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EVAPORATION MEASUREMENT FOR THE PRESERVATION OF HISTORICAL BUDDHIST MONASTERY AJINA TEPA, TAJIKISTAN

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One of the destruction mechanisms of historical earthen walls in Ajina Tepa site, Tajikistan is the salt crystallization. Halite, calcite and gypsum are found as the major salts crystallized on the historical walls. Because the rate of crystallization is thought to be a function of evaporation, the evaporation from four earthen walls was measured by using a newly developed portable evaporation meter. Before the measurement, the accuracy of the evaporation meter was carefully studied under the no-wind and the wind conditions in laboratory and field tests in Japan. The effect of average wind velocity on the evaporation measurement was also evaluated before the measurement. It was found that the evaporation rate is big at the foot of the historical wall and is decreasing with height. This feature implies that moisture is mainly supplied from ground and the protection cover of which height is at least 1m is needed to prevent the destruction of historical wall due to the salt crystallization.

Key Words: Ajina Tepa, evaporation, new evaporation meter, accuracy check, salt crystallization

1. INTRODUCTION

Historical monuments such as citadels, palaces, buildings and so forth that are situated in arid and semi-arid area were mainly constructed by using mud brick and/or rammed earth. Many preservation works have been performed to protect those monuments from the destruction due to erosion, weathering and failure. The major mechanism of the destruction can be divided into three; (1) failure of unstable walls, (2) continuous decay and erosion from the wall surface by the repetition of wetting and drying and (3) damage by salt crystallization occurring on and beneath the wall surface. Unstable walls can be stabilized by support works such as the buttress made of mud bricks and the continuous decay and erosion may be prevented by covering the walls with mud brick and/or plaster layers. Shelter coating can decrease the rain infiltration. However, the salt crystallization is difficult to stop. Some of the salts crystallizing in open spaces on and beneath the surface expands its volume and can destroy the wall from the surface. The intensity of the salt crystallization is thought to be the function of evaporation rate from the wall surface, so that, the evaporation should be properly evaluated for developing effective ways of the preservation. However, evaporation measurement at arbitrary points on wall is not so easy to solve. In this study, the evaporation rate from four walls of Ajina Tepa, that is a historical Buddhist monastery constructed during 7-8 Centuries along the ancient Silk Road, was measured by using a portable equipment that was newly developed (hereafter, this equipment is written as “evaporation meter”[1) ~ 5)]). The preservation of the Buddhist monastery has been performed as a project of the UNESCO/Japan trust fund for world heritage.

2. AJINA TEPA AND PRESERVATION WORKS

Fig. 1 illustrates the location of the Ajina Tepa. This historical site is locating at about 100km south from Dushanbe that is the capital city of Tajikistan[6), 7)]. The site is now situating a wide cotton field.

According to the internet site of world weather information service, the average annual precipitation measured during 1961-1990 at Kurgan-Tube, that is a town locating about 15km west from the site, is about 260 mm/year and the rainy season is continuing from November to May.

Fig.1 Location of Ajina Tepa

Fig. 2 is the 3-D graphics made by the authors during 2006-2007 by using the technique of photogrammetry[6)]. The Ajina Tepa site is divided into two parts, the stupa area and the monastery area. **Fig. 3** shows the damaged historical walls in the monastery area. The historical walls were constructed with mud bricks and Pakhsa (local name of the rammed earth) and have been much decayed after the archeological excavation conducted during 1960-1975 [7)]. **Fig. 4** shows an example of the support and the surface cover newly constructed for the stabilization of an unstable wall by using new mud bricks.

Walls in the site are covered with soil debris. Some of these walls in the site were cleaned with removing debris before the preservation work. Intense salt crystallization on the wall immediately occurred after the cleaning. **Fig. 5** displays the salt crystallization on a mud brick wall after the cleaning performed in the end of April, 2007. Major salts are halite, gypsum and calcite. The evaporation on the two mud brick walls (MB-1 and MB-2) and two Pakhsa walls (Pakhsa-1 and Pakhsa-2) were measured for basically evaluating salt crystallization at four points as illustrated in **Fig. 2**.

3. EVAPORATION MEASUREMENT

(1) Basic idea of evaporation measurement

The basic idea of evaporation measurement method is based on the water vapor concentration

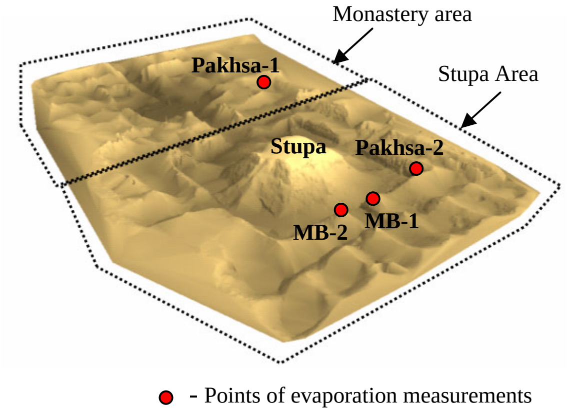

Fig.2 3-D graphic for Ajina Tepa

Fig.3 Damaged historical walls in the monastery area

Fig.4 Support and surface cover constructed for the stabilization

Fig.5 Salt crystallized on a historical wall

gradient method (Watanabe, K.$^{1)}$). It can be assumed that the vapor flux supplied by evaporation from the surface is upwardly transported by the molecular diffusion in the thin laminar layer formed just above the surface. A vapor flux or evaporation rate could be calculated by Eq.1 (See in **Fig. 6**).

$$Ev = D\frac{\Delta\theta}{\Delta n} = D\frac{(Rh_1.Sr_1)-(Rh_2.Sr_2)}{\Delta n} \qquad (1)$$

where D is the diffusion coefficient of water vapor (m^2/s), $\Delta\theta$ is the absolute humidity difference between two sensors in $(\theta_2-\theta_1)$ (g/m^3), Δn is the distance between two sensors in the normal direction to the surface (X_2-X_1) (m), Rh_1 and Rh_2 are relative humidity obtained from sensor 1 and sensor 2, Sr_1 and Sr_2 are vapor saturation at sensor 1 and sensor 2. The relative humidity (Rh) and temperature (T) are measured by two sensors (sensor1 and sensor2) at different vertical distance from the surface of soil as schematically illustrated in **Fig. 6**.

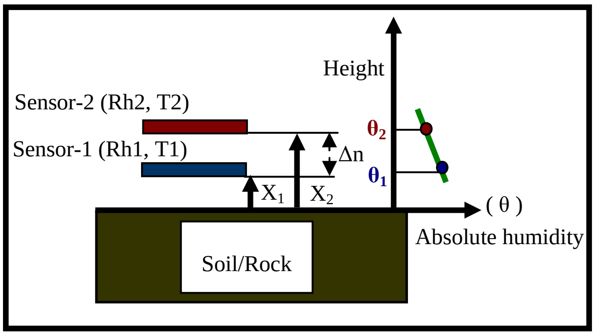

Fig.6 Schematic diagram of evaporation measurement

The absolute humidity (θ) at each sensor can be calculated from the relative humidity (Rh) and vapor saturation (Sr). Since the vapor saturation (Sr) is a function of temperature (T) and it can be expressed as follows$^{1)}$;

$$Sr = 0.0192.T^2 + 0.2087.T + 5.3848 \qquad (2)$$

The diffusion coefficient (D) in Eq.1 is also the function of temperature (T). It can be approximately expressed by$^{1)}$;

$$D = 2.41\times10^{-5} + 1.5\times10^{-7}(T-15) \qquad (3)$$

In Eq.1 and Eq.2, T is the average temperature of sensor-1 and sensor-2 in Celsius unit.

(2) Measurement apparatus

The main part of the new evaporation meter (Tokyo Keisoku ETH 6101) is composed of two pairs of humidity sensor and thermistor. The shape and the size of the sensor part of the measurement equipment are illustrated in **Fig. 7**.

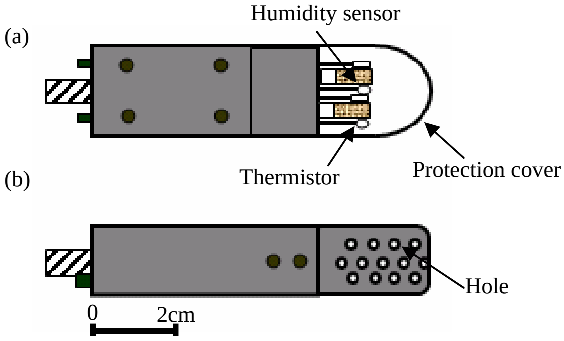

Fig.7 Schematic diagram of sensor part of evaporation meter
(a) plan view and (b) side view

The humidity sensor has a plate shape with the size of about 5mm x 3mm. Thermistor is spherical in shape with 2mm diameter. The shape of plastic protection cover surrounding these two sensors is semicircular and its size is about 2.5cm x 2cm and the height is about 1.5 cm. The distance Δn between two pairs of the humidity sensor and thermistor is fixed as 7mm. The other parts of this evaporation meter are an anemometer and a data logger including a small computer. The schematic diagram of the evaporation measurement is illustrated in **Fig. 8**. All data (i.e. temperature and relative humidity from two sensors and wind velocity from anemometer) are sent to the data logger and the evaporation rate is calculated from the absolute humidity difference $(\theta_2-\theta_1)$ between two sensors. Evaporation rate and wind velocity value are displayed on the monitor of data logger. The response time of sensor is about 60 seconds and average evaporation values were recorded in the data logger.

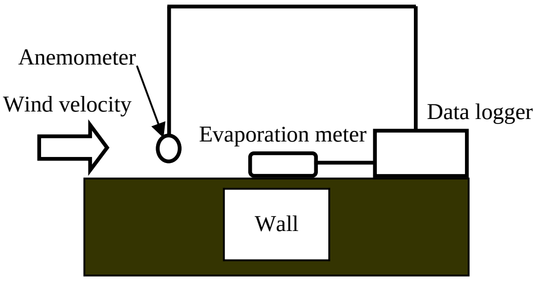

Fig.8 Schematic diagram of field measurement by a new evaporation meter

(3) Accuracy check of the measurement

Accuracy of the measurement by the evaporation meter was studied under room temperature condition in the laboratory and in the field. The accuracy was investigated with comparing between measured evaporation rate from the evaporation meter and the true evaporation rate calculated from the weight losses of the specimen. Two types of measurements were performed. The first measurement was conducted under the no-wind condition and the second measurement was carried out under the wind condition. These measurements are described in details as bellows.

(a) Accuracy check under the no-wind condition

Six disk type specimens of mud stone (S-1 to S-6) were used for the accuracy check under no-wind condition. Disk shape specimens at which diameters are 7cm and thickness of 1~2cm were used. Both the side wall and the bottom of these specimens were completely sealed with sealant. Therefore, evaporation was allowed from the surface of specimens only. The weight of the specimen decreased if the water from the specimen evaporated and the weight increased when the specimen sucks the vapor in air. Thus, the true evaporation could be estimated from the weight changes of these specimens. The schematic diagram of the accuracy check test was illustrated in **Fig. 9**. The accuracy tests were carried out for a period of 2 hours under no-wind condition. The comparisons between 2 evaporation rates (i.e., measured evaporation rate and true evaporation rate) were shown in **Fig. 10**. From this figure it was found that, the evaporation rate (E_m) measured from the evaporation meter gave the good agreement with true evaporation rate (E_c) calculated from the weight change. Difference of evaporation rate is mainly due to the difference of saturation conditions of specimens used in the test. The region of saturation was 50%~100%.

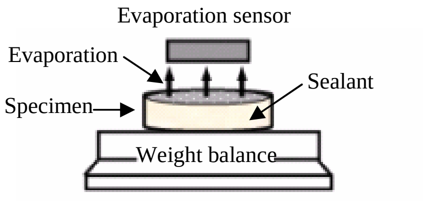

Fig.9 Schematic diagram of accuracy check test (under the no wind condition)

(b) Accuracy check under wind condition

In the actual field, vapor is transported not only by diffusion but also by turbulent motion of air$^{3)}$ and the thickness of the laminar layer becomes small. For the reason, the accuracy of the measurement under the wind condition was carried out in the laboratory and two fields in Japan during the summer time. A wind fun was used for the laboratory test for changing wind velocity. The wind velocity was measured at 5mm above the surface of specimen by an anemometer. The measurement was performed with record time interval of 60 seconds for a period of 1 hour measurement time. The effect of wind is evaluated with using the coefficient (C) in Eq.4 that is the ratio between true evaporation (E_c) and the measured evaporation rate (E_m).

$$C = \frac{E_c}{E_m} \tag{4}$$

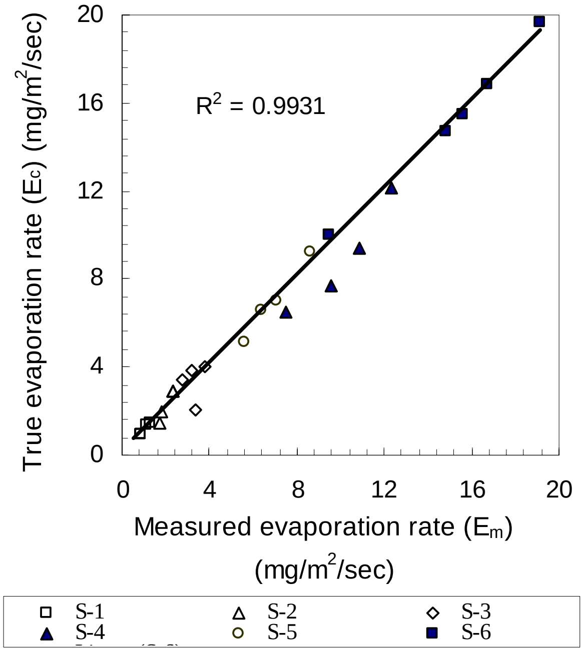

Fig.10 Comparison between true and measured evaporation rate

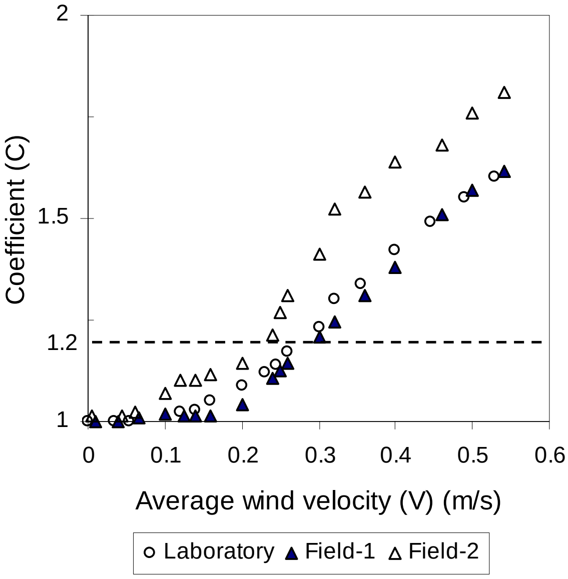

Fig.11 Three examples of accuracy tests results. The relations between coefficient (C) and the average wind velocity (V) are presented. Actual evaporation rate is 0~20 mg/m^2/sec.

Fig. 11 shows the results of three tests and the relations between the coefficient (C) in Eq.4 and the average wind velocity (V) measured at 5mm above the surface of specimen are presented. The coefficient (C) values increasing with the increase of the average wind velocity (V). It looks difficult to formulate the relation between C and V, because the effect of wind can not be estimated from only the average velocity fluctuation of wind velocity is also important. However, under the condition that the average wind velocity is less than 0.2 m/s, the coefficient (C) were less than 1.2. This result implies that when the measurement could be performed under the average wind velocity less than 0.2 m/s, the maximum measurement error is lower than 20%.

4. RESULTS OF THE MEASUREMENT IN AJINA TEPA SITE

Fig. 12 shows the meteorological data in May, 2007, that was provided from the meteorological station located at Kurgan-Tube. Only the data of daily average temperature and daily precipitation were provided. Four broken lines in this figure illustrate the days of evaporation measurements.

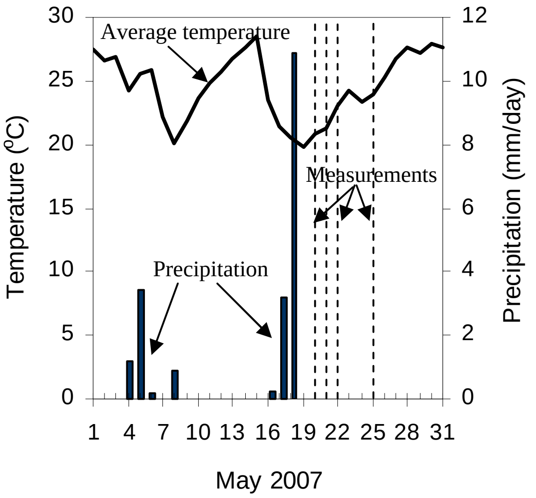

Fig.12 Daily precipitation and average temperature measured at Kurgan-Tube

Evaporation measurements were performed 5 times ((1) 20 May, 9:00~10:30, (2) 20 May, 12:00~13:30, (3) 21 May, 14:30~15:00, (4) 22 May, 9:00~10:30, (5) 25 May, 9:00~9:30) at 4 points (MB-1, MB-2, Pakhsa-1 and Pakhsa-2) in **Fig. 2**. **Fig. 13** displays those selected 4 walls (MB-1, MB-2, Pakhsa-1 and Pakhsa-2). **Fig. 14** schematically illustrates the possible two ways of moisture movement due to the evaporation in the historical wall; one is the rain water origin and another one is the ground water origin. One objective of this measurement was focused to study the major moisture movement in the historical walls. If the evaporation rate is very big at the foot of the wall and

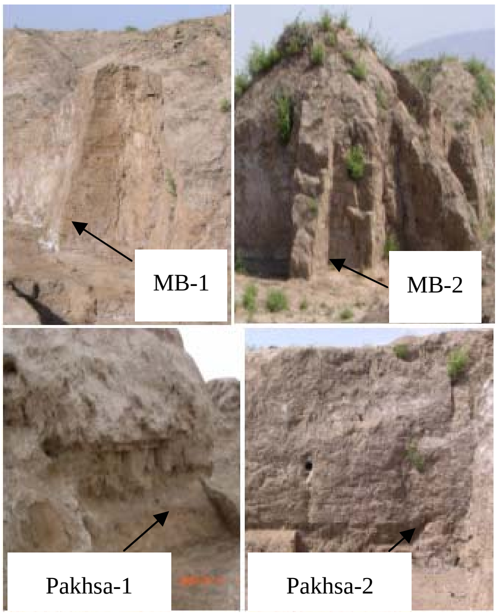

Fig.13 Evaporation measurements on the selected four historical walls (MB-1, MB-2, Pakhsa-1 and Pakhsa-2)

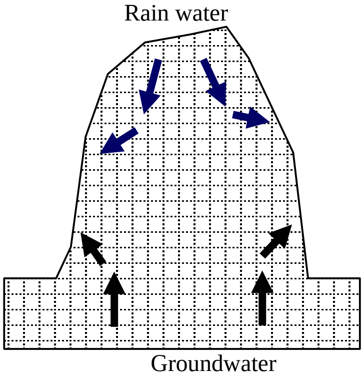

Fig.14 Two possible ways of the moisture movement due to the evaporation in the historical wall

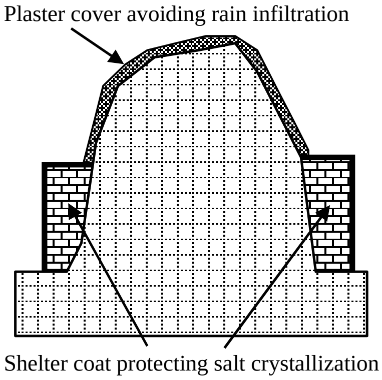

Fig.15 The protection covers of historical wall due to salt crystallization and weathering processes

decreasing with the increase of the wall height, it can be thought that the moisture supplied from the ground is more dominant than the rain water origin. If so, the foot part of the historical wall should be properly coated with thick mud bricks layers to protect the historical wall from the salt crystallization as illustrated in **Fig. 15**. The top part of the historical wall should be also covered with the plaster to avoid the rain infiltration and the decay of wall due to the repetition of drying and wetting processes.

All of these measurements were carried out when the average wind velocities measured at 5 mm above the wall surfaces were less than 0.2 m/s with considering the accuracy of measurement. Because the evaporation rates are influenced by the moisture condition in walls, contact condition of sensor on wall, air humidity, air temperature, and so forth, the measured values are fluctuated and not the same for all measurements. For this reason, average values of 5 measurements for each location were considered. The average values may be enough to consider the general tendency of the moisture flow and protection works. **Fig. 16** displays the vertical profiles of the evaporation rate on these walls (MB-1, MB-2, Pakhsa-1 and Pakhsa-2). Vertical and horizontal axes of the figure are the height from the ground surface and measured evaporation rate (mg/m2/s), respectively.

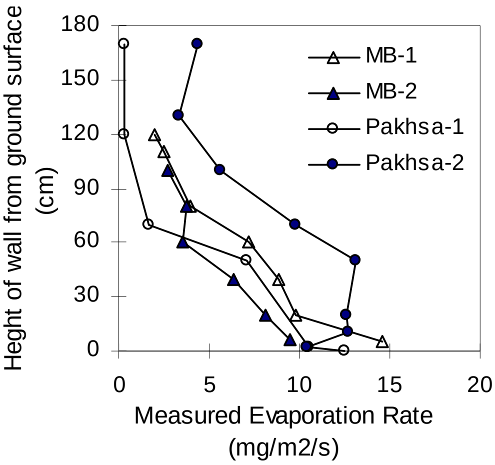

Fig.16 Average evaporation on the mud brick walls (MB-1 and MB-2) and Pakhsa walls (Pakhsa-1 and Pakhsa-2)

It is clearly found from this figure that the evaporation rates are big near the ground surface and gradually decrease with the height. This feature implies that the moisture is essentially supplied from the ground, then, it is going up in the wall by capillary suction and evaporates from the wall surface. As the general tendency, the evaporation rate becomes small when the height of wall is larger than 1.0~1.2m. Because evaporation rate is big at the foot of wall, the intensity of salt crystallization is thought to be also intense just above the ground surface. So that, wall tends to be destructed from its foot part. It can be concluded that the shelter coat of which height is, at least, larger than 1.0m is needed to reduce the decay of historical wall due to the intense salt crystallization for this site (see in **Fig. 15**).

5. CONCLUSION

Evaporation from four historical walls in the Ajina Tepa site, Tajikistan was measured by using a newly developed evaporation meter. The accuracy and the effect of wind velocity were evaluated by the laboratory and two field tests in Japan before the field measurement. It is concluded that the accuracy is good under the no-wind condition. And also it is found that when the measurement could be performed under the average wind velocity less than 0.2 m/s, the maximum measurement error is lower than 20%. From the field measurement carried out on 4 historical walls in the Ajina Tepa site, it was clearly found that the evaporation rate is large near the level of ground surface on the wall and it is decreasing with height. Protection wall of which height is at least 1.0m seems to be needed to reduce the destruction caused by the salt crystallization.

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