Numerical analysis on salt damage suppression of the Buddha statue carved into the cliff by controlling the room temperature and humidity in the shelter

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Abstract

Motomachi Sekibutsu is a Buddha statue that was carved into a cliff in Oita City, Japan, during the 11th or 12th century. It was designated as a national historic site in 1934. The stone statue is constantly affected by the penetration of heat and moisture into the cliff, and concerns have been raised about its deterioration. Various preservation measures have been taken to prevent this; however, the main cause of deterioration, salt damage, has not been eliminated. Here we develop a numerical analysis model to calculate the heat and moisture behaviour in the statue and its shelter. Using this model, we reproduce the shelter's hygrothermal environment before and after renovation and evaluate it with respect to damage caused by sodium sulphate. Our results show that the improvement in airtightness drastically contributes to decreasing the evaporation from the statue and suppressing the salt phase change; thus, the renovation of the shelter suppressed sodium sulphate salt damage to the statue.

Keywords: conservation environment, architectural environment, coupled heat and moisture transfer, sodium sulphate, phase change

1. Research aim

Motomachi Sekibutsu *(Fig. 1)* is a stone statue of Buddha that consists of tuff and was carved into a cliff in Oita City, Japan, during the 11th or 12th century. The statue is constantly affected by the hygrothermal environment in the room and heat and moisture transfer through the cliff (from which it cannot be separated). Therefore, the statue has suffered salt damage, exfoliation and growth of mould and bryophytes.[1] Salt damage, caused by so-

Figure 1: Motomachi Sekibutsu

Figure 2: Shelter exterior

dium sulphate, has long been a concern. To prevent these deteriorations, various preservation measures have been undertaken from 1986 to 1996 and again from 2011 onward. These include constructing a shelter *(Fig. 2)*, boring a tunnel behind the statue to reduce groundwater and renovating the shelter. Salt damage by sodium sulphate is considered to be halted as a result of the shelter renovation during November 2015.[2]

Our aim is to suppress the further degradation of the statue from salt damage by controlling the hygrothermal environment of the shelter that houses the Buddha statue. Previously, using calculations of the heat and moisture behaviour of the statue and considering the shelter's hygrothermal environment, we clarified that salt damage tends to occur at the knee of the statue under the room environment before the renovation in 2013.[3] In this study, we focus on how the hygrothermal environment in the shelter is produced, and we reproduce it using numerical analysis. In addition, we examine a method for coordination of the room environment, which suppresses the salt damage of the statue.

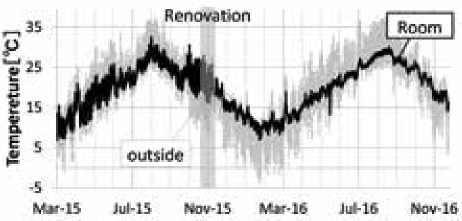
2. Motomachi Sekibutsu Room Environment

2.1. Shelter

At Motomachi Sekibutsu, the shelter was renovated twice, in 1995 and in 2015. In 1995, various construction works were done to improve thermal insulation, such as insulating the wall by a thermal insulation material and installing a windbreak room at the entrance.[1] In 2015, the renovations focused on salt damage due to sodium sulphate and aimed to protect from solar radiation, improve the performance of thermal insulation and improve the airtightness of the windows.[2] During that renovation, thermal insulation was improved, a door closure was mounted, the windbreak room was mounted, and the windows were covered with solar shading sheets. In this study, we refer to that renovation as 'the renovation'.

2.2. Room temperature, humidity and ventilation rate

We measured the hygrothermal environment inside and outside the shelter from November 2014. *Figures 3 and*



Figures 3: Variation of the measured temperature inside and outside the shelter

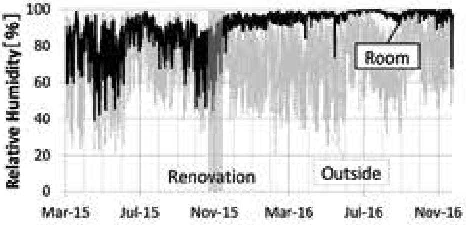


Figure 4: Variation of the measured relative humidity inside and outside the shelter

4 show the inner and outer temperature and relative humidity from March 2015 to November 2016. After the renovation, the daily fluctuation in room temperature decreased but the relative humidity maintained its high value. We measured the inside and outside concentrations of CO_2 from October 3 to October 4, 2016, and calculated the ventilation rate via the decrease in CO_2 concentration after opening or closing the window. The ventilation rate was 0.21 times per hour when the windows were closed, and it was 9.9 times per hour when they were opened.

3. Method for Examining Salt Damage

Salt damage to the porous statue material is caused by precipitated salt. The porous body is destroyed by volume expansion of salt, which is caused by crystallisation, thermal expansion and hydration.[4] To destroy the statue material, the following processes must occur: i) salt must precipitate in the material, and ii) the crystal pressure of salt must be high enough to break the material. Motomachi Sekibutsu consists of a tuff., the most prevalent damaging salt is sodium sulphate, and it is assumed that the pressure occurs when the precipitated salt ch-

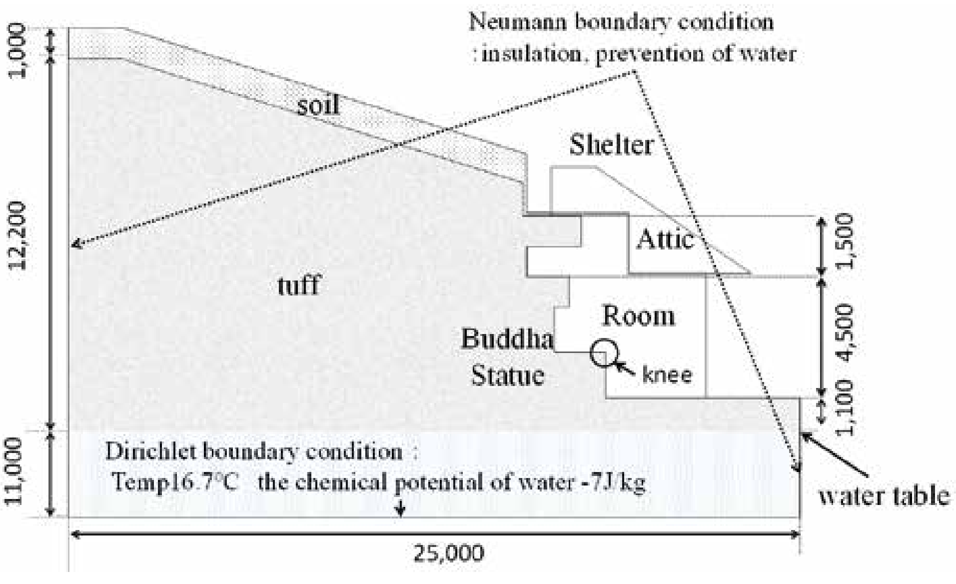


Figure 5: Schematic of the numerical model of the cliff, including the statue

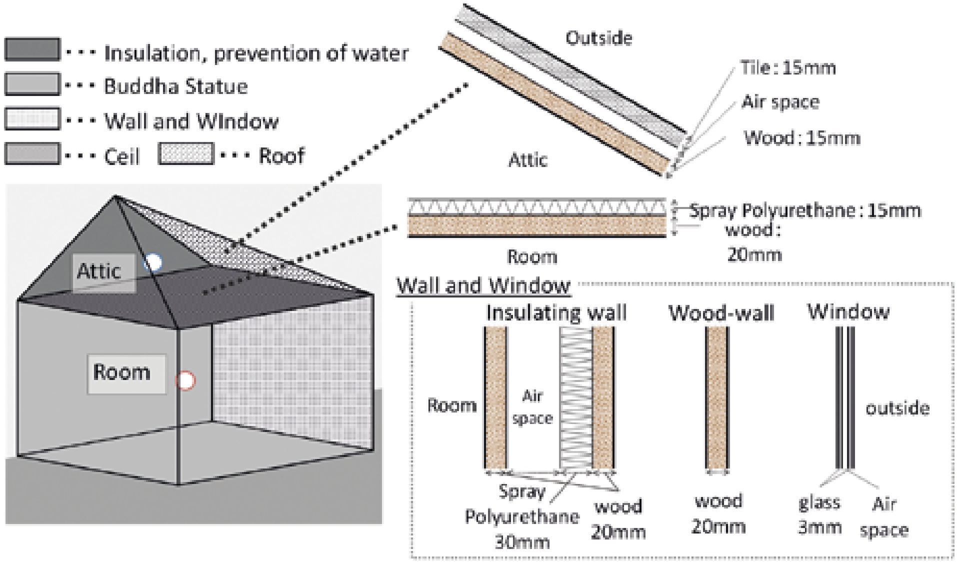


Figure 6: Model for analysing the room environment

anges its phase from thenardite (Na_2SO_4) to mirabilite ($Na_2SO_4.10H_2O$).[5] The salt precipitates when the solubility decreases with decreasing temperature and/or water evaporates.

4. Numerical Analysis

4.1. Methodology

We developed a numerical model to calculate the heat and moisture behaviour in the statue and shelter. The cliff, including the statue, is represented as a two-dimensional model, as used in our previous study[3] and shown in *Fig. 5*. The analytical model of the temperature and humidity in the shelter is shown in *Fig. 6*. We divided the shelter into room space and attic space. The shelter includes three kinds of walls: the insulated wall, the wooden wall and the glass window. The walls are oriented along the northeast, southeast and southwest directions. The roof is inclined at 30°. We calculated the amount of solar radiation by considering the angle of inclination. The surface area of the statue was obtained by multiplying the length of each of the two-dimensional models by the depth, 10.8 m. The volumes of the room and the attic are 164.2 m^2 and 100 m^3, respectively.

We used the heat and moisture balance equations [6] to analyse the heat and moisture behaviour in the statue and wall. The equations are written as follows:

Heat balance

$$c\rho \frac{\partial \rho}{\partial \rho} = \nabla \cdot \{(\lambda + r\lambda'_{Tg})\nabla g\} + \nabla \cdot (r\lambda'_{\mu g} \nabla \mu)$$

(1)

Moisture balance

$$\rho_w \left(\frac{\partial \psi}{\partial \mu}\right) \frac{\partial \mu}{\partial \mu} = \nabla \cdot [\lambda'_{\mu} (\nabla \mu - n_x g)] + \nabla \cdot (\lambda'_T \nabla \mu)$$

(2)

where the relation between the chemical potential of water μ and relative humidity h is given by

$$\mu = R_v T \ln h = R_v T \ln \frac{p}{p_{sat}} \tag{3}$$

The boundary conditions for heat and moisture, respectively, are:

$$\alpha(T_0 - T_i) + r\alpha_m'(p_0 - p_i) + q_s = -(\lambda + r\lambda_{Tg}')\frac{\partial T}{\partial n} - r\lambda_{\mu g}'\frac{\partial \mu}{\partial n} \tag{4}$$

$$\alpha_m'(p_0 - p_i) + J_p = -\lambda_\mu'\left(\frac{\partial \mu}{\partial n} - n_x g\right) - \lambda_T'\frac{\partial T}{\partial n} \tag{5}$$

The boundary equations of the space are written as

Heat balance

$$c_A \rho_A V \frac{\partial T}{\partial t} = \sum S\alpha_i (T_w - T_i) + \sum c_A \rho_A V N (T_O - T_i) + Q \tag{6}$$

Moisture balance

$$\rho_A V \frac{\partial A}{\partial t} = \sum S\alpha_i (P_w - P_i) + \sum \rho_A V N (A_O - A_i) \tag{7}$$

where Q is the heat, which includes absorbed solar radiation in the space, transmitted through the windows.

4.2. Analysis conditions

In this analysis, the outside temperature and humidity, which are boundary conditions, were obtained from measured values (obtained from April 1, 2013 to March 31, 2014 and January 1, 2016 to December 31, 2016) [7]. The heat and moisture properties of each material were estimated from the literature.[8, 9] The coefficients of heat and moisture were 9.3 W/m2K and 2.85 × 10−8 kg/m² Pa for the room/attic space, respectively, and 23.3 W/m2K and 1.14 × 10−7 kg/m² Pa for the outside, respectively. *Table 1* shows the calculation conditions. We aimed to clarify how the room's hygrothermal environment was changed by each renovation; therefore, we divided the renovation into the following factors to create our model.

i) Ventilation rate. Before the renovation, the ventilation rate between the room and the outside was 10.0 times per hour; however, after the renovation, it was 0.2 times per hour. Furthermore, the ventilation rate was 2.0 times per hour between the room and the outside and 0.1 times per hour between the room and the attic.

ii) Thermal insulation performance of the wall and window. Before the renovation, the U-value (the average transmission rate) of the wall was 4.55 W/m2K. After the renovation, the U-value was 1.23 W/m2K.

iii) Solar radiation shielding. Before the renovation, the rate of solar trans-

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5
Ventilation rate	A	B	A	B	B	A
Thermal insulation	A	B	B	A	B	A
Solar transmission	A	B	B	B	A	A

'A' means after the renovation, and 'B' means before the renovation

Table1: Analysis conditions

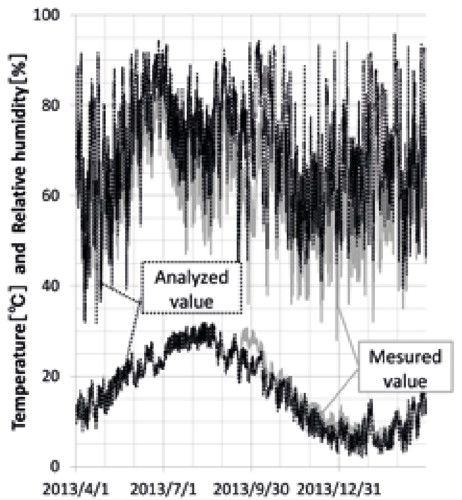


Figure 7: Comparison in Case 0

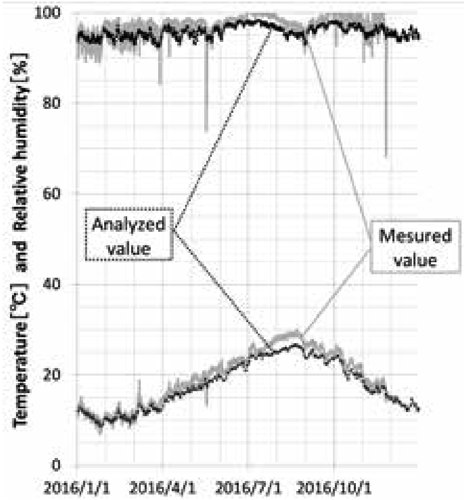


Figure 8: Comparison in Case 0

mission of the window was 0.75.[3] The amount of solar radiation incident on the statue was calculated by considering the shape of the roof and the position of the sun.[3] After the renovation, the rate of solar transmission was 0.6 and the amount of solar radiation that reached the statue was zero.

Using these conditions, we reproduced the room temperature and humidity in 2016 with Case 0 and reproduced from April 2013 to March 2014 with Case 1, respectively. In Cases 2–5, we considered in detail how each renovation affected the room environment.

5. Results and Discussion

5.1. Comparison of the measured and calculated values

Fig. 7 and Fig. 8 show the measured and calculated values of the temperature and relative humidity in the room for Case 0 and Case 1. In both cases, the annual fluctuation of the calculated value agrees very well with that of the measured value, although there is a mismatch over a short period. Those errors can be mainly attributed to the constant ventilation rate throughout the year or the heat and moisture flux from the statue.

5.2. Water evaporation from the statue

We examined the trends in salt precipitation for Cases 1–5. Here we assumed that the moisture flux from the surface of the statue is equal to the evaporation in the statue. *Figure 9* shows the annual amount of water evaporation in the statue, and *Fig. 10* shows the monthly amount of evaporation. Comparing Case 1, before the renovation, to Case 2, it can be seen that water evaporation is suppressed by the decreasing ventilation rate. Similar results are obtained because of the improvement in insulation performance and prevention of solar transmission. These results show that after the renovation, evaporation and salt precipitation was drastically suppressed throughout the year. Here we focus on the effects of each renovation factor. The decreasing ventilation rate suppresses the evaporati-

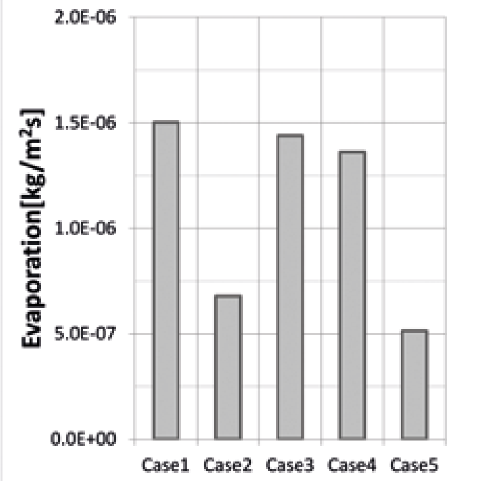


Figure 9: Annual evaporation from the surface of the statue

on and, in especially, contributes well in summer. The improvement in insulation performance suppresses the evaporation from winter to spring, but there is a possibility of promoting the evaporation from summer to autumn. The prevention of solar transmission suppresses the evaporation, and the amount of evaporation does not change significantly across all seasons. The decreased ventilation rate has the greatest influence on the evaporation from the statue, and the improved insulation performance has the least influence.

5.3. Phase change of sodium sulphate at the statue surface

At Motomachi Sekibutsu, salt damage can be seen at the knee of the statue *(Fig. 11)*. In this section, we plot the calculated temperature and relative humidity at the surface of the statue on the phase diagram of Na_2SO_4 and examine the possibility of the resulting salt damage. *Figure 12* shows the results of Case 1, Case 3 and Case 4, and *Fig. 13* shows that of Case 1, Case 2 and Case 5. In Case 2 and Case 5, which are decreased-ventilation-rate cases, the phase change from Na_2SO_4 to Na_2SO_4-$10H_2O$ rarely occurs because the

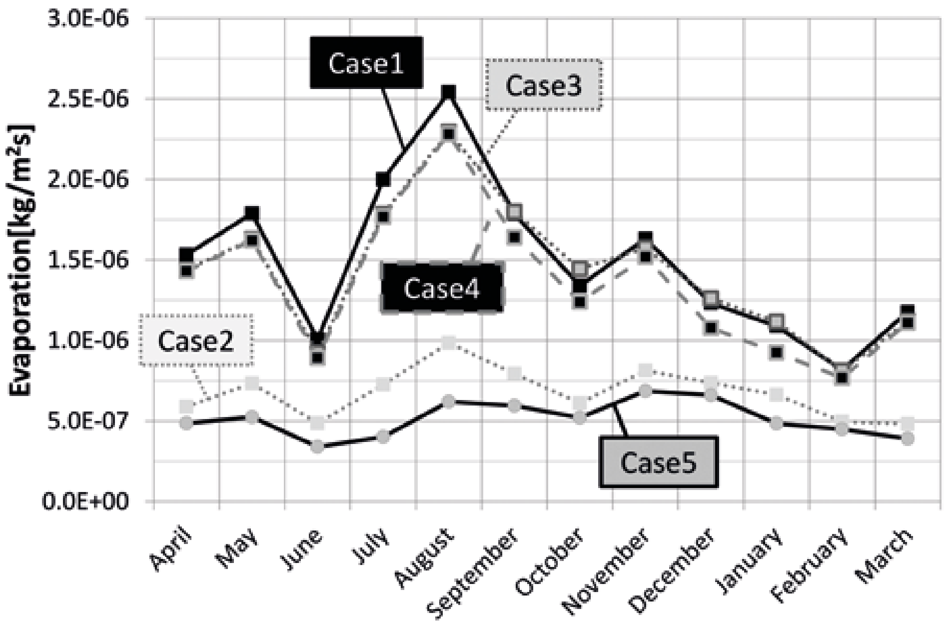


Figure 10: Monthly average evaporation from the surface of the statue

Figure 11: The knee of the statue

relative humidity is very high. However, in Case 1, Case 3 and Case 4, the temperature fluctuates around the low relative humidity, and phase change occurs easily. By focusing on the effect of each renovation factor, in Case 2, we see that the temperature fluctuates around the high humidity and the fluctuation of relative humidity is smaller in Case 2 than in Case 1 before the renovation.

The temperature and humidity in Case 3 are approximately equivalent to those in Case 1, but from winter to spring, the relative humidity is higher in Case 3 than in Case 1. Therefore, the phase change from Na_2SO_4-$10H_2O$ to Na_2SO_4 is restrained during these seasons. Considering the solar transmission, the temperature is lower and the relative humidity is higher in Case 4 than in Case 1 throughout the year. These results suggest that the improvement of airtightness strongly contributes to the suppression of salt damage to the statue.

6. Conclusion

In this study, we developed a numerical analysis model to calculate the heat and moisture behaviour in the statue and shelter. Using this model, we reproduced the shelter's hygrothermal environment before and after the renovation and evaluated it with respect to sodium sulphate salt damage. The model was valid for recreating the hygrothermal environment in the shelter before and after the renovation. The renovation caused the evaporation from the statue to be suppressed by improving the airtightness and insulation performance and preventing solar radiation. The improvement in airtightness drastically decreased evaporation from the statue and suppressed the phase change of salt. Our results show that the renovation of the shelter suppressed sodium sulphate salt damage to the statue.

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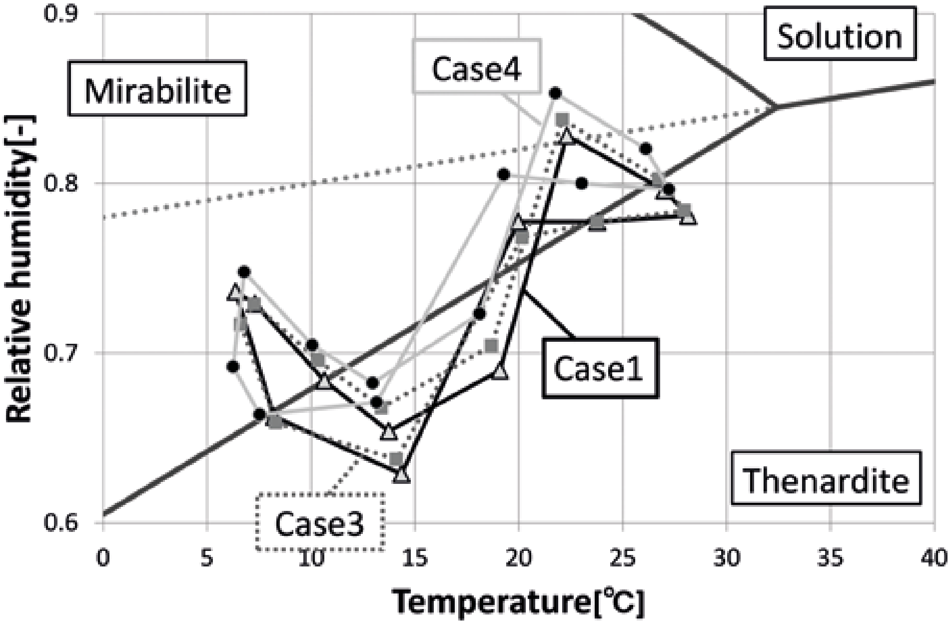

Figure 12: Phase diagrams for Case 1, Case 3 and Case 4

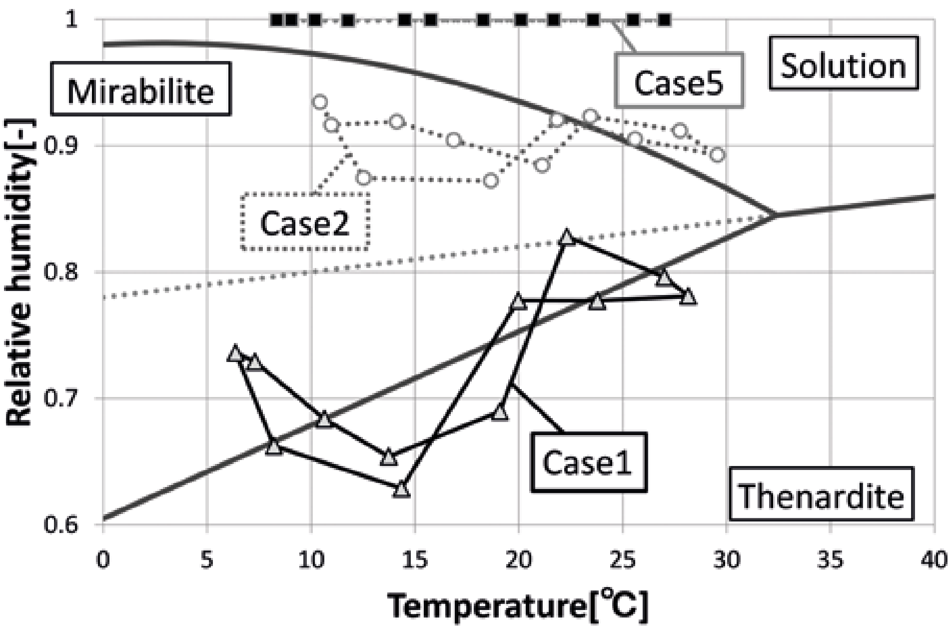

Figure 13: Phase diagrams for Case 1, Case 2 and Case 5

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