FROST DAMAGE OF ROOF TILES IN RELATIVELY WARM AREA IN JAPAN
- CONDENSATION ON EXTERNAL SURFACE -

Chiemi Iba[1], Shuichi Hokoi[2]

[1]Building Environment Section, Environmental Engineering Department,
Hokkaido Northern Regional Building Research Institute, Asahikawa, Japan
[2]Department of Architecture & Architectural Engineering, Faculty of Engineering,
Kyoto University, Kyoto, Japan

ABSTRACT

Even in relatively warm area in Japan, frost damage of roof tiles occurs. In this study, the influences of several factors on frost damage are considered from a thermal environmental point of view. Condensation on the external surfaces of roof tiles, which is caused by a temperature drop due to nocturnal radiation, is estimated as one of the most important factors to the frost damage. The frequency of condensation was calculated by a numerical analysis. The influence of the parameters, such as the inclination angle and the orientation of the roof, is investigated. It is clarified that a surface condensation on the roof tiles occurs very frequently even in a warm area of Japan, regardless of the orientation of the roof.

KEYWORDS

Frost Damage, Roof Tile, Condensation, Nocturnal Radiation, Surface finishing

INTRODUCTION

Moisture inside building materials significantly influences the durability of building envelopes. In cold regions, the accumulated moisture sometimes freezes in the building materials, and causes serious damage to the material (Powers 1945, Matsumoto et al. 1993).

Not only in cold regions but also in relatively warm areas in Japan such as Kyoto, frost damage has been observed. The flaking off of the roof tile is one of the typical examples (Figure 1). Freezing is caused by a temperature drop along with an increase in water content inside the material.

In the field of material science and technology, roof tiles which absorb less water have been developed by baking at a higher temperature. However, high baking temperature causes an increase in the production cost, and some kinds of soil, that roof tiles are made of, cannot endure the high temperature. In this study, not only the material properties but also thermal environmental conditions around the roof are taken into consideration.

A roof is usually open to the sky, thus its temperature is significantly influenced by nocturnal radiation. The temperature drop causes the surface condensation on roof tiles. It is often seen especially in the early morning as shown in Figure 2. Not only rain absorption but also condensed water can be a cause of water content increase. Considering these factors, frost damages may occur even in a relatively warm area where the minimum temperature is slightly below 0 deg.C (Hokoi and Iba 2000).

The purpose of the present paper is to clarify the influence of nocturnal radiation on the roof surface temperature and the frequency of surface condensation by a numerical analysis, and to find out how the water content and the temperature in the roof tile change in freezing-thawing processes.

Figure 1 Roof tile dameged by freezing (Kyoto)

Figure 2 Surface Condensation on roof tile

Table 1. Basic Equations

Moisture balance	$\frac{\partial \rho_l \psi_l}{\partial t} = \nabla \cdot \left(\lambda'_{Tg} \nabla T\right) + \nabla \cdot \left\{\left(\lambda'_{\mu g} + \lambda'_{\mu l}\right) \nabla \mu\right\} - \frac{\partial \rho_i \psi_i}{\partial t}$	(1)
Energy balance	$c\rho\psi \frac{\partial T}{\partial t} = \nabla \cdot \left(\lambda \nabla T\right) + H_{gl}\left\{\nabla \cdot \left(\lambda'_{Tg} \nabla T\right) + \nabla \cdot \left(\lambda'_{\mu g} \nabla \mu\right)\right\} + H_{li} \frac{\partial \rho_i \psi_i}{\partial t}$	(2)
Freezing condition	$\mu = H_{li} \log_e \left(T / T_o \right)$	(3)

Where, T = absolute temperature [K]; T_0 = freezing temperature of free water (=273.16) [K]; c = specific heat [J/kgK]; t = time [s]; λ = thermal conductivity [W/mK]; ρ = density [kg/m^3]; Ψ = moisture content [m^3/m^3]; μ = water chemical potential (referenced to free water) [J/kg]; λ'_T = moisture conductivity by temperature difference [kg/msK]; λ'_μ = moisture conductivity by water chemical potential difference [kg/ms(J/kg)]
Subscript w = water; s = solid; g = gas; l = liquid; i = ice

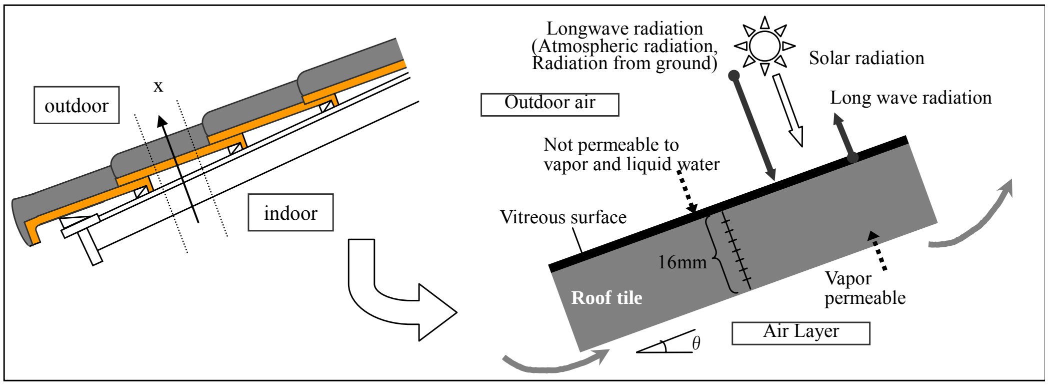

Figure 3. Calculation Model

RESEARCH METHODS

Basic equations for analysis

The equations for simultaneous heat and moisture transfer, which take into account freezing and thawing, are used for the analysis (Gao 1992, Matsumoto et al. 1993). These equations are shown in Table 1.

Numerical analysis using the basic equations was carried out with respect to the materials such as brick (Iba and Hokoi 2003) and glass fiber board (Hokoi et al. 2000). The validity of the equations was confirmed by comparison with the experiments in these studies.

Calculation model

A roof tile with a thickness of 16mm was analyzed in one-dimensional calculation (Figure 3). The outer surface is directly exposed to the outdoor air, and an air layer on the back side is connected to the outdoor. The outer surface is impermeable to vapor and liquid water. The inclination angle of the roof (θ) is 20 degrees (=π/9 [rad.]), and the roof is oriented to the north. In this calculation, the roof tile is divided into 8 segments with 2mm thickness. In order to simplify the calculation, the back side of the tile is assumed to be adjacent to an air layer whose temperature and humidity are same as the outdoor air.

Material Properties

Before the calculation, the vapor permeability and water absorptivity (assumed as the maximum water content) of the roof tile were measured. The measured results are used for the calculation; vaper permeability is 4.57 [ng/msPa], and the maximum water content is 15.75[vol.%]. The other physical properties such as the heat and moisture transfer coefficients are referenced to the database of 'Brick' in the IEA ANNEX 24 report (Kumaran 1995).

Boundary and Calculation conditions

As the outer boundary conditions, the meteorological data in Kyoto is used (Figure 4). The data is from Expanded AMeDAS Weather Data (AIJ 2000). Though Figure 4 shows the amount of precipitation, it is not considered in this calculation.

The heat and moisture transfer coefficients are listed in Table 2. Heat transfer at the outer surface is caused by the convective heat transfer, solar and longwave radiations, and condensation and evaporation of water. The long wave radiation is composed of the atmospheric radiation, the radiation from the ground and the radiation from the outer (front) surface of the roof tile.

The calculation is performed for five months from November to March. The initial temperature and relative humidity of the tile are set at 14.4 [deg.C] and 70%RH, respectively.

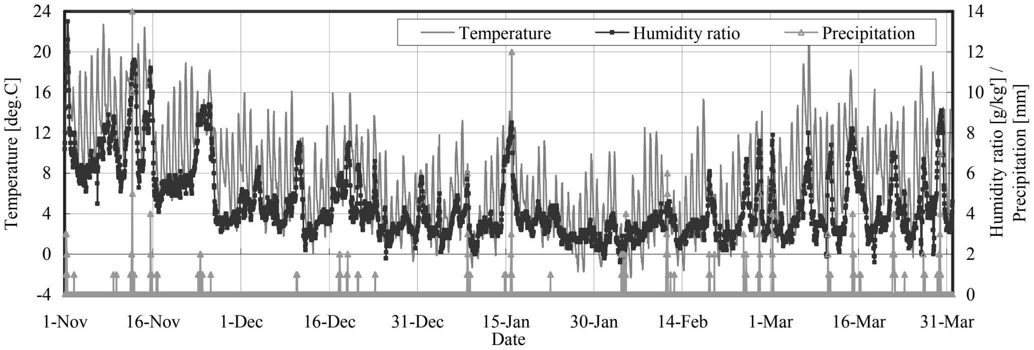

Figure 4. Meteorological data in Kyoto (Expanded AMeDAS Weather Data)

Table 2. Boundary conditions (Case 1: standard case)

Outside Air (on the front side)	Convective heat transfer coefficient	α_{co}	18.6	[W/m^{2}K]
	Solar Absorptivity	α_s	0.8	[-]
	Long wave Emittance	ε_L	0.9	[-]
	Moisture transfer coefficient	α'_o	0.0185	[kg/m^{2}s(kg/kg')]
Air layer (on the back side)	Combined Heat transfer coefficient	α_i	9.3	[W/m^{2}K]
	Moisture transfer coefficient	α'_i	0.00444	[kg/m^{2}s(kg/kg')]

Table 3. Calculated cases (the other parameters are same as standard case)

Case No.	Parameter	Value	Remarks
2-1	Outside α_{co}, α'_o	α_{co} : 27.9, α'_o : 0.02775	Wind speed = 5.0 [m/s]
2-2	Outside α_{co}, α'_o	α_{co}: 9.3, α'_o : 0.00925	Wind speed = 1.0 [m/s]
3-1	θ	θ=45 degrees	Influence of nocturnal radiation
3-2	θ	θ=11.3 degrees	Influence of nocturnal radiation
4	Vapor permeable at outer surface		
5	Vapor resistance 0.00574[m^{2}sPa/ng] is attached to both surfaces		Influence of surface finishing

Parameters

Table 3 shows the calculated cases to examine the influence of several parameters. In case 2 and case 3 series, the outer convective heat transfer coefficient and the slope of the roof are changed in order to investigate the influence of nocturnal radiation. In cases 4 and 5, the effect of the surface finishing on the water content distribution inside the tile is examined.

RESULTS AND DISCUSSION

Influence of nocturnal radiation

Figure 5 shows the convective heat fluxes at the outer surface in the first week of February in cases 1, 2-1 and 2-2. The heat flow ranges from 35 to 60 [W/m^2] during nighttime depending on the value of the convective heat transfer coefficient (α_{co}).

The net heat fluxes by long wave radiation at the outer surface in cases 1, 3-1 and 3-2 are shown in Figure 6. These nocturnal radiation always takes negative values, what is, the heat goes out from the surface. The net heat flux in case 3-2 (θ=11.3°) is almost the same as that in the standard case (θ=20°) in the nighttime, while that in case 3-1 (θ=45°) is about 10 [W/m^2] less. Since there is no solar radiation in the nighttime, the outer surface temperature is determined by the convective and longwave heat transfer.

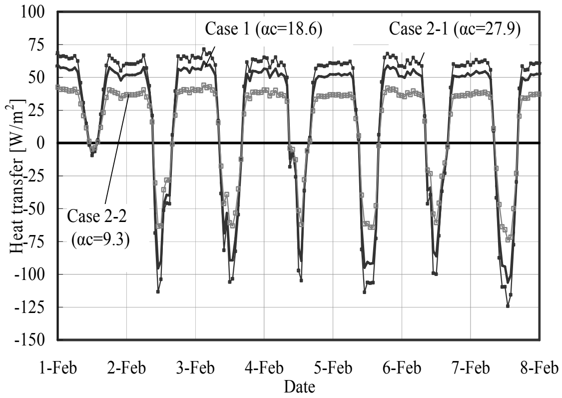

Figure 5. Convective heat flux at outer surface

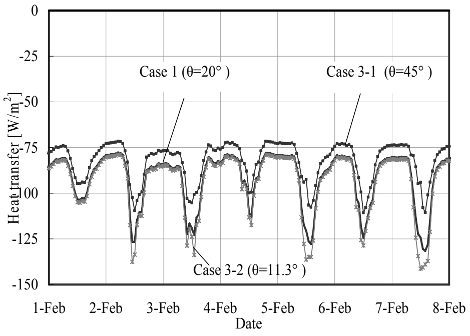

Figure 6. Long wave heat flux at outer surface

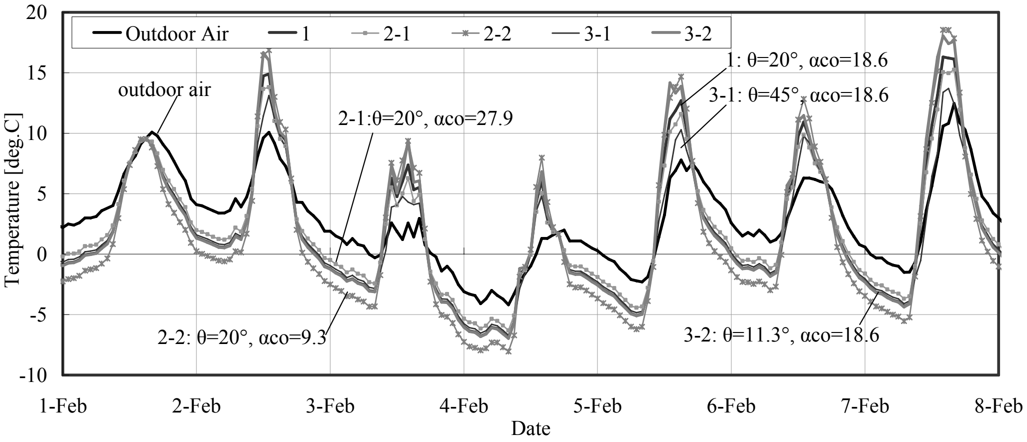

Figure 7. Outdoor air and outer surface temperatures (in the first half of February)

Table 4. Frequency of surface condensation and amount of condensed water

Case No.	1	2-1	2-2	3-1	3-2
Outer surface condensation [times]	52	35	87	40	52
Time percentage of surface condensation [%]	11.9	7.04	23.53	9.99	12.12
Maximum amount of condensed water [kg/m^2]*	0.72	0.73	0.81	0.65	0.75

* integrated value during 1 hour

The outer surface temperature in the first week of February is shown in Figure 7. The period is in the coldest season in Kyoto. In all cases, the outer surface temperature becomes lower than the outdoor temperature in the nighttime due to nocturnal radiation. Particularly, the temperature in case 2-2 (α_{co} =9.3[W/m2K]) is about 5.0 [deg. C] lower than the outdoor temperature. Therefore, the surface temperature of the roof tile drops beneath 0 deg. C almost every day in the coldest season if the outdoor wind hardly blows. The difference according to the inclined angle is not significant in the range from 11.3 degs. to 45 degs.

Frequency and amount of condensation

The amount of condensed water W [kg/m^2] is caluculated as follows;

When condensed water does not exist,

$$X_o = X_S \quad (4)$$

where, X_o, X_i: humidity ratio of outdoor air and outer surface [kg/kg'].

If the dewpoint of outdoor air T_{do} is lower than the surface temperature Ts, condensation occurs and X_S is assumed as saturated absolute humidity at T_S. The amount of condensed water is;

$$\Delta W = \alpha'_o \left(X_o - X_S\right)\cdot \Delta t \quad (5)$$

$$W = W + \Delta W \quad (6)$$

where, Δ t: time increment [s]

When W>0 and X_S >X_o, the condensed water evaporates and ΔW becomes negative.

The frequency of condensation and amount of condensed water are shown in Table 4. 'Surface condensation [times]' is defined as an event that starts from an occurrence of condensation and ends as a disappearance of the condensed water. 'Time percentage of surface condensation' is the percentage of the time when the surface is covered with condensed water over the whole calculation period. In the standard case, the surface condensation occurs 52 times from November to March. It means that the surface condensation occurs every 3 days. In case 2-2, where the surface temperature is the lowest, the surface condensation occurs longer than a half of the whole period. Particulaly from December to February, the surface temperature generally drops beneath 0 deg.C when the condensation occurs.

The maximum amount of condensed water in the calculation period is 0.81 [kg/m^2]. This is equivalent to 0.81[mm] precipitation, thus it is not negligible.

Water content distribution in materials

The liquid water and ice content distribution at 8:00 on 5th of February, the coldest day, is shown in Figure 8. The liquid water content is kept low because the outdoor air is dry in winter. A freezing occurs in a region close to the outer surface in case 1. In case 2-2, where the material temperature is the lowest, freezing occurs at the both surfaces. In case 4, where the both surfaces are vapor permeable, the region near the outer surface is nearly saturated with ice, because the water vapor is absorbed and water content of the material increases. In case 5, where vapor resistances are attached to the both surfaces, a freezing does not occur in the present calculation conditions.

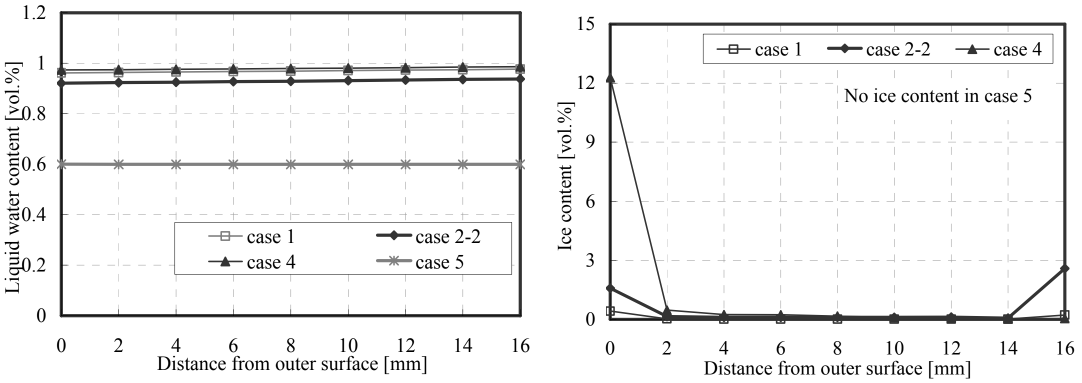

Figure 8. Liquid and ice content distribution at 8:00 on 5th of February

Although the accelerated aging test for roof tiles is carried out as a part of this study (Figure 9), the validation of the present analytical model is a future work.

CONCLUSION

Using a meteorological data in Kyoto, the surface condensation on the roof was investigated. It was shown that not only rain absorption but also condensation water could have an influence on the freezing damage of roof tiles.

Depending on the wind speed (related to the values of heat and moisture transfer coefficients), nocturnal radiation and surface finishing, the frequency of condensation changes significantly.

ACKNOWLEDGMENT

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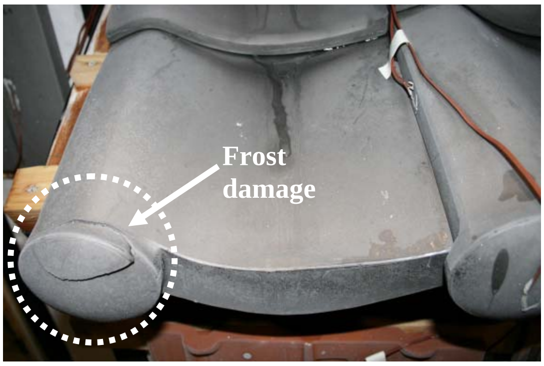

Figure 9. Example picture of accelerated aging test