報文〕 Moisture Characteristic Curves of the Soil of Takamatsuzuka Tumulus

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ABSTRACT

In Asian countries there are well known historical tumuli that contain mural paintings. One of these tumuli is Takamatsuzuka Tumulus that was found on 21st March, 1972 in Asuka village, Nara prefecture. It was built with mural paintings in the stone chamber around the end of the 7th century or at the beginning of the 8th century in Japan. Recently fungi were found on the wall surface and causing severe damages to the paintings. The special committee for the conservation of these paintings decided to keep these paintings in the tumulus in a condition similar to that before the excavation. In order to clarify the cause of the fungi and find suitable protective measures, it is necessary to know the moisture conditions and other necessary physical properties of the mound soil and stone chamber. For this purpose, soil samples were obtained from the mound by air boring method. Then moisture characteristic curves of both the soil and stone of Takamatsuzuka Tumulus were measured and analyzed. Three separate experiments were implemented to establish the moisture characteristic curves: hanging water experiment, plate pressure experiment and chemical solution experiment. These measured physical properties were used to propose protective measures for the Takamatsuzuka Tumulus.

1. INTRODUCTION

The stone chamber of Takamatsuzuka Tumulus is well known for its mural paintings. It was found on 21st March, 1972 in Asuka village, Nara prefecture and soon registered as a national treasure. The tumulus consists of a circular mound. The stone chamber is located about 3m deep from the ground surface. Because of its high inside humidity and high water content of the lime plaster wall, fungi appeared on some parts of the wall.[1] After the discovery, it was decided to preserve the mural paintings on the site and monitor the inside conditions carefully. We performed a study of moisture and other physical properties of the Takamatsuzuka soil.[2, 3] Excavation and boring studies of the mound, as shown in Figure 1, were carried out. Three locations were assigned to obtain undisturbed samples: B-1, B-2 and B-3 as shown in Figure 2. Weathered granite samples were obtained from the lower part of the mound.

2. PHYSICAL PROPERTIES OF TAKAMATSUZUKA SOIL AND STONE

Physical properties such as dry density, particle density, void ratio, gravimetric water content, volumetric water content and saturation degree of the mound soil located 1m below the compacted soil surface (elevation 111m) at site B-3, which is 2m east from the outside wall of the stone chamber, are 1.25 g/cm^3, 2.62 g/cm^3, 52.2%, 21.6 %, 27.1% and 56.7%, respectively.[3] Measured volumetric water content of Takamatsuzuka soil by oven dry method is shown in Figure 3.

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Fig.1 Boring core sampling of mound soil

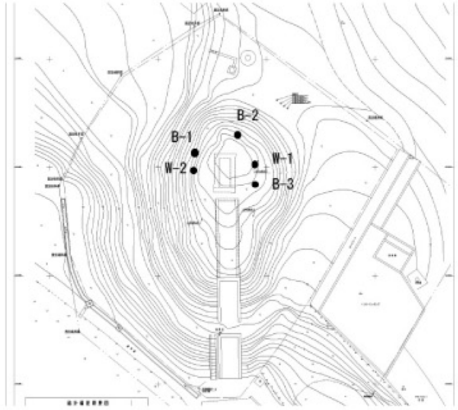
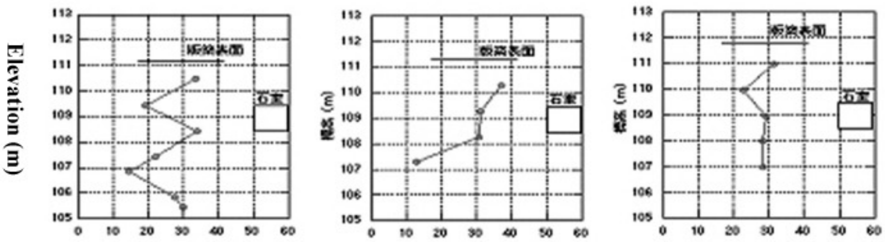


Fig.2 Horizontal plan and sampling locations of Takamatsu Tumulus



Water content (%)	**Water content (%)**	**Water content (%)**
West side (B-1)	**North side (B-2)**	**East side (B-3)**

Fig. 3 Measured volumetric water content of Takamatsuzuka soil

3. VOLUMETRIC WATER CONTENT AND RELATIVE HUMIDITY

The Undisturbed Takamatsuzuka soil samples were investigated and analyzed experimentally to study the relation between relative humidity and volumetric water content. Three experiments were carried out: water hanging method, plate pressure apparatus method and chemical solution method.

HANGING WATER COLUMN (RANGE – 100 cm < h < 0)

A hanging water column consists of water saturated, highly permeable porous ceramic plate connected on its underside to a water column and terminating in a reservoir open to atmosphere. Water saturated samples of soil 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 soil samples through the ceramic plate to the reservoir until the total water potential of the system is constant. The water hanging set up used in this study is shown in Figure 4.

Fig. 4 The water hanging columns experiment set up

PRESSURE PLATE EXTRACTORS (RANGE 15000 cm < h < 100 cm)

Laboratory analysis of the moisture characteristics of both soil and stone samples are carried out using pressure plate extractors as shown in Figure 5. The pressure plates consist of an airtight chamber enclosing a porous ceramic plate connected on its underside to a tube that passes through the chamber to the open air. Saturated soil samples are packed into rings and placed in contact with the ceramic on the top side. The chamber is then pressurized, which causes water to flow from the soil pores through the ceramic and out the tube. By using this equipment, it is possible to produce the moisture release curve (the amount of water available within the soil at different pressures). This enables parameters such as hydraulic conductivity to be calculated for a particular soil sample. As pressure plate method range is considered quite important, we will give a brief detail of the experiment process.

Fig. 5 Plate pressure experiment set up

Vacuuming and saturating of the samples

All samples are vacuumed and then saturated until the top of the soil glistens.

Using the pressure plate

A. After the samples are saturated, each one is weighed and recorded.
B. The plate containing the samples is placed into the pressure chamber.
C. The outlet hose is attached to the plate.
D. The top is placed on the chamber, making sure that each screw is tightened well.
E. The drainage hose is put into a cylinder and the cylinder is covered with a piece of parafilm.
F. The chamber is set to desired pressure.

Measuring moisture loss

A. The amount of moisture in the cylinder is daily recorded.
B. When there is no change in the amount of moisture flowing into the cylinder, the plate is removed from the chamber.
C. When the plate is removed from the chamber, the pressure should be released before removing the top.
D. The weight of each sample is recorded.

Drying the surrounding samples

A. After all the pressures are measured, the samples are removed from the plate.
B. One drying can is obtained for each of the samples.
C. The weight of each empty drying can is recorded.
D. The soil from the rings is removed.
E. Each soil sample is dried at 105℃ for 24 hours in the lab oven.
F. The weights of the dry soil and can for each sample are recorded.

Developing moisture curves

A. Data are entered into a pressure plate calculation spreadsheet.
B. Gravimetric and volumetric moisture are obtained for each soil.
C. Moisture curves for the samples are generated.

SATURATED SALT SOLUTION (RANGE $h < -15000$ cm)

By adding pre-calibrated amount of certain salts, the energy level of a reservoir of pure water may be lowered to any level specified. If this reservoir is brought into contact with a moist soil 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 soil sample and condensation in the reservoir until equilibrium is reached. The experiment set up is shown in Figure 6.

Fig. 6 Saturated salt solutions experiment set for Takamatsuzuka soil and stone

Methodology

Five desiccators of constant temperature equal to 20℃ that contain ESPEC PR-4K inside were used. The saturation salt solutions of potassium nitrate, potassium chloride, sodium chloride, sodium bromide, and magnesium chloride (KNO_3, KCl, NaCl, NaBr and $MgCl_2 \cdot 6H_2O$) were poured into the desiccators smoothly. Six soil samples taken from Takamatsuzuka Tumulus in six acrylic cups were inserted into each desiccator.

Among 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 starts when they were fully saturated with the distilled water. The sample weights, inside each desiccator, were measured once a week.

When the measurement of sample weights became fixed, the samples are 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 1.

Table 1 The type of each salt used in the experiment and equilibrium relative humidity percentage at saturation level

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

The latest measurement was maintained inside the desiccators with fixed relative humidity till the samples reached equilibrium condition. Water potentials of the samples were calculated from the relative humidity of salt solutions at equilibrium condition, using the formula:

$$h_r = exp\ (\ \phi_w M / RT) \qquad (1)$$

where h_r: relative humidity, ϕ_w: water potential ($J\ kg^{-1}$), M: mol mass of water ($0.018\ kg\ mol^{-1}$), R: gas constant ($8.3143\ J\ mol^{-1}\ K^{-1}$) and T: temperature (K).

Then the calculated water potential was converted to suction.[4)] It could be noticed that by increasing suction, the volumetric water content decreased almost linearly.

4. RESULTS

Figure 7 shows the relationship between the volumetric water content and the suction of compacted soil in the tumulus mound based on the experiments of hanging water column, pressure plate extractors and saturated salt solutions. The suction value is plotted in the 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 1. The relationship between the volumetric water content and the calculated relative humidity is shown in Figure 8. This graph shows that the equivalent relative humidity is almost 100% when the volumetric water content is above 10%. Since the volumetric water content of the compacted soil of Takamatsuzuka Tumulus is approximately 30%, as shown in Figure 3, the equilibrium relative humidity of the mound soil is 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 fungi and bacteria 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 soil lower than 10%. Therefore, this method of reducing the relative humidity inside the stone chamber was not adopted as protective measures against fungi. This moisture characteristic curve of the mound soil gave important information related to the establishment of protective measures against biological activities in the stone chamber.

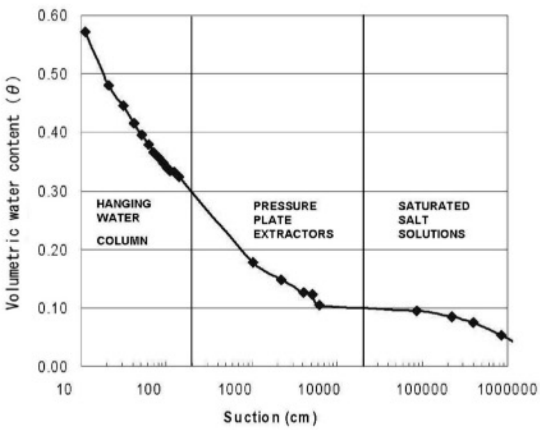


Fig. 7 The relation between volumetric water content and suction of Takamatsuzuka soil

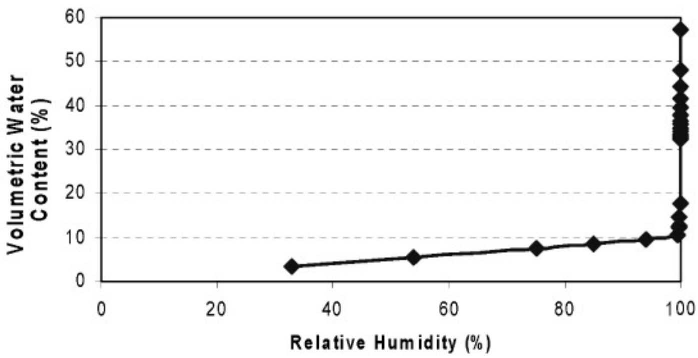


Fig. 8 The relation between volumetric water content and relative humidity of Takamatsuzuka soil

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要旨

高松塚古墳墳丘土の水分特性の測定

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高松塚古墳墳丘土の土質，水分特性，熱特性を調査するために，古墳墳丘部の石室から東，北，西方向に，石室から約２ｍの所でボーリングを行い版築土の不攪乱試料を採取した。土試料の水分特性を調べるために，つり下げ法，加圧板法，飽和塩法の３つの方法で，体積含水率とサクション圧との関係を調べた。ここで，サクション圧とは多孔質体中の水分を吸引するのに必要な圧力のことであり，水分のエネルギー状態を示す値である。このサクション圧から熱力学的な手法により，平衡の相対湿度を求めることができる。これらの測定から，体積含水率は，サクション圧が増加すると徐々に減少することが分かった。また，体積含水率は，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。ボーリング結果により，版築部分の体積含水率はほぼ30%であるので，これと平衡する相対湿度は100%となる。この結果は，石室内の相対湿度は，ほぼ100%であることと対応している。石室内の微生物対策として，墳丘部の含水率を下げて石室内部の湿度を低下させることも提案された。しかし，この実験結果から，周囲の土の含水率を低下させて石室内の湿度を100%以下にするためには，周囲の土の体積含水率を10%以下にしなくてはならないので，墳丘部の大きな改変なしには実施できないことが分かった。この版築土の水分特性は，高松塚古墳の生物対策としての墳丘部分の水分制御の効果を考える上で基礎的なデータとなった。

キーワード：高松塚古墳（Takamatsuzuka Tumulus）；墳丘土（mound soil）；水分特性曲線（moisture characteristic curve）；サクション圧（suction pressure）

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