Frost Damage of Roof Tiles in Relatively Warm Areas in Japan

Influence of Surface Finish on Water Penetration

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INTRODUCTION

- Moisture in building materials significantly influences the durability of building envelopes.
- Accumulated moisture occasionally freezes in the building materials, severely damaging them.

- Frost damage has been observed
  - ✓ not only in cold regions but **also in relatively warm areas** in Japan.
  - ✓ mainly **in roof tiles** due to night-sky radiation.

INTRODUCTION (continued)

From Previous Field surveys

Minor spallings and **flakings** are the typical examples of frost damage in roof tiles in warm areas.

Minor circular spallings

From Standard freezing–thawing test

- Test specimens are fully saturated with water before the freezing.
- The method is ***not suitable*** for evaluating the actual damage to the roof tiles.

INTRODUCTION (continued)

The purpose of our research is…

to clarify the mechanisms and causes of frost damage in roof tiles in relatively warm area.

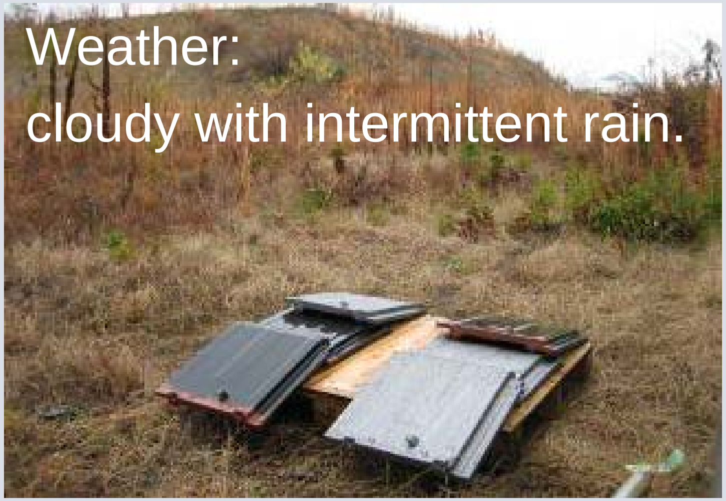
In this paper…

- Review of the previous experiments
  - Water penetration experiment to examine moisture distribution in tiles
  - A new freezing–thawing test to propose more suitable methods
- Numerical analysis of the freezing–thawing process
  - The analysis does ***not*** correspond to the above experiment's conditions.
  - Focus on the influence of surface finish and moisture permeability

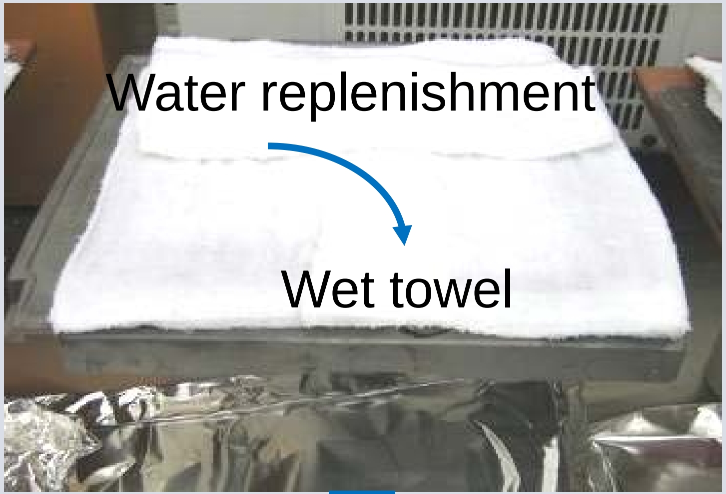
REVIEW OF PREVIOUS EXPERIMENTS

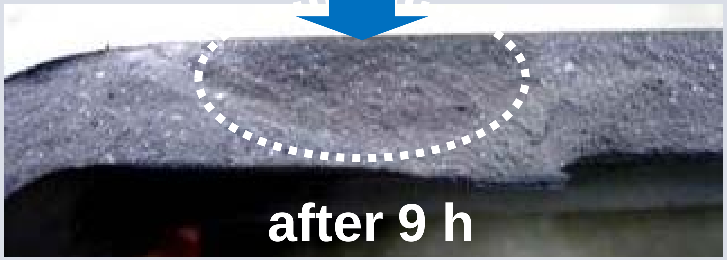
Water Penetration Experiments

In Outdoor Environment



In Laboratory





- The area that absorbed water is clearly distinguished.
- The water content distribution is not uniform even in a single tile.

Water Penetration Experiments

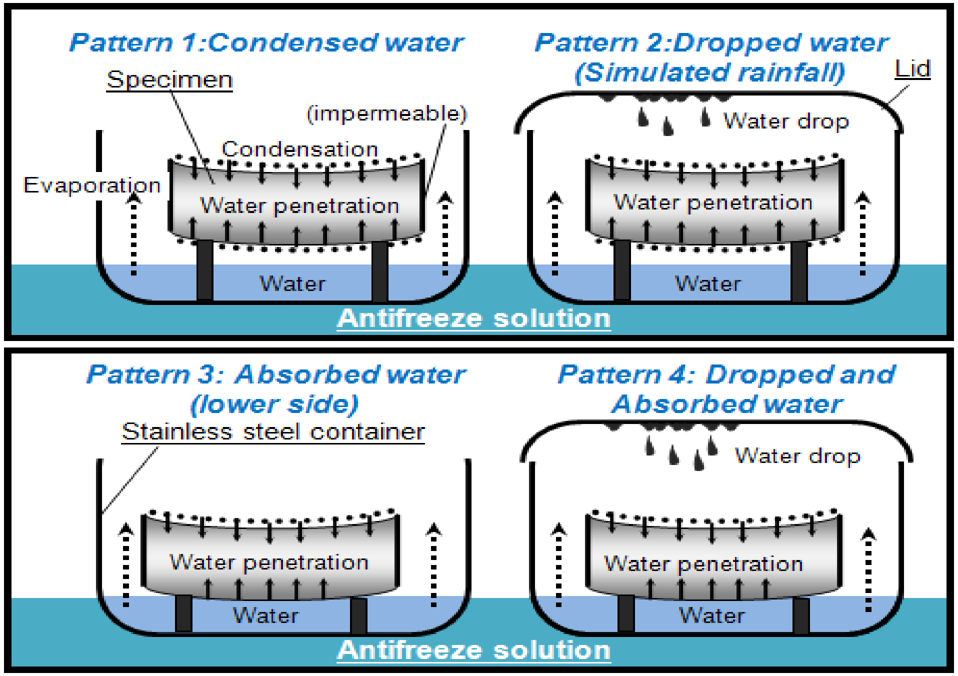
Summary of water penetration experiments

- Japanese roof tiles generally have a surface finish to prevent rain water penetration.
- Although the water resistance of a surface finish is much higher than that of the tile body, a small amount of water could penetrate through the finish.
- The water distribution does ***not*** necessarily correspond to small visible cracks or scratches on the surface finish.
- The water may penetrate through invisible pinholes on the surface.
- The water content increases in particular small areas and non-uniform moisture distribution is formed.

New Freezing-Thawing Test: Four types of water supply

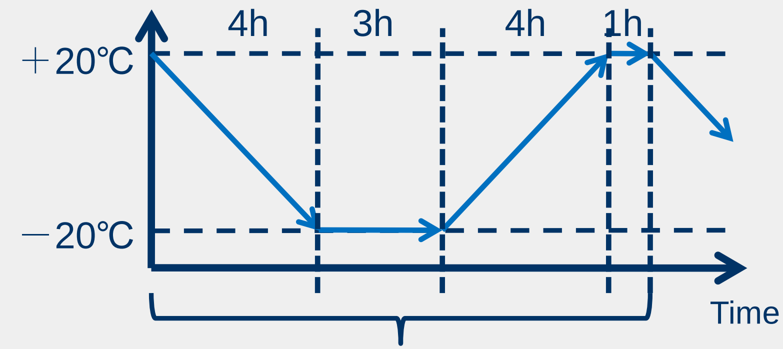
- Simulate actual water supply:
  - Partially immersed in water
  - Small droplets
  - Surface condensation

Try to cause damages similar to those found in actual environment



The amount of water supplied increases successively from Pattern 1 to 4.

Test apparatus based on ***RILEM TC 176*** ,
'Test Methods of Frost Resistance of Concrete'

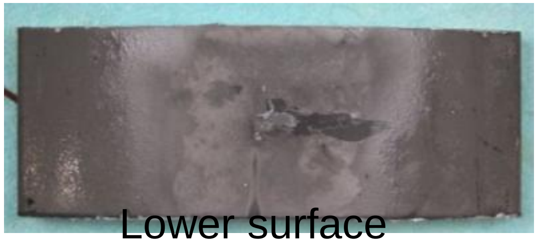
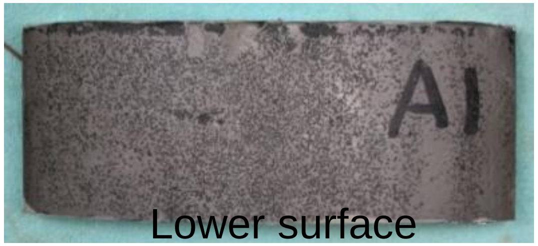


1 cycle = 12 h
Temperature change in antifreeze solution

New Freezing-Thawing Test: Results (Pattern 3&4)

Appearance of the specimens after 56 cycles

Spalling near the edge

Pattern 3: Absorbed water (lower side)	Pattern 4: Dropped and Absorbed water
 Upper surface	 Upper surface
 Lower surface	 Lower surface

Spalling near the edge

Many fine flakings

Summary of freezing-thawing test

- Similar damage to that found under actual conditions was observed.
- If droplets continuously fall on the specimens, even small droplets can penetrate the tile and can cause damage.

Supposition from Experimental Results

1. Invisible pinholes on the surface finish cause high water content in particular small areas (maybe near the surface).

2. When the temperature of the tile decreases below the freezing point, freezing occurs only in high water content area.

3. Small spallings or fine flakings are caused only in the area where the ice content is sufficiently high.

To examine supposition 1 & 2, following analysis is conducted.

NUMERICAL ANALYSIS OF FREEZING–THAWING PROCESS

Basic Equations

The equations for simultaneous heat and moisture transfer, which consider freezing and thawing (Matsumoto et al. 1993)

Moisture balance:
$$\frac{\partial \rho_l \psi_l}{\partial t} = \nabla \cdot \left(\lambda'_{Tg} \nabla T\right) + \nabla \cdot \left\{ \left(\lambda'_{\mu g} + \lambda'_{\mu l}\right) \nabla \mu \right\} - \frac{\partial \rho_i \psi_i}{\partial t}$$

Energy balance:
$$c\rho\psi \frac{\partial T}{\partial t} = \nabla \cdot \left(\lambda \nabla T\right) + H_{gl} \left\{ \nabla \cdot \left(\lambda'_{Tg} \nabla T\right) + \nabla \cdot \left(\lambda'_{\mu g} \nabla \mu\right) \right\} + H_{li} \frac{\partial \rho_i \psi_i}{\partial t}$$

Freezing condition:
$$\mu = H_{li} \log_e \left(T / T_o \right)$$

The amount of ice formation is determined according to the heat and moisture transfer balance.

Unsaturated water permeability: $\lambda'_{\mu l} = A \times \psi_l + (\lambda'_{\mu l,sat} - A \times \psi_{l,sat}) \times (\psi_l / \psi_{l,sat})^N$

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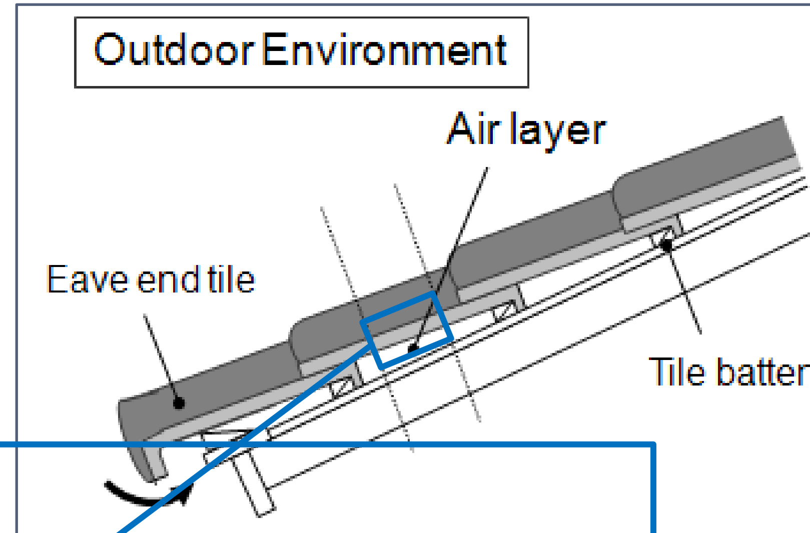
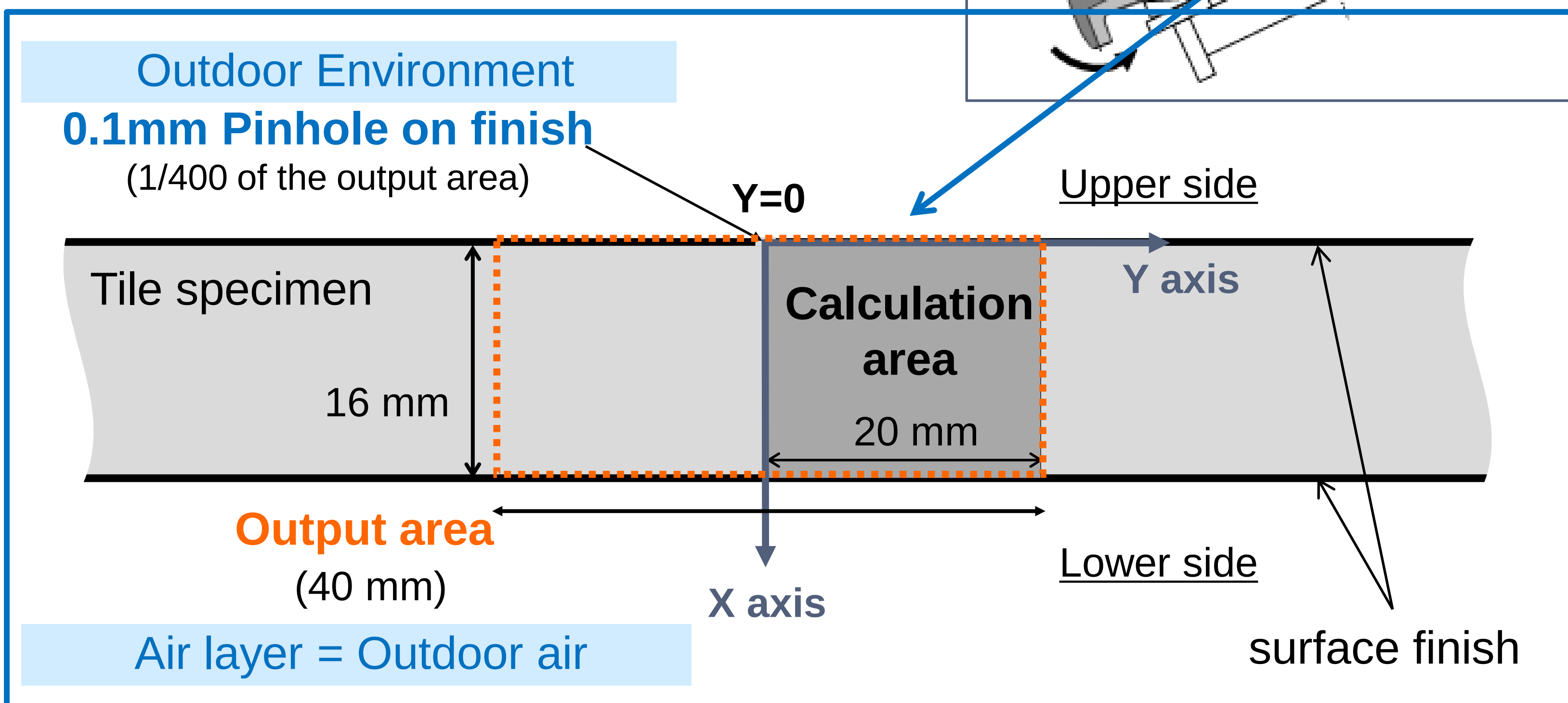
where
T = absolute temperature, K, T_0 = freezing temperature of free water (=273.16), K, t = time, s,
λ = thermal conductivity, W/(m × K), ρ = density, kg/m^3, c = specific heat, J/(kg × K),
λ'_μ= moisture conductivity by water chemical potential difference, kg/(m × s × J/kg)
λ'_T = moisture conductivity by temperature difference, kg/(m × s × K)
ψ = moisture content, m^3/m^3, μ = water chemical potential (free water standard), J/kg
$\lambda'_{\mu l}$ = Unsaturated water permeability, kg/m s (J/kg), A = Linear factor ,N = Exponential factor
Subscript w = water; s = solid; g = gas; l = liquid; i = ice, sat = saturated

Calculation Model

- Typical roof installed with roof tiles
- The undersurface of the roof tile is exposed to an air layer.

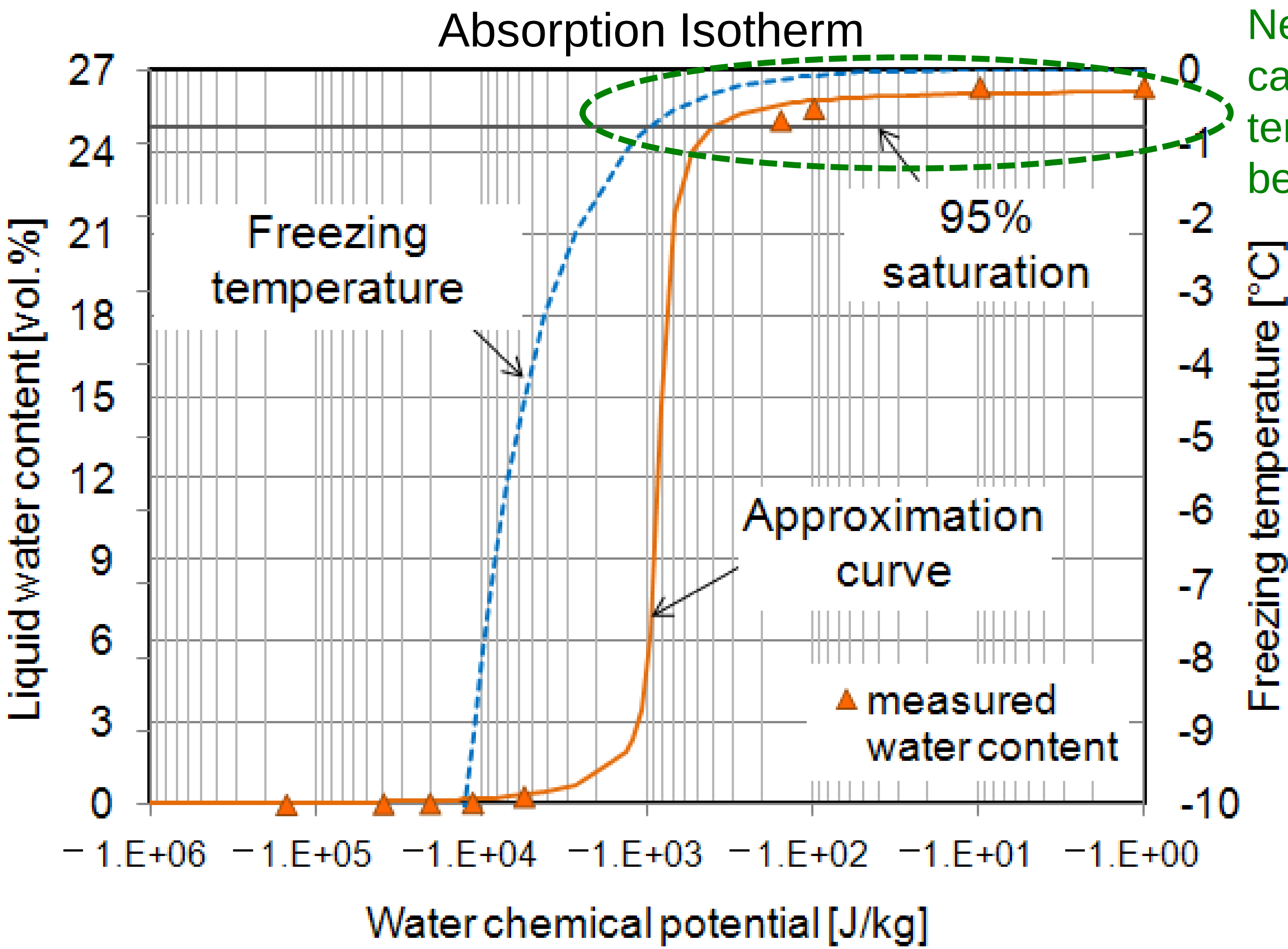


A part of a tile



NUMERICAL ANALYSIS OF FREEZING-THAWING PROCESS

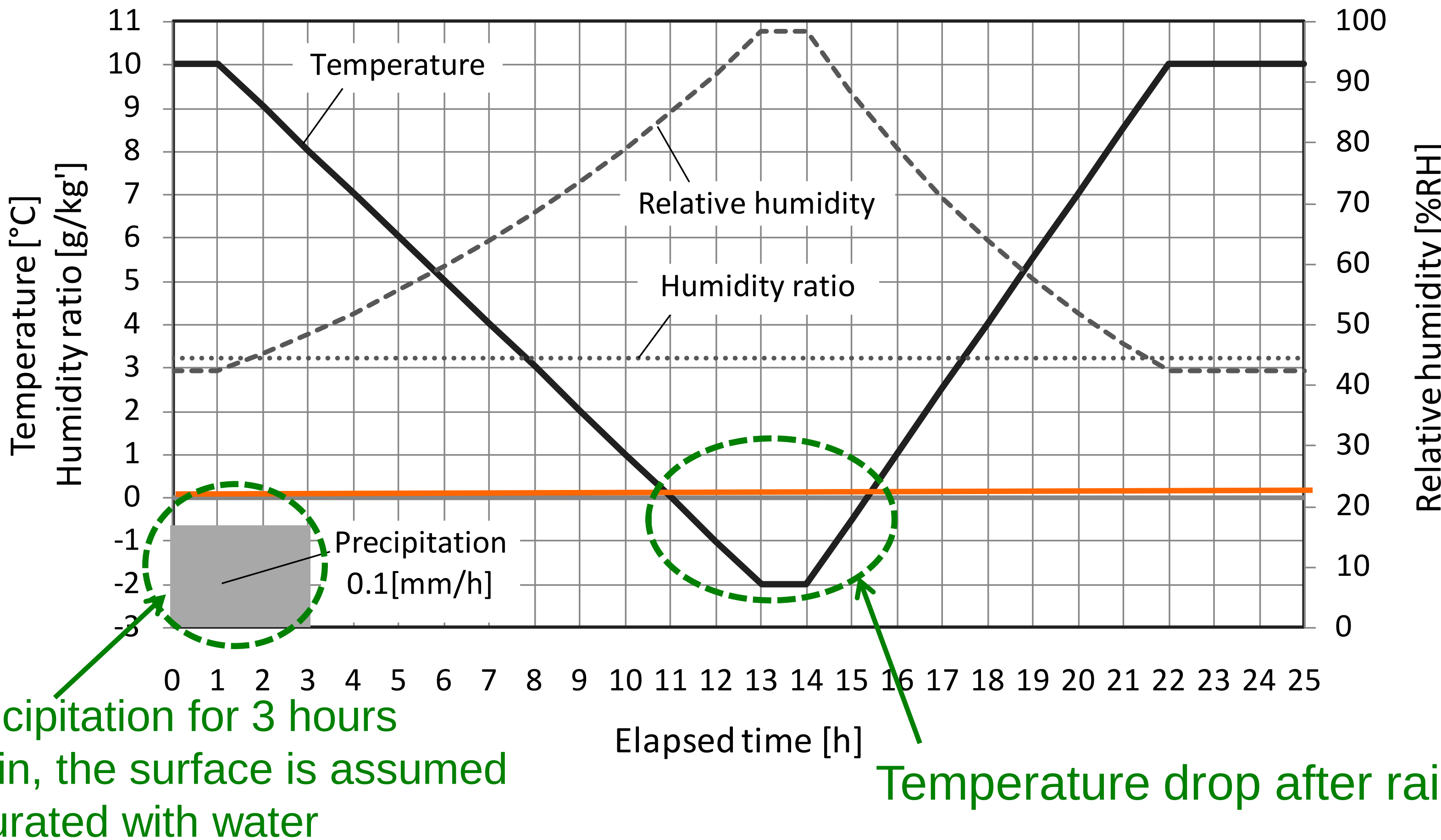
Relation between Water content and Freezing temperature



Nearly saturated, it can freeze at a temperature slightly below 0°C.

Environmental Conditions

- Colder conditions of a warm area in Japan are assumed.
- Solar radiation and night-sky radiation is not considered.



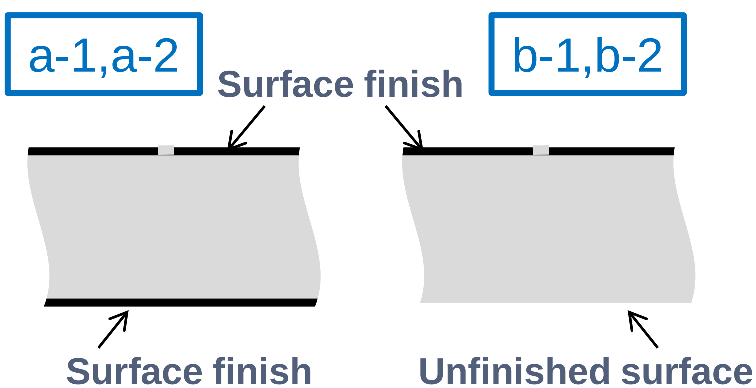
Calculation Patterns

To examine the influence of …

- ◆Surface finish
- ◆Moisture permeability

} on moisture the distribution

Pattern No.	Surface finish	Parameter A	Note
a-1	Both surfaces	5.0×10^{-10}	
a-2	Both surfaces	2.5×10^{-9}	A: ×5 of a-1
b-1	Only upper surface	5.0×10^{-10}	
b-2	Only upper surface	2.5×10^{-9}	A: ×5 of b-1

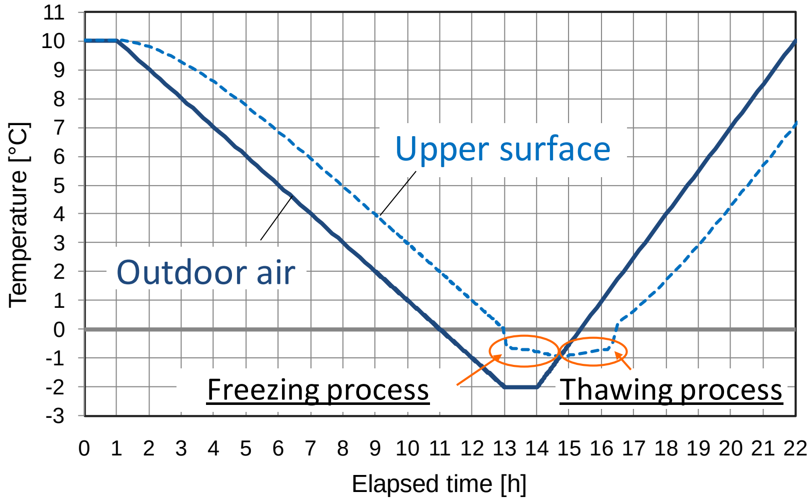


Unsaturated water permeability:

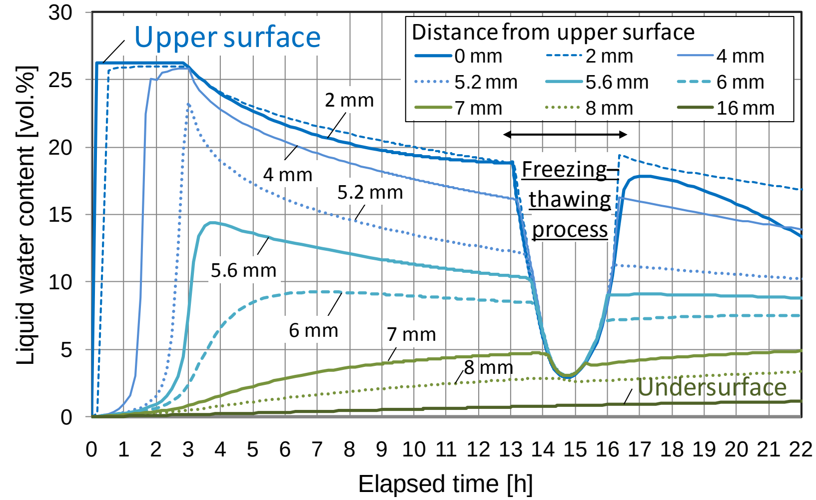
$$\lambda'_{\mu l} = \mathbf{A} \times \psi_l + (\lambda'_{\mu l,sat} - \mathbf{A} \times \psi_{l,sat}) \times (\psi_l/\psi_{l,sat})^N$$

Moisture diffusion in the tile body becomes faster as a parameter A increases.

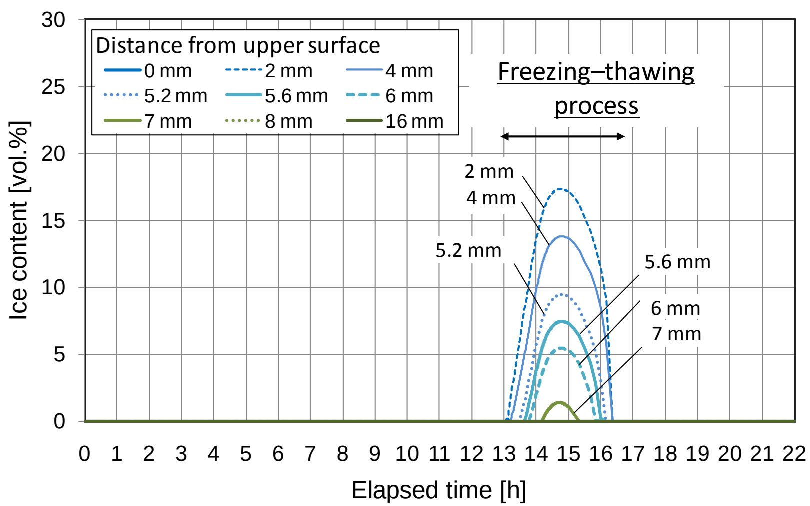
Results: Time profile for Pattern a-1



Temperature



Liquid water content

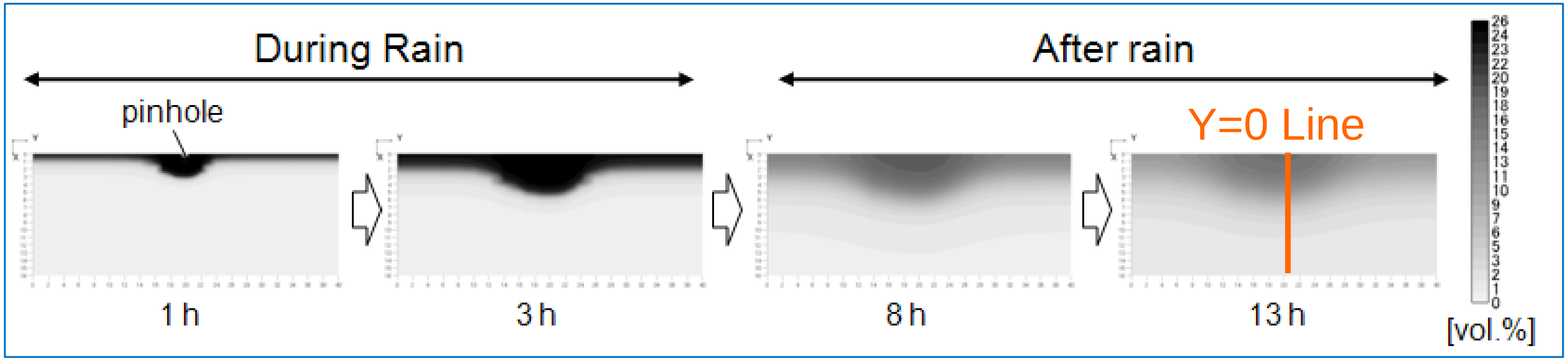


Ice content

- Water content rapidly increases in the area near the surface during rain.
- When the temperature drops below the freezing point, water begins to freeze only in high water content area and ice content increases.

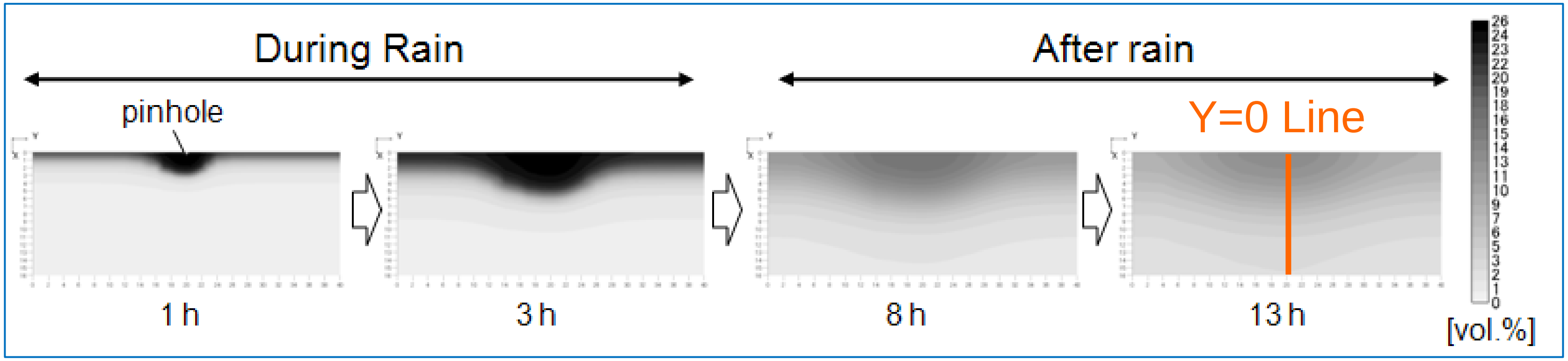
Results: Change in moisture distribution (before freezing)

a-1



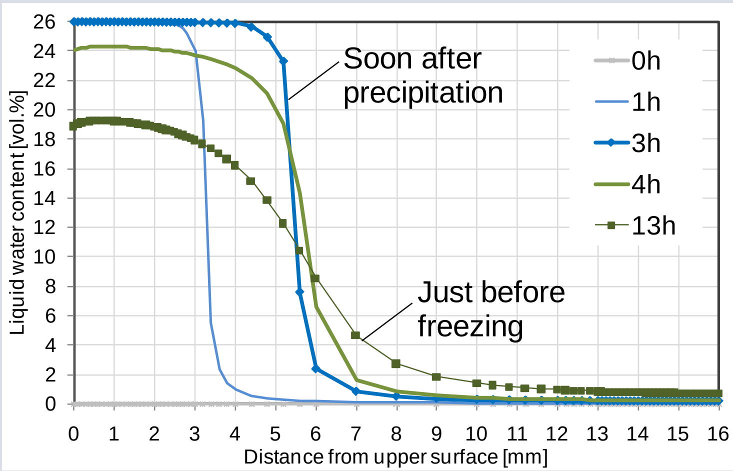
Moisture diffusion in the tile body → **slower** / **faster**

a-2

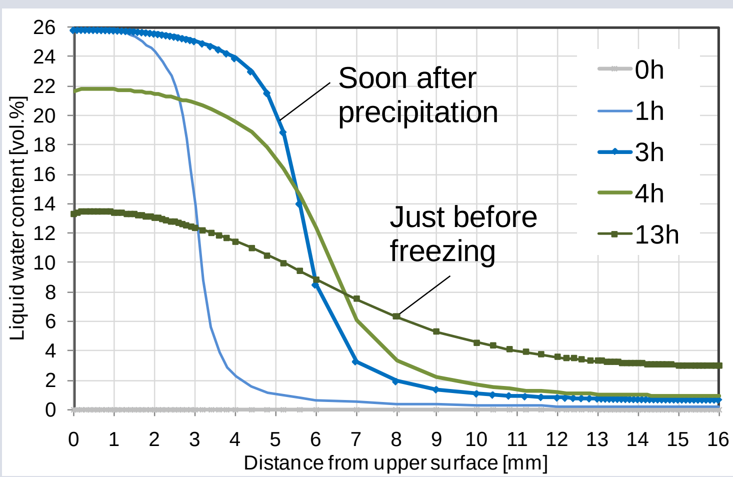


NUMERICAL ANALYSIS OF FREEZING-THAWING PROCESS

Liquid water content distribution before freezing (Y=0)

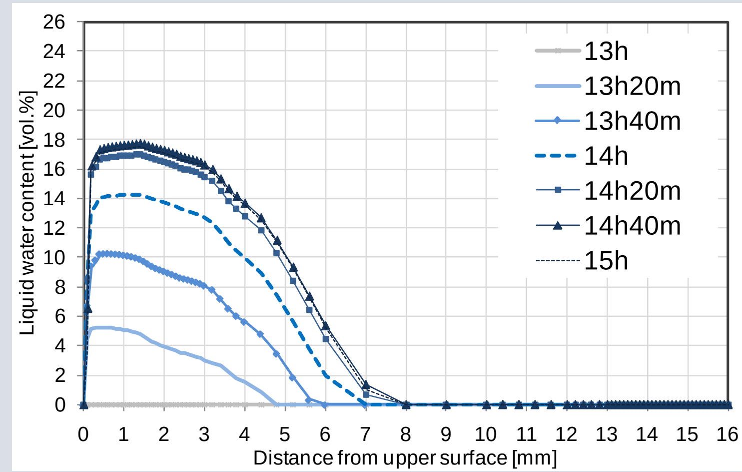


Pattern a-1

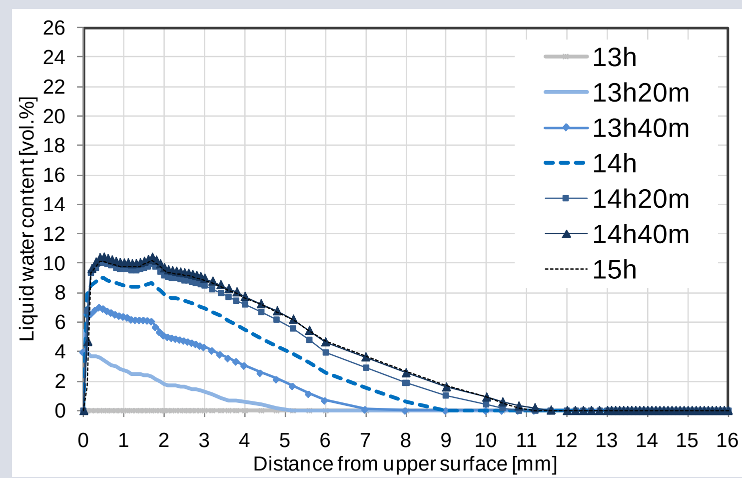


Pattern a-2

Ice content distribution during the freezing process (Y=0)



Pattern a-1



Pattern a-2

Summary of Numerical Analysis

- Even a small pinhole can allow significant amounts of water to penetrate into the tile body.
- If such pinholes are randomly distributed on the surface finish, the moisture content will show non-uniform distribution.
- If freezing occurs in the nearly saturated zone, the expansion pressure could damage the tile body. Not only expansion pressure of ice but also unfrozen water pressure is supposed to cause the destructive effect.
- Random moisture content distribution could be one reason for small spallings or flaking in an actual situation.

CONCLUSIONS

- In this study, the characteristics and causes of frost damage in roof tiles were investigated through water penetration experiments, a freezing–thawing test, and a numerical analysis.
- When the water content inside a tile increases in particularly small area and the temperature decreases below the freezing point, freezing can occur only in the areas having high water content, causing minor spalling.

  When the water permeability is small, high local water content tended to occur, that increases the risk of frost damage.

- This information about hygrothermal properties of the surface finish and the tile body will help in material development and advancement in the future.

THANK YOU

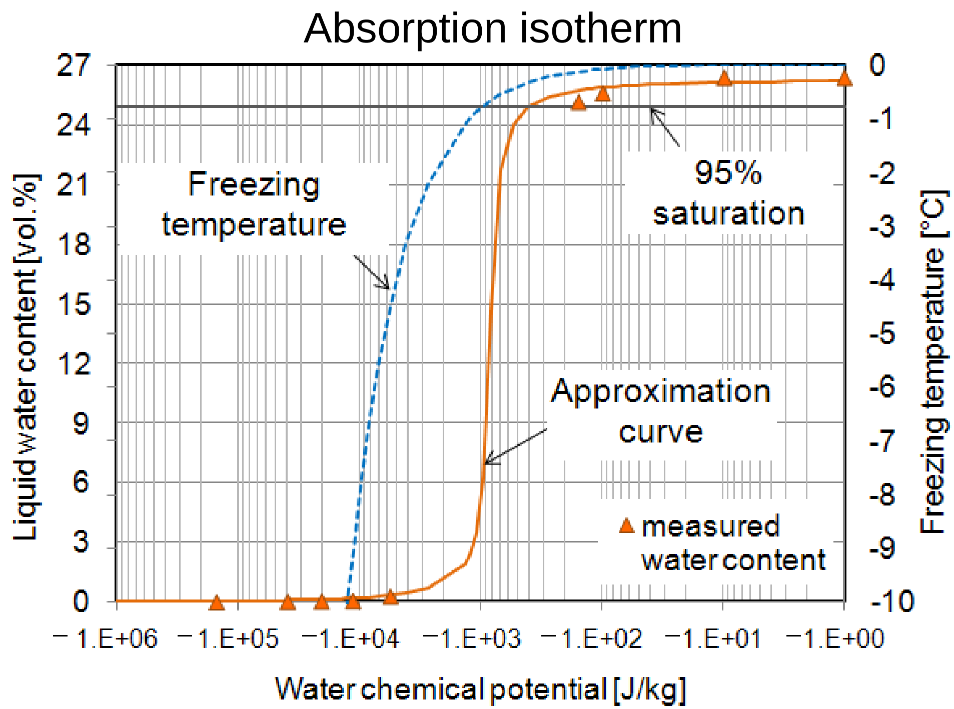
FOR YOUR ATTENTION !

CONTENTS

Material Properties

Tile body

Thermal conductivity (dry condition)	0.937	W/m K
Vapor permeability	4.139×10^{-12}	kg/m s Pa
Water permeability (saturated condition)	3.66	m/s
Specific heat	920	J/kg K
Density	2100	kg/m^3
Porosity (= Maximum moisture content)	26.2	%

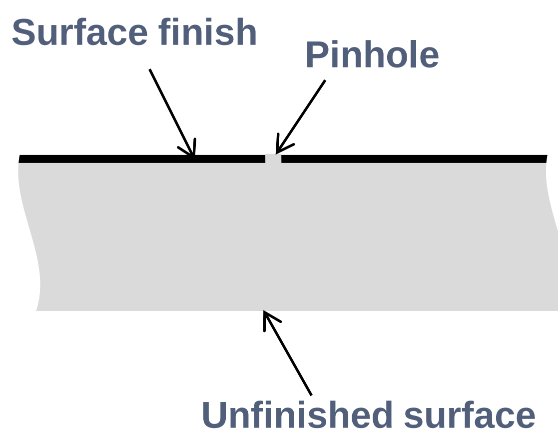


Surface finish

Thermal resistance	Not considered	
Vapor resistance	5.35×10^9	m^2 s Pa/kg
Water resistance	9.92×10^9	m^2 s Pa/kg

Pinhole or Unfinished surface

Vapor resistance (pinhole or unfinished surface)	2.42×10^6	m^2 s Pa/kg
Water resistance (pinhole)	37015.0	m^2 s Pa/kg
Water resistance (unfinished surface)	2677.8	m^2 s Pa/kg



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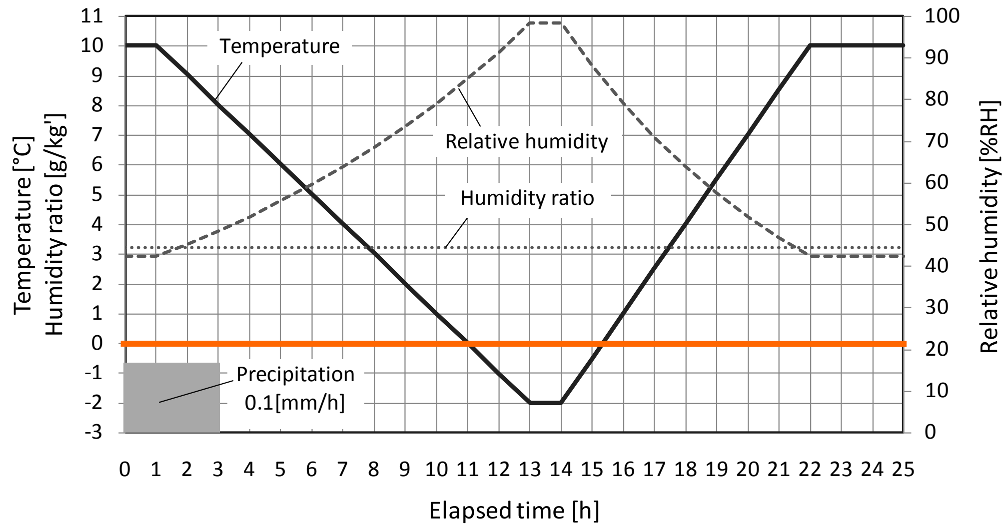
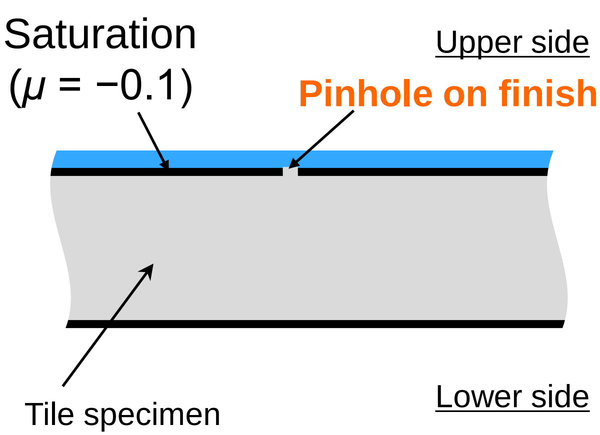


Boundary conditions

During rain



Heat transfer coefficients

Upper side	Convective heat transfer coefficient	18.60	W/m^2 K
	Radiative heat transfer coefficient	4.65*	W/m^2 K
Lower side	Convective heat transfer coefficient	2.30	W/m^2 K
	Radiative heat transfer coefficient	4.65*	W/m^2 K

*Design value of indoor heat transfer, assuming emissivity of material to be 0.9

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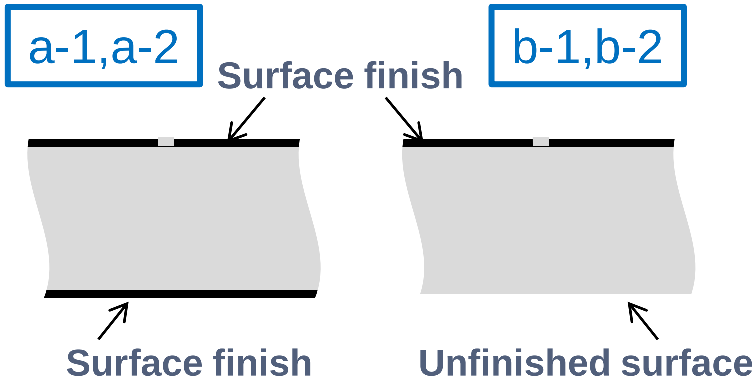

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