〔報文〕 Simulation Analysis on the Drying Process of Tuff Breccia Stone Composing the Stone Chamber of Takamatsuzuka Tumulus

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Abstract

The mural paintings of Takamatsuzuka Tumulus were found in March 1972 in the village of Asuka, in Nara prefecture. The mural paintings were designated as a national treasure in April 1974. In 2001, fungi were widely found on the wall plaster. In order to restore mural paintings, the stone chamber was dismantled and the mural paintings were moved to a restoration facility in 2007. This paper reports the material characterization of the tuff breccia and the simulation analysis of the moisture content change of the Takamatsuzuka stone in a climatic chamber using Delphin 5 software developed by TU-Dresden.

1. Introduction

The mural paintings of Takamatsuzuka Tumulus were found in March 1972 in the village of Asuka, in Nara prefecture. The tumulus was designated as a special historic site in April 1973 and the mural paintings were designated as a national treasure in April 1974. In 2001, fungi were widely found on the wall plaster. The Agency for Cultural Affairs organized an emergency conservation committee for the mural paintings of Takamatsuzuka Tumulus in 2003 and a long-term conservation committee in 2004 to develop protective measures against the biological problems of the tumulus. The committee studied various protective measures but finally concluded in 2005 that it was difficult to conserve the mural paintings *in situ* and recommended removing the stones for the restoration of the mural paintings. Following this decision, the stone chamber was dismantled and the mural paintings were moved to a restoration facility in 2007. After this procedure, the moisture content in the stones of the stone chamber changed drastically due to the change of the surrounding condition. This paper reports the material characterization of the *tuff breccia* and the simulation analysis of the moisture content change of the Takamatsuzuka stone in a climatic chamber using Delphin 5 software developed by TU-Dresden[1)].

2. Physical properties of the stone chamber

The stone used for the stone chamber is *tuff breccia* taken from Mt. Nijozan in Nara prefecture[2)]. In order to make a simulation analysis of moisture flow in porous material, it is

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necessary to obtain the physical properties of the stone such as water retention curve, sorption isotherm, hydraulic conductivity and vapor diffusivity. These physical properties were measured for *tuff breccia* stone samples obtained from Mt. Nijozan. The measured water retention curve and sorption isotherm curve are shown in Fig. 1 and Fig. 2, respectively.

When suction pressure is applied to porous material, pore water is gradually removed from the material. With increasing suction pressure, volumetric water content decreases gradually as shown in Fig. 1. This relationship is quite important for evaluating moisture flow in porous material. In Fig. 2, with increasing relative humidity up to 95%, volumetric water content increases gradually. With increasing relative humidity above 95%, volumetric water content shows a steep relative humidity curve. At a relative humidity of 60%, volumetric water content is about 5%.The hydraulic conductivity and the water vapor diffusivity of tuff breccia are estimated by measurement of water vapor diffusion (modified dry-cup and wet-cup experiment) and moisture conductivity (using a tension infiltrometer having a working range between 1000Pa to 50000Pa, and head-permeameter at moisture saturation).

The application of physical based multi-modal pore structure model[3] to water retention data in combination with inverse modeling of drying and wetting experiments leads to important transport functions, as given in Fig. 3.

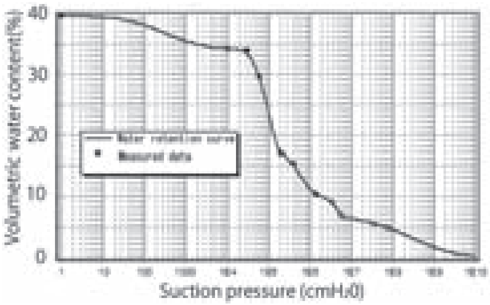

Fig. 1 Moisture retention curve of tuff breccia

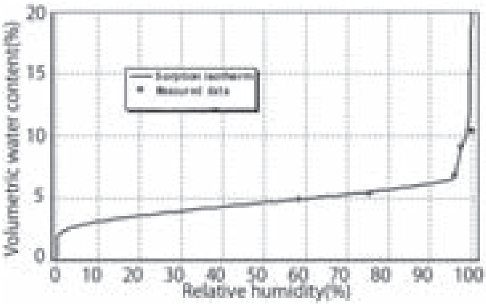

Fig. 2 Sorption isotherm curve of tuff breccia

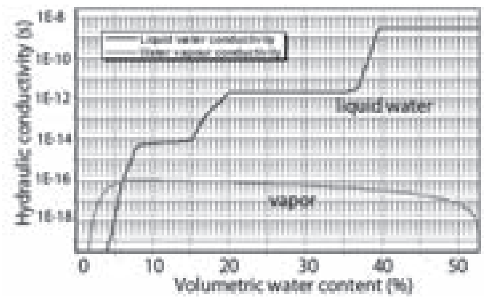

Fig. 3 Hydraulic conductivity of tuff breccia

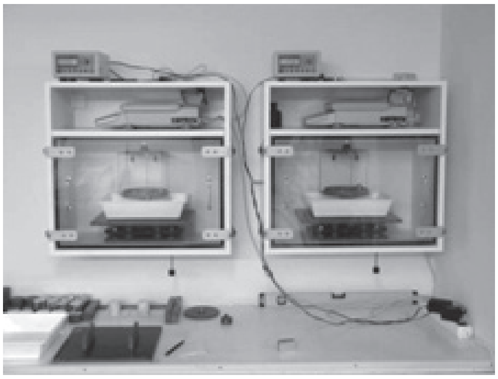

Fig. 4 Test apparatus for water uptake test

3. Evaluation of the physical parameters by water uptake and drying tests

Water uptake is conducted to evaluate and adjust the physical properties of transport function. A picture of the apparatus is shown in Fig. 4. In this experiment, a dry sample is attached to the water reservoir and water is induced to flow by capillary force. The weight of the sample increases due to water uptake. When the curve became a horizontal line, it shows that the specimen has reached capillary saturation. During this process, the weight of the sample is measured at set time intervals.

In Fig. 5 the measured values of two experiments are shown by dot marks and calculated values are given by the line. The lateral axis shows the square root of elapsed time in seconds. The vertical axis shows the amount of water uptake. The value unit is kg/m^2. The calculated curve corresponds with the measured values. This shows the validity of the determination of the physical properties.

4. Evaluation of the physical properties by drying test

For drying, water saturated samples are placed into a wind channel where relative humidity, temperature, wind velocity and the total mass of the specimen are measured. In Fig. 6, the dots show the measurement results of the mass change with time for two experiments. The weight of

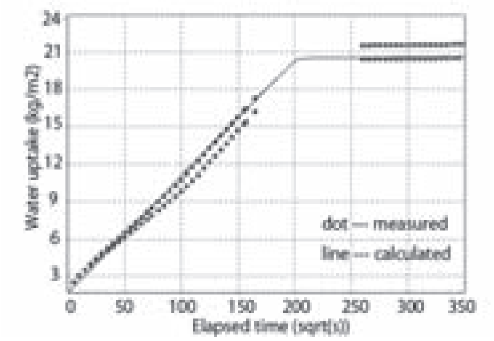

Fig. 5 Test results for water uptake test

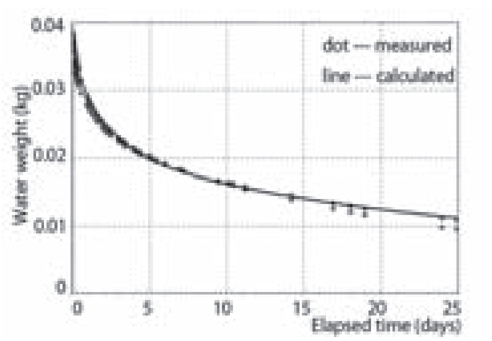

Fig. 6 Test results for drying test

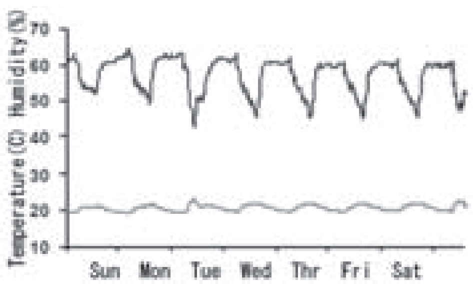

Fig. 7 Humidity and temperature change

the sample decreases due to water evaporation. The curve shows the calculated change of water weight with time, using given material functions. The calculated line corresponds well with the measured values.

5. Boundary conditions

For the restoration of the mural paintings of Takamatsuzuka Tumulus, the stones are placed on special tables in the facility for the restoration of mural paintings, where the temperature and humidity boundary conditions are kept approximately constant. The corresponding relative humidity and temperature measured at 10 minute intervals is given in Fig 7. It can be seen that temperature deviates 2°C around 21°C. Relative humidity shows a daily change between 50 and 60%.

6. Calculated results

For numerical simulation, the given material properties and boundary conditions are applied to model the drying of the tumulus stones.

The initial moisture condition of Takamatsuzuka Tumulus was estimated by the weight and size of stone during the relocation of the stones. The estimated volumetric water content was 20%. After the relocation of the stones to the restoration facility, the relative humidity around the stones was reduced to 60% in order to prevent biological activities on the lime plaster surface with mural paintings.

The change of volumetric water content profile due to this drastic change of environmental condition was calculated by using heat and mass transfer simulation software (Delphin 5) with the physical properties of the stones. As a boundary condition, the relative humidity was set to 100% before the dismantlement of the stone chamber and it was set to 60% after it was relocated to the restoration facility.

Here volumetric water content profile of the north wall with the mural painting of Black Tortoise (Genbu) was calculated. The size of the stone is 116cm (lateral length) x 151cm (vertical length) x 45cm (depth). In the calculation, lateral length was set to 58 cm, considering the symmetrical condition of the stone. The calculated volumetric water content profiles in 1 day, 7 days, 100 days, 1 year, 2 years and 3 years after the relocation of the stone to the restoration facility are shown from Fig. 8a to Fig. 8f, respectively. The lateral axis shows the distance from the side of the stone to the middle of the stone. The plaster surface shows the location of the lime plaster with mural paintings. The vertical axis shows the calculated volumetric water content in each location.

Fig. 8b shows that the initial volumetric water content of the stone was 20% and that after 7 days the volumetric water content near the surface was reduced to 5%. This corresponds well with the relationship between the volumetric water content and relative humidity in Fig. 2. Fig. 8c shows that the volumetric water content of the stone near the surface decreased gradually. The 5% volumetric water content region gradually increases after 1 year and 2 years (Fig. 8d and Fig.8e). After 3 years, the volumetric water content of almost all of the parts reduced to 5%.

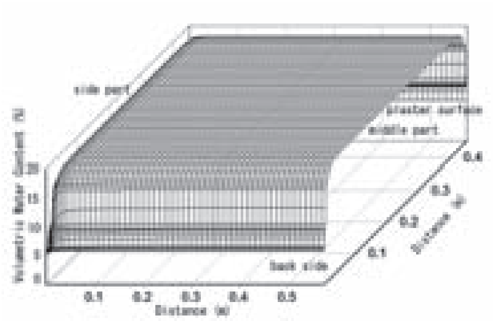

Fig. 8a Volumetric water content profile (1 day)

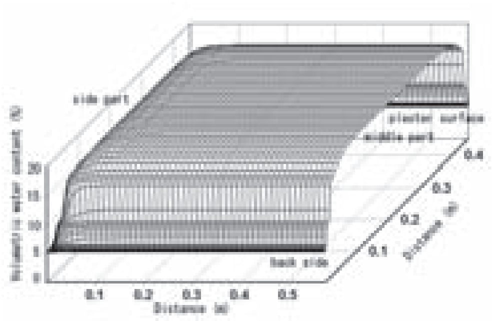

Fig. 8b Volumetric water content profile (7 days)

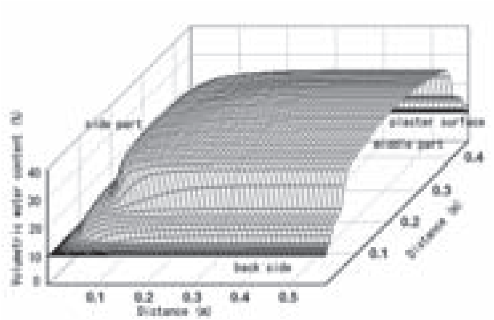

Fig. 8c Volumetric water content profile (100 days)

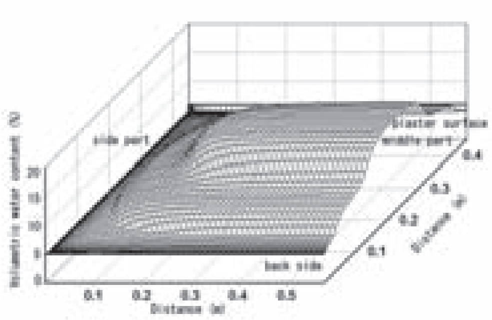

Fig. 8d Volumetric water content profile (1 year)

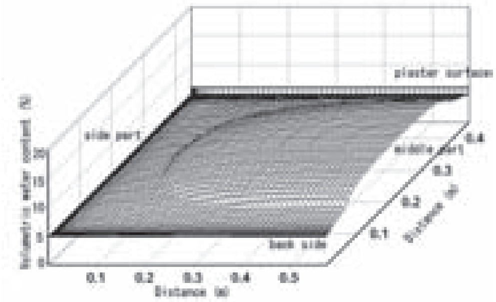

Fig. 8e Volumetric water content profile (2 years)

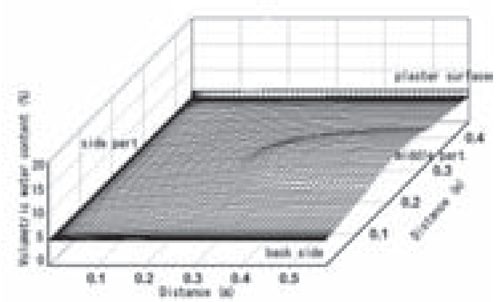

Fig. 8f Volumetric water content profile (3 years)

7. Conclusion

The extended measurements of material parameters for the *tuff breccia* stone were conducted and hydrophysical material functions for the simulation were derived. In combination with the measured boundary conditions we made a simulation analysis of the moisture profile change of the stone chamber of Takamatsuzuka Tumulus after the relocation of the stone chamber to the restoration facility. Based on the physical properties, the change of the moisture profile was calculated by heat and mass transfer software (Delphin 5) developed by TU-Dresden. The calculated results showed that in 3 years the volumetric water content of almost all parts reduced to 5%. The simulation technique is quite effective to evaluate the inside condition of cultural properties where direct monitoring is difficult in a non-destructive way.

8. References

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高松塚古墳石室石材（凝灰角礫岩）の乾燥過程シミュレーション解析

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要旨

2005年６月に開催された国宝高松塚古墳壁画恒久保存対策検討会にて，壁画保存のために，石室を解体し壁画を修理することが決定された。この決定に基づき，2007年４月に石室の取り出し作業を開始し，８月に石室取り出し作業が終了した。石室を構成するすべての石材は，その後，国営飛鳥歴史公園内に建設した仮設修理施設に運ばれ，本格修理が行われている。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，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。すなわち，石室が墳丘部内にあった時，周囲の湿度が100％であったが，仮設修理施設に運ばれてからは，平均湿度がほぼ60％となっている。この周囲湿度の低下のため，石材内の水分量は徐々に低下する。ここでは，ドレスデン工科大学で開発された熱水分移動解析ソフト Delphin 5 を用いて，石材内の水分量の変化を解析した。

多孔質体の水分移動解析を行うためには，試料の水分特性曲線，平衡含水率曲線，透水係数などの物性値が必要である。測定には，高松塚古墳石室に使われている凝灰角礫岩と組成の類似している二上山の凝灰角礫岩試料を用いた。水分特性曲線は，つり下げ法，加圧板法，飽和塩法で求めた。また，透水係数は，試料の吸水試験および乾燥試験により求め，間隙構造から試料の毛管モデルを作成した。

壁石周囲の境界条件としては，石室解体前は，周囲湿度が100％，仮設修理施設へ移された後は，室内の湿度の測定結果よりほぼ60％として，石材周囲からの石材の乾燥過程に関して解析を行った。計算対象としては，玄武の絵のある北壁を選択した。石材の大きさは，縦，横，厚さが，116cm，151cm，45cm である。計算は，対称性を考えて，縦方向は半分の58cm で計算している。計算結果から，移設から７日後に，試料周囲で20％から５％の体積含水率まで低下しているのが計算された。凝灰角礫岩の平行含水率曲線から，相対湿度60％に対応する体積含水率は約５％であるので，既に資料周辺部では，周囲の湿度環境と平衡状態になっている。その後，壁石の周囲から徐々に乾燥が進み，壁石の移設後３年後，試料中心部までほぼ体積含水率が５％に近くなり，ほぼ壁石全体で体積含水率が一様になっていることが計算された。

キーワード：高松塚古墳（Takamatsuzuka Tumulus）；解体（dismantlement）；壁石（stone wall）；乾燥過程（drying process）；シミュレーション（simulation）

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