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Coupled hygrothermal and mechanical simulations of highly anisotropic building material during freezing and thawing

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1 Nomenclature

2	Scalar	
3	a	Coefficient related to the volumetric thermal expansion of pore volume
4		occupied by each phase $[K^{-1}]$
5	С	Specific heat [J/(kg·K)]
6	С	Volumetric heat capacity of wet material [J/(m ³ ·K)]
7	Ε	Young's modulus [Pa]
8	E_{45}	Young's modulus in the 45° direction from the thickness direction [Pa].
9	G	Shear modulus [Pa]
10	h	Heat transfer coefficient between air and a material surface $[W/(m^2 \cdot K)]$
11	Н	Latent heat of solidification $(334 \times 10^3 \text{ J/kg})$
12	Κ	Bulk modulus [Pa]
13	т	Mass of water contained in a unit volume of bulk material [kg/m ³]
14	N	Biot tangent modulus [Pa]
15	N_{ii} , N_{il} , N_{ii} , and N_{l}	Generalized Biot coupling modulus [Pa]
16	n	Pressure [Pa]
17	S S	Saturation
18	\tilde{T}	Temperature [K]
19	T	Melting point of bulk water [K]
20		Air temperature [K]
21	Т ош Т.	Reference temperature [K]
21		Coefficient related to the volumetric thermal expansion of nore volume $[K^{-1}]$
22	u_{ϕ}	Surface tension between air and liquid water [N/m]
23	Ygl	
24	γli	Surface tension between liquid water and ice [N/m]
25	Δs	Melting entropy (= 1.2 MPa/K)
26	φ	Increment of the porosity
27	ϕ	Porosity
28	ϕ_0	Porosity in a reference state
29	ν	Poisson's ratio
30	ρ	Density $[kg/m^3]$
31	ρ^0	Density in a reference state $[kg/m^3]$
32	1	
33	Tensor	
34	α	Tensor of the coefficient of linear thermal expansion of a skeleton $[K^{-1}]$
35	b	Biot tangent tensor
36	Ď	Elastic stiffness tensor [Pa]
37	F	Body force vector [N/m ³]
38	J	Vectors of moisture flow $[kg/(m^2 \cdot s)]$
39	n	Unit vector normal to the surface
40	0	Vectors of heat flow $[W/m^2]$
41	v t	External force vector $[N/m^2]$
42	c	Strain tensor
12	2	Tansor of thermal conductivity [W/(m,K)]
43	λ),	Tensor of moisture normachility [w/(mr.k)]
44	۲,	Tensor of molsure permeability [kg/(m·s·Pa)]
45	σ	I otal stress tensor [Pa]
46	a 1	
47	Subscripts	
48	a	Bulk material in dry state
49	g	Water vapor
50	l	
51	n	Direction normal to the thickness of a material
52	l	Liquid water
52	1	Liquid water

53 s
54 t
55 Solid phase of a material
56 Directions along the thickness of a material

55 **1. Introduction**

The freezing of porous building materials is one of the main causes of deterioration in cold environments. Many studies have investigated freeze-thaw processes, damage risks, and mechanisms behind deformation and damage to predict deterioration, propose proper countermeasures, and create frost-resistant materials (Powers, 1945; Penttala, 1998; Scherer and Valenza II, 2005).

60 While numerous studies have experimentally investigated freeze-thaw resistance of building 61 materials, e.g., (Fagerlund, 1997; Feng, et al., 2019), numerical simulations are considered an effective 62 measure for addressing such challenges. To reveal freeze-thaw processes or evaluate frost damage 63 risks, hygrothermal models for unsaturated materials have been successfully implemented to calculate the time evolution of temperature, liquid water content, and ice content distribution in building 64 materials or walls (Hokoi, et al., 2000; Matsumoto, et al., 2001; Zhou, et al., 2017; Fukui, et al., 2021a). 65 66 In addition, efforts have been made to develop a model with wider applications; Gawin et al. (2019) 67 proposed a model that describes non-equilibrium freezing and hysteresis of the freezing and thawing. 68 Moreover, based on the theory of poroelasticity (Biot, 1941) and poromechanics (Coussy, 2004), 69 models have been developed and widely used to predict water pressure evolution and deformation in 70 a material due to freezing (Coussy, 2005; Coussy & Monteiro, 2008; Wardeh and Perrin, 2008a; 71 Wardeh, et al., 2010; Sun and Shcerer, 2010; Zeng, et al., 2013; Gong, et al., 2015), considering various 72 mechanisms behind the development of water and ice pressure, such as pore-confined pressure, 73 hydraulic pressure (Powers, 1945), cryosuction, and crystallization pressure (Scherer, 1999). These 74 mechanical models do not consider heat and moisture movement in a material; therefore, they are used 75 for sealed specimens, specimens with small size or low water permeability, or materials with entrained 76 air in which water movement occurs locally due to sufficient pore space that allows the escape of pore 77 water.

78 Among these models, coupling models of thermal and/or moisture transfer and mechanical 79 behavior are considered powerful tools to reveal freeze-thaw processes and damage risks as well as 80 to propose proper countermeasures under various environmental conditions and combination of 81 material properties. Zuber and Marchand (2000) developed a hygro-mechanical model that was used 82 by Wardeh and Perrin (2008b) to examine the causes of pressure development in fired clay materials 83 during freezing. Zeng et al. (2011; 2016) used coupled hygrothermal and mechanical models to 84 investigate the freeze-thaw processes of cement-based materials and supercooling effects. Recently, 85 the applicability of such models has been enhanced to various problems, such as hysteresis in the 86 freeze-thaw process (Koniorczyk, 2015), pore structure changes due to cyclic freezing and thawing 87 (Koniorczyk, et al., 2015), and air-entrained effects (Eriksson, et al., 2018).

88 Porous building materials are often anisotropic, such as board materials, wood, stones, fired clay 89 materials, and bio-based materials, because of their cellular or laminated structure; the anisotropy of 90 transport properties and the strength of these materials have been investigated in the literature (Bech, 91 et al., 2003; Nguyen, et al., 2016). As geomaterials, such as rocks and soils, also exhibit anisotropy 92 either due to layered or microstructural characteristics, the theory of anisotropic poroelasticity has 93 been developed to describe the mechanical behaviors of such materials. This theory was first 94 developed by Biot (1955) and then examined by many researchers (Thompson and Willis, 1991; Cheng, 1997). This approach has also been applied to building materials. Rafsanjani et al. (2015) 95 96 investigated the anisotropy of the swelling process of wood using a poromechanical model. Based on 97 the theory of the anisotropic poroelasticity, the material strain is determined by Biot coefficient as well 98 as stiffness tensor when the deformation is caused by pore pressure, i.e., swelling and drying, salt 99 crystallization, freezing and thawing, and so on. Therefore, the consideration of the anisotropy of Biot 100 coefficients is essential for the prediction of the stress and strain of anisotropic materials. However, 101 the freeze-thaw processes of anisotropic porous building materials have not been sufficiently 102 examined. As the poromechanical approach can potentially be applied for building wall scale (Moonen, 103 et al., 2010; Koniorczyk & Gawin, 2012; Castellazzi, et al., 2013), the mechanical behaviors of individual materials should be properly considered to understand their interactions with other materialsand behavior on a wall scale.

106 This study investigates prevalent numerical models for the coupled hygrothermal and mechanical behaviors of anisotropic building materials during freezing and thawing. In a previous study (Fukui, 107 108 et al., 2021b), we conducted a parametric study to compare the calculation results with various 109 combinations of Biot coefficient values. In this study, the anisotropy of the Biot coefficient is further 110 investigated based on anisotropic poroelasticity, as well as consideration of anisotropy of the 111 mechanical properties. First, strain measurements are reported to demonstrate the anisotropy of deformation during freezing and thawing using an ordinal brick and simulated roof tile, that have 112 113 strong anisotropy of material properties. Then the calculation model which corresponded to the measurement was developed based on the conservation laws of the momentum, heat and moisture. 114 115 The model was based on the poromechanics theory and included the anisotropy of the mechanical and 116 poroelastic properties. The calculation results are then compared with the measurement results using 117 the roof tile; moreover, the impact of the anisotropy of each material property on the anisotropy of deformation and the determinant of the magnitude of the deformation in each direction is investigated. 118

119 **2.** Theory of the anisotropic poroelasticity

120 After being established by Biot (1941), Biot himself extended the theory of poroelasticity to include anisotropic materials (Biot, 1955). Later, the constitutive relations were reinterpreted and reformed 121 for easier application (Thompson and Willis, 1991; Cheng, 1997). In this study, the anisotropy of the 122 123 Biot coefficient is estimated according to the interpretation by Cheng (1997). This interpretation is 124 characterized by adopting micro-homogeneity and micro-isotropy assumptions to reduce the number of independent parameters necessary for calculations, which means the skeleton of porous materials 125 is homogeneous and isotropic at microscopic scale. In the theory, the heterogeneity of the material can 126 127 be attributed to the distribution of the micro homogeneous constituents and its anisotropic can be 128 attributed to directional pores or fissure arrangement.

129 The generalized linear stress-strain relationship is

130
$$\boldsymbol{\sigma} = \mathbf{D}\boldsymbol{\varepsilon} - \mathbf{b}\boldsymbol{p}$$

After micromechanical analysis (for more details, see (Cheng, 1997; Abousleiman and Cui, 2000)),
 the Biot tangent tensor for an orthotropic material can be expressed as

(1)

133
$$b_1 = 1 - \frac{D_{11} + D_{12} + D_{13}}{3K_s}$$

134
$$b_2 = 1 - \frac{D_{21} + D_{22} + D_{23}}{3K_s}$$
(2)

135
$$b_3 = 1 - \frac{D_{31} + D_{32} + D_{33}}{3K_s}$$

Building materials and geomaterials are often transverse isotropic due to the pressing, laminating, or
deposition processes. For a material with its third-axis as the axis of rotational symmetry, assuming
$$E_1 = E_2 = E$$
, $E_3 = E'$, $v_{12} = v$, and $v_{31} = v_{32} = v'$:

139
$$D_{11} = D_{22} = \frac{E(E' - Ev'^2)}{(1 + v)(E' - E'v - 2Ev'^2)}$$

140
$$D_{12} = D_{21} = \frac{E(E'v - Ev'^2)}{(1+v)(E' - E'v - 2Ev'^2)}$$

141
$$D_{13} = D_{23} = \frac{EE'v'}{E' - E'v - 2Ev'^2}$$
(3)

142
$$D_{33} = \frac{E'^2(1-v)}{E'-E'v-2Ev'^2}$$

143 **3. Strain measurement**

144 In this section, the measurements are reported using a commercial brick and simulated roof tile.

145 *3.1. Methods*

Among other building materials, fired clay materials are susceptible to frost actions. To deal with the increasing risks associated with the internal insulation of masonry walls intended to improve building energy efficiency (Zhou, et al., 2017; Feng, et al., 2019) and to preserve historical tiles and bricks (Iba, et al., 2016), it is becoming more and more important to understand the mechanisms behind deformation and damage of fired clay materials due to frost actions. Moreover, these materials are known to have anisotropic properties (Stolecki, et al., 1999) and anisotropy of the cracking due to the freezing has been observed (Perrin, et al., 2011).

153 In this study, two fired clay materials are employed: commercial brick and simulated roof tile. The 154 bricks are made by a local manufacturer in Aichi Prefecture, Japan. The simulated roof tile is the same 155 as that used in our previous study (Fukui, et al., 2021a). The clay commonly used for producing roof 156 tiles in this area is sintered at a temperature of 1000 °C to prepare the simulated roof tile. The material is not grazed or coated to avoid spoiling its homogeneity. In addition, because the material is thin, the 157 158 temperature distribution during the sintering is expected small, which also contributes to its 159 homogeneity than commercial bricks. Both materials are compressed along the thickness during the 160 shaping process; therefore, they are expected to exhibit anisotropic properties and be most deformable along the thickness (Stolecki, et al., 1999). The logarithmic differential pore volume distributions of 161 162 the two materials obtained by mercury intrusion porosimetry are shown in Fig. 1. The peak of the pore volume of the brick and simulated roof tile appears at the pore diameters of 8.5 and 0.14 µm, 163 respectively, which correspond to the freezing points of -0.015 and 0.9°C, respectively (Brun, et al., 164 1977). Additionally, the basic material and mechanical properties are listed in Table 1, showing that 165 166 the mechanical properties of both the materials are strongly anisotropic.

167

168 [insert Figure 1]169

170 **Table 1.** Mechanical and some basic material properties of the two kinds of fired clay materials.

Property		Commercial brick	Simulated roof tile
Dry density		1940 kg/m ³	1800 kg/m ³
Water content at vacu (regarded as porosity)	um saturation	$0.246 \text{ m}^3/\text{m}^3$	$0.299 \text{ m}^3/\text{m}^3$
Young's modulus	E_t	$6 \times 10^9 \mathrm{Pa}$	$3 \times 10^9 \text{ Pa}$
	E_n	$19 \times 10^9 \mathrm{Pa}$	$11 \times 10^9 \mathrm{Pa}$
Poisson's ratio	V _{tn}	0.14	0.12
	V _{nt}	0.44	0.44
	V _{nn}	0.32	0.19

171 *Subscripts *t* and *n* represent the directions along and normal to the thickness, respectively.

172 A schematic of the strain measurement specimens is presented in Fig. 2. Specimens with the 173 original material thickness (approximately 60 and 20 mm for the brick and simulated roof tile, 174 respectively) are used. The specimens are rectangles with a bottom surface of 59.8 mm \times 206.1 mm 175 and 46.4 mm × 94.7 mm, and a height of 98.1 mm and 21.0 mm for the brick and simulated roof tile, 176 respectively. The height of the specimen corresponds to the material thickness. Strain gauges and 177 thermocouples are attached to the center of the top surface and to one of the $98.1 \text{ mm} \times 206.1 \text{ mm}$ and 178 $21.0 \text{ mm} \times 94.7 \text{ mm}$ sides of the commercial brick and roof tile specimens, respectively using 179 cyanoacrylate adhesive. The strain gauges employed are KFLB-5-120-C1-11 R3M3 (Kyowa Electronic Instruments Co., Ltd). The strain is measured normal to and along the height on the top and 180 181 side surfaces, respectively, to confirm the anisotropy of deformation during freezing and thawing. Due 182 to the complexity to govern the equilibrium relationship among the three phases (air, liquid water, and ice) in the numerical simulations, the specimens were fully (vacuum-)saturated during the experiment 183 184 for easier comparison. After attaching the strain gauges and thermocouples and saturating the 185 specimen in a vacuum, the specimen is loosely covered with a thin plastic wrap to hinder surface vaporization but not to restrict the expansion of the specimen, allowing liquid water movement 186 thorough the surfaces. The thermal resistance of the wrap is confirmed negligible prior to the 187 188 experiment. The specimen is placed on a mesh to minimize thermal and mechanical interactions due 189 to direct contact with the test chamber. In addition, the specimen is covered with a mesh basket to 190 prevent direct exposure to the wind in the chamber.

- 191192 [insert Figure 2]
- 193

194 To stabilize the distribution of the temperature in the specimen, the temperature of the air inside 195 the test chamber with the specimen is first maintained at 20 °C for 30 min. The set temperature is then 196 changed in a stepwise manner and maintained at -20 °C and 20 °C for 4 h during the cooling and 197 heating periods, respectively, for the simulated roof tile. However, the minimum temperature is set to 198 -10 °C for the commercial brick specimen due to the restrictions of experimental devices. From the 199 pore volume distribution (shown in Fig. 1) and expected freezing temperature, this temperature is 200 sufficient to freeze most of the pore water in the brick specimen. Considering the higher minimum temperature and larger dimensions of the commercial brick specimen, the cooling and heating periods 201 are prolonged to 21 h and 15 h, respectively. The strain and temperature of the specimen are recorded 202 203 every second during the experiment as well as the temperature of the air in the chamber.

204 *3.2. Results*

205 The measured time evolution of the temperature and strain of the specimens during the freeze-thaw 206 experiments are shown in Figs. 3. Figure 4 displayed the measured strain changes as a function of the 207 temperature. The strain evolutions on both the top and side surfaces (normal to and along the thickness, 208 respectively) are presented in Figs. 3 and 4, but the temperature is not shown on the top surface in Fig. 209 3 as the evolutions of temperature at the two measuring points are similar. The strain is shown referring 210 to the values at 20 °C during the cooling process. In Fig. 3 (a), there is a sudden rise of the air 211 temperature in the chamber at the elapsed time of 18 h due to open of the door of the test chamber to 212 check the condition inside.

- 213 214 [insert Fi
- 214 [insert Figure 3]215 [insert Figure 4]
- 216

For the roof tile, the surface temperature once decreased to -4.8 °C and then suddenly increased due to the freezing of the supercooled water during an early stage of the cooling period. Then the measured temperature of both of the two materials stopped decreasing at sub-zero temperature due to the release of the latent heat. At the same time, the strain in the thickness direction of both of the materials start increasing.

The measurement results indicate that the strain along the thickness of both the materials significantly increases as the temperature decreases below 0 °C. In the direction normal to the thickness, the commercial brick specimen contracts and then expands as the temperature decreased.

- 225 This expansion is faster than that along the thickness, but the magnitude is significantly smaller. After
- the elapsed time of 12h, the increase of the strain in both directions stopped, which indicated most of
- the freezable water solidified at this moment. From these results, the anisotropy of the deformation of the brick due to the frost action was confirmed.
- Moreover, the simulated roof tile demonstrates the stronger anisotropy of deformation due to frost actions. It expanded more significantly in the thickness direction that the brick, but negligibly expands in the direction normal to the thickness and rather contracts.

4. Numerical simulation

In this section, the hygrothermal and mechanical simulations are described based on the theory of poromechanics. Herein, the simulated roof tile is selected as the object of calculation. The material has a significantly strong anisotropy in its mechanical properties and simple dimensions, which allows the use of a simple assumption in predicting the poroelastic properties that are not measured for general building materials.

238 4.1. Methods

239 4.1.1. Constitutive equations

240 Constitutive equations are based on the theory of poromechanics.

241
$$\boldsymbol{\sigma} = \mathbf{D} \left[\boldsymbol{\varepsilon} - \boldsymbol{\alpha} \left(T - T_r \right) \right] - \mathbf{b} p \tag{4}$$

242
$$\varphi = \mathbf{b} : \mathbf{\epsilon} + \frac{p}{N} - \alpha_{\phi} \left(T - T_r \right)$$
(5)

243 When pores contain ice and liquid water, equations (4) and (5) are expressed as

244
$$\boldsymbol{\sigma} = \mathbf{D} \Big[\boldsymbol{\varepsilon} - \boldsymbol{\alpha} \big(T - T_r \big) \Big] - \big(\mathbf{b}_i p_i + \mathbf{b}_1 p_l \big)$$
(6)

245
$$\varphi_i = \mathbf{b}_i : \mathbf{\varepsilon} + \frac{p_i}{N_{ii}} + \frac{p_l}{N_{il}} - a_i \left(T - T_r\right) \qquad \varphi_l = \mathbf{b}_l : \mathbf{\varepsilon} + \frac{p_i}{N_{li}} + \frac{p_l}{N_{ll}} - a_l \left(T - T_r\right)$$
(7)

246 Coussy (2005) and Coussy & Monteiro (2008) expressed \mathbf{b}_i and \mathbf{b}_l in equations (6) and (7) as values 247 proportional to the ice and liquid water saturation, respectively, i.e.,

$$\mathbf{b}_{i} = \mathbf{b}S_{i} \quad j = i,l \tag{8}$$

In addition, the anisotropy of α is ignored considering thermal effects on the deformation was not significant compared with the water pressure development during the freezing; therefore, the thermal expansion coefficient of the material is represented by one value, α . The final forms of the constitutive equations are

253

254
$$\boldsymbol{\sigma} = \mathbf{D} \Big[\boldsymbol{\varepsilon} - \boldsymbol{\alpha} \big(T - T_r \big) \mathbf{I} \Big] - \mathbf{b} \big(S_i p_i + S_l p_l \big)$$
(9)

255
$$\varphi_i = S_i \mathbf{b} : \mathbf{\epsilon} + \frac{p_i}{N_{il}} + \frac{p_l}{N_{il}} - a_i \left(T - T_r\right) \qquad \varphi_l = S_l \mathbf{b} : \mathbf{\epsilon} + \frac{p_i}{N_{ll}} + \frac{p_l}{N_{ll}} - a_l \left(T - T_r\right)$$
(10)

256 The poroelastic parameters a_i , **b**, N_{ii} , and N_{il} in equations (9) and (10) are to be given, but **b** can be 257 calculated using equation (2) following the Cheng's assumption when K_s is obtained. As it is difficult 258 to fully determine the set of the poroelastic parameters from the measurement, we approximate these 259 values considering the strong anisotropy of the material. Considering the laminated structure of the material, it is assumed to have parallel pores which were vertical to the thickness direction. This 260 assumption leads to a relationship $E_s = E_n / (1 - \phi)$ and $v_s = v_{nn}$. K_s is then obtained using the 261 relationship $K_s = E_s / (3 (1 - 2v_s))$. Next, the equations derived by Aichi and Tokunaga (2011) are used 262 263 to obtain N_{ii} and N_{il} . It is assumed that the Young's modulus along the thickness of the material is significantly smaller than that in the direction normal to the thickness $(E_t \le E_n)$ or that the deformation 264 in the normal direction is considerably smaller than that along the thickness. We obtain 265

266
$$\frac{1}{N_{ll}} \approx \frac{b_t - \phi_0}{E_s} S_l^2 \quad \frac{1}{N_{li}} = \frac{1}{N_{il}} \approx \frac{b_t - \phi_0}{E_s} S_l S_i \quad \frac{1}{N_{ii}} \approx \frac{b_t - \phi_0}{E_s} S_i^2$$
(11)

The derivation of a_j has not been reported for anisotropic materials in (Coussy, 2004). Since the anisotropy of the thermal expansion coefficient of solid volume is ignored in this study, the thermal expansion of pore volume is assumed to be isotropic. Therefore, a_j is derived assuming isotropy (Coussy, 2004), as

$$a_j = 3\alpha \left(b_i - \phi_0 \right) S_j \qquad j = i,l \tag{12}$$

272 Finally, the main simplifications used in the aforementioned equations can be summarized as follows:

• Plastic deformation of the material is ignored.

- As expressed in equation (8), b_i and b_i are set to values proportional to the saturation S (Coussy, 2005; Coussy and Monteiro, 2008).
- The anisotropy of the thermal expansion coefficient α is ignored.

• The poroelastic parameters a_j , N_{ji} , and N_{jl} are given in simplified forms. This is reasonable because the simulated roof tile exhibits strong anisotropy.

279 4.1.2. Equilibrium relationship between ice and liquid water

280 The Clausius–Clapeyron equation is expressed (Coussy and Monteiro, 2009) as

281
$$\frac{p_i}{\rho_i} - \frac{p_i}{\rho_i} = \frac{\Delta s}{\rho_i} (T - T_m)$$
(13)

To express the dependencies of water density on the pressure p of each phase and temperature T, linearized form (Coussy, 2005; Coussy and Monteiro, 2008) is used as

284
$$\frac{1}{\rho_{j}} = \frac{1}{\rho_{j}^{0}} \left(1 - \frac{p_{j}}{K_{j}} + 3\alpha_{j} \left(T - T_{r} \right) \right) \qquad j = i, l$$
(14)

Liquid water saturation S_l is obtained from the difference between ice pressure p_i and liquid water pressure p_l under thermodynamic equilibrium conditions. The model as suggested by van Genuchten (1980) is

288
$$S_{l} = \left[\frac{1}{1 + (\beta(p_{i} - p_{l}))^{n}}\right]^{m}$$
(15)

289 where *m*, *n*, and β are fitting parameters.

The difference in the shape of the interface between ice and liquid water causes hysteresis during freezing and thawing (Koniorczyk, et al., 2015; Gawin, et al., 2019). However, the freezing and thawing processes are not distinguished in the calculation, i.e., the hysteresis is ignored, assuming that it does not strongly affect the directionality of deformation.

294 4.1.3. Conservation equations

295 The momentum balance and conservation equations for the heat and moisture mass are expressed as

$$\nabla \cdot \mathbf{\sigma} + \mathbf{F} = 0 \tag{16}$$

297
$$\frac{\partial}{\partial t} (CT - Hm_i) = \nabla \cdot (\lambda \nabla T)$$
(17)

298
$$\frac{\partial}{\partial t} (m_i + m_i) = \nabla \cdot (\lambda' \nabla p_i)$$
(18)

299 where

318

$$C = c_d \rho_d + c_i m_i + c_l m_l \tag{19}$$

301 Note that $\mathbf{F} = 0$ because no source of the external force is considered

302 4.1.4. Calculation model, numerical solution, and calculation conditions

303 Figure 5 presents the calculation model corresponding to the strain measurements described in the 304 previous section. The calculation is performed two-dimensionally to examine the relationship of the 305 strain in the two directions. The three-dimensional effects were not considered to reduce the calculation cost given that the material is long and the heat and moisture transfer in the direction of 306 307 the long sides of the bottom surfaces is not dominant. The calculated region was on a quarter of a 40 308 $mm \times 20$ mm cross-section (shown with a black square in Fig. 5), provided that the specimen is 309 symmetric. The direction of the 20-mm sides corresponds to the direction along the material thickness. 310 A plane-strain state is assumed as the strain in the depth direction was not significant. The x- and y-311 axes of the rectangular coordinate system are set in the directions of the 40- and 20-mm sides, respectively (shown in Fig. 5). The discretization of the conservation equations with respect to space 312 313 is performed using the Galerkin finite element method based on the monolithic approach, and 2 mm × 2 mm bilinear elements are used. The calculation results do not depend on the mesh size as confirmed 314 315 by comparing the calculation results using elements with half sides. Vectors of nodal values Te, pe, 316 and \mathbf{u}_{e} are used to express temperature T, liquid water pressure p_{l} , and displacement vector \mathbf{u} , respectively as well as the shape functions N and N_u as 317

$$T = \mathbf{N}\mathbf{T}_{\mathbf{e}} \quad p_l = \mathbf{N}\mathbf{p}_{\mathbf{e}} \quad \mathbf{u} = \mathbf{N}_{\mathbf{u}}\mathbf{u}_{\mathbf{e}} \tag{20}$$

319 After discretization, the following system are obtained

320
$$\begin{bmatrix} \mathbf{C}_{\mathrm{TT}} & \mathbf{C}_{\mathrm{Tp}} & \mathbf{C}_{\mathrm{Tu}} \\ \mathbf{C}_{\mathrm{pT}} & \mathbf{C}_{\mathrm{pp}} & \mathbf{C}_{\mathrm{pu}} \\ \mathbf{C}_{\mathrm{uT}} & \mathbf{C}_{\mathrm{up}} & \mathbf{C}_{\mathrm{uu}} \end{bmatrix} \frac{\partial}{\partial t} \begin{bmatrix} \mathbf{T}_{\mathrm{e}} \\ \mathbf{p}_{\mathrm{e}} \\ \mathbf{u}_{\mathrm{e}} \end{bmatrix}$$
$$= \begin{bmatrix} \mathbf{K}_{\mathrm{TT}} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{K}_{\mathrm{uu}} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{T}_{\mathrm{e}} \\ \mathbf{p}_{\mathrm{e}} \\ \mathbf{u}_{\mathrm{e}} \end{bmatrix} + \begin{bmatrix} \mathbf{f}_{\mathrm{T}} \\ \mathbf{f}_{\mathrm{p}} \\ \partial \mathbf{f}_{\mathrm{u}} / \partial t \end{bmatrix}$$
(21)

where equation (16) is differentiated based on time. Components in equation (21) are presented in the appendix. The finite difference method is used to discretize the basic equations with respect to time with a backward difference. The time step is set to 1 s.

325 [insert Figure 5]

327 The initial and boundary conditions are listed in Table 2. The initial temperature of the material is 328 set to a uniform value, and the average of the temperatures at the two measuring points at the beginning 329 of the freeze-thaw experiment is used. The initial liquid water pressure p_l for the material is assumed 330 to be 0 Pa as the specimen is vacuum saturated at the beginning of the experiment. On the symmetry 331 axes (x = 0 or y = 0 in Fig. 5), the displacement is restricted normal to the axis directions and no heat or moisture flow is given. The surface vaporization is prevented by plastic wrap during the experiment; 332 however, the wrap is not stiff and not considered to restrict movement of liquid water through the 333 334 surfaces. Therefore, liquid water pressure p_l on the material surface is assumed to be 0 Pa. The heat 335 flow through the surfaces is calculated using the Robin boundary condition and the measured air temperature in the test chamber. A stress-free boundary condition is assumed on the surfaces of the 336 337 material. The thermal transfer coefficient h is set to 6.5 $[W/(m^2 \cdot K)]$ for the calculated temperature 338 changes to agree with the measurement results.

	Position	Coordinates (shown in Fig. 5)	Heat	Moisture	Stress and displacement
Initial conditions	Calculation area	$0 \le x \le L_x$ and $0 \le y \le L_y$	Measured temperature	$p_l = 0$	$\mathbf{u}=0$
Boundary conditions	Axes of symmetry	x = 0 or y = 0	$\mathbf{Q} \cdot \mathbf{n} = 0$	$\mathbf{J} \cdot \mathbf{n} = 0$	$\mathbf{u} \cdot \mathbf{n} = 0$
	Material surfaces	$x = L_x$ or $y = L_y$	$\mathbf{Q} \cdot \mathbf{n} = h \left(T - T_{out} \right)$	$p_l = 0$	$\boldsymbol{\sigma} \cdot \boldsymbol{n} = \boldsymbol{0}$

Table 2. Initial and boundary conditions of the calculation.

340 *4.1.5.* Hygrothermal and mechanical properties

The properties of the simulated roof tile with constant values necessary for the calculations, dry density, porosity, specific heat, thermal expansion coefficient, Young's modulus, and Poisson's ratio are listed in Table 3. The thermal expansion coefficient α is determined from the slope of the strain as a function of the temperature above 0 °C in Fig. 4 (b). The table includes the anisotropy of the Young's modulus, and Poisson's ratio. The shear modulus *G* of the material is calculated as (Hayashi, 1954)

346
$$\frac{1}{G} = \frac{4}{E_{45}} - \left(\frac{1}{E_t} + \frac{1}{E_n} - \frac{V_{tn}}{E_t}\right)$$
(22)

347 It is assumed that E_{45} is the average of E_t and E_n .

324

326

348 **Table 3.** Material properties of the simulated roof tile with constant values.

Property	Unit	Symbol	Value	Source
Dry density	kg/m ³	$ ho_d$	1800	(Fukui, et al., 2021a)
Water content at vacuum saturation (regarded as porosity)	m ³ /m ³	ϕ_0	0.299	(Fukui, et al., 2021a)
Specific heat	J/(kg·K)	\mathcal{C}_d	840	(Kumaran, 1996)
Thermal expansion coefficient	K^{-1}	α	$4.8 imes 10^{-6}$	Measurement
Young's modulus	Pa	E_t	3×10^9	Measurement
		E_n	11×10^9	Measurement
Poisson's ratio		V _{tn}	0.12	Measurement
		V _{nt}	0.44	Measurement
		V _{nn}	0.19	Measurement

For simplicity, the anisotropy of the thermal conductivity is ignored as it does not significantly affect the directionality of the deformation. Measurements are performed on specimens with various S_l values using the transient hot-wire method. From the results, the relationship between S_l and λ is obtained as (Fukui, et al., 2021a)

$$\lambda = 1.26S_l + 0.55 \tag{23}$$

Additionally, the Maxwell equation, referring to de Vries (1963), is used to apply equation (23) to the freezing and thawing processes as (Fukui, et al., 2021a)

$$\lambda = 1.26S_i + 2.15S_i + 0.55 \tag{24}$$

Here the equation in the literature was rewritten using the saturation degree instead of the volumetricwater content.

The moisture retention curve of the material is obtained using the gas absorption and pressure plate methods (Fukui, et al., 2021a). Figure 6(a) presents the measurement results and fitted curve. For the fitted curve, the form suggested by van Genuchten (1980) is used as

362
$$S_{l} = \left[1 + \left(\beta \left(p_{g} - p_{l}\right)\right)^{n}\right]^{m}$$
(25)

The parameters in the equation are determined as follows: m = 0.57, n = 2.3, and $\beta = 1.12 \times 10^{-6}$ Pa⁻¹. Using the calibrated parameters, the liquid water saturation of the saturated material during freezing and thawing is calculated considering the difference in the interfacial energy between the water vapor and liquid water and between the liquid water and ice, as (Zeng, et al., 2011)

367
$$S_{l} = \left[1 + \left(\beta'(p_{i} - p)\right)^{n}\right]^{-m}$$
(26)

368 where $\beta' = (\gamma_{gl} / \gamma_{li}) \times \beta$ [Pa⁻¹]. As stated earlier, the hysteresis during the freeze-thaw processes is 369 ignored. 370

371 [insert Figure 6]

372

During the experiment, the water in the specimen is expected to move towards the surfaces from the inside of the specimen due to the pressure development induced by freezing. Consequently, the water pressure in the specimen can be relaxed to some extent. Therefore, the moisture transfer properties of the material are considered important for predicting freezing strain. The water diffusivity *D* in the direction normal to the material thickness is obtained using the Boltzmann transformation from time evolution of the water content distribution during water uptake measured using the gammaray attenuation method (Fukui, 2021a). As the material is thin such that the moisture profile along the

thickness cannot be obtained using the same, mass measurements are performed during water uptake

to compare the average D (Kumaran 1999) along and normal to the thickness. From the results, the

average D is 2.1 times lesser along the thickness than in the direction normal to the thickness. Next,

383 D in the entire saturation range is assumed 2.1 times smaller along the thickness. The λ ' calculated

from *D* and the water retention curve are presented in Fig. 6 (b) along with the fitted curve.

385 *4.1.6. Poroelastic properties and calculation cases*

The values of the Biot coefficient calculated from equation (2) with the Young's modulus and Poisson's ratio listed in Table 3 are 0.679 and 0.219 along and normal to the thickness, respectively. Therefore, not only the Young's modulus and Poisson's ratio but also the Biot coefficient of this material are strongly anisotropic.

In equations (6) and (7), the anisotropy of the material strain is determined by the stiffness tensor and Biot coefficient. Therefore, the anisotropy of the Young's modulus, Poisson's ratio, and Biot coefficients has broad effects on the evolution of the material strain. The following three calculations are conducted to examine the effects of each property.

- For Case 1, only the anisotropy of water permeability is considered.
- For Case 2, the anisotropy of Young's modulus and Poisson's ratio is considered as well as that
 of the water permeability.
- For Case 3, the anisotropy of the Biot coefficient is considered as well as that of the water permeability, Young's modulus, and Poisson's ratio.

These three cases are summarized in Table 4. When the isotropy of the Biot coefficients, Young's modulus, and Poisson's ratio are assumed, the properties in the thickness directions are applied in all the directions (values are provided in Table 3). Note that the anisotropy of the water permeability is considered in all of the calculation cases because the property is related to the significance of the pressure development and deformation, but the other material properties are assumed isotropic.

404

Table 4 The consideration of anisotropic properties in each calculation case

	Young's modulus	Poisson's ratio	Biot coefficient			
Case 1	Isotropy*	Isotropy*	Isotropy*			
Case 2	Anisotropy	Anisotropy	Isotropy*			
Case 3	Anisotropy	Anisotropy	Anisotropy			
*The prope	erties in the thickness	s directions are ap	oplied in all directions.			

405

406 *4.2. Results*

407 Figures 7 and 8 present the results of the calculation of Case 1, as well as the measured temperature 408 and strain evolution, respectively. The strain evolution on both the top and side surfaces (normal to 409 and along the thickness, respectively) is presented in Fig. 8, but the temperature is not shown on the 410 top surface in Fig. 7 as the evolutions of temperature at the two measuring points are similar. Below 411 0 °C, the calculated strain along the thickness increases as the temperature decreases, same as the 412 measured strain. The difference in the magnitude of the calculated and measured evolutions of the strain may be due to the inaccuracy in material properties, such as the moisture diffusivity and water 413 414 retention curve (These properties are related to the rate of the solidification and the water escape 415 toward the surfaces of the material due to the pressure development and consequently affect the magnitude of the deformation. For example, smaller moisture diffusivity prevents moisture movement 416 417 when the pressure increases due to the freezing, which induces more significant pressure rise and strain. 418 Consequently, the agreement between the measurement and calculation will become better.) In 419 addition, the changes in the mechanical properties due to the water content changes (Fukui et al., 2019)

420 or evolution in the plastic strain can attribute to the difference between the measured and calculated 421 results. However, the trend in the measured strain change is well reproduced in the calculation.

423 [insert Figure 7]

424 [insert Figure 8]425

For Case 1, the calculated strain in the direction normal to the thickness also increases and completely disagrees with the measurement results that decrease during freezing. Therefore, the mechanically and poroelasitically isotropic models are insufficient for reproducing the measured results.

Next, Figs 9 and 10 present the results of Cases 2 and 3. The calculated strain along the thickness
and the temperature do not significantly change from those in Case 1 (the temperature is not shown in
this paper). Although the strain change in the direction normal to the thickness during freezing in Case
2 (shown in Fig. 9) is smaller than that in Case 1, the material still expands in this direction. The
material contracts in this direction in Case 3 in which the anisotropy of the Biot coefficient is
considered, which is consistent with the measured results.

- 436 437 [insert Figure 9]
- 438 [insert Figure 10]
- 439

422

440 *4.3. Discussion*

In this section we compare the contribution of the temperature changes, water pressure development, and Poisson's effects to the strain evolution based on the calculation results where the anisotropy of the Young's modulus, Poisson's ratio, and Biot coefficient is considered, and analyze the dominant sources of the deformation in each direction of the material. First, thermal contraction due to the temperature changes during the freeze-thaw cycle along and normal to the thickness is determined based on the calculated temperature evolution as

447 $\varepsilon_{tt}^{T} = \varepsilon_{nn}^{T} = \alpha \left(T - T_{r} \right)$ (27)

Here we ignored the anisotropy of the thermal expansion coefficient. T_r is the set value of the initial temperature (20 °C). Next, the strain change due to water (liquid water and ice) pressure development in the material (excluding Poisson's effects) is obtained based on the calculated ice and liquid water saturation and pressure as

452
$$\varepsilon_{tt}^{H} = \frac{b_{t}}{E_{t}} \left(S_{i} p_{i} + S_{l} p_{l} \right) \qquad \varepsilon_{nn}^{H} = \frac{b_{n}}{E_{n}} \left(S_{i} p_{i} + S_{l} p_{l} \right) \tag{28}$$

Finally, the Poisson's effects due to the expansion associated with water pressure development in the vertical direction are considered as

455
$$\varepsilon_{tt}^{P} = -\frac{v_{tn}b_n}{E_t} \left(S_i p_i + S_l p_l \right) \qquad \varepsilon_{nn}^{P} = -\frac{v_{nt}b_t}{E_n} \left(S_i p_i + S_l p_l \right) \tag{29}$$

456 As no external force was considered in the calculations, these three factors are main determinant of 457 the deformation of the material.

Using equations (27) to (29) with the calculated temperature, water saturation, and pressure evolution in Case 3, the strain due to the thermal contraction, hydrostatic pressure, and Poisson's effect were calculated. Figure 11 shows comparison of the contribution of these causes of the deformation to the strain evolution. Due to the restriction of the deformation from the neighborhood elements, the sum of the strain caused by the three causes is not consistent perfectly with the calculated overall strain shown in Fig. 10. However, it seems that they mainly determine the magnitude and trend

464 of the deformation. From Fig. 11 (a), the expansion along the thickness is mainly attributed to the 465 increase in the hydrostatic pressure in the material due to freezing; moreover, the thermal contraction 466 and Poisson's effects are almost negligible. In contrast, Fig. 11 (b) shows that the three components of strain evolution compete in the direction normal to the thickness. The expansion associated with 467 468 the hydrostatic pressure development is suppressed due to the small Biot coefficient and large Young's 469 modulus in this direction, while the Poisson's effect is dominant because of the large expansion along 470 the thickness. According to these results, the contribution of the water pressure rise in pores to the deformation of the specimen is relatively small in the direction normal to the thickness compared with 471 the contribution of the Poisson effect accompanied by the expansion along the thickness. This resulted 472 473 in the contraction of the material in the direction normal to the thickness. Therefore, a model that only 474 considers the anisotropy of the general mechanical properties (Case 2) cannot reproduce such a 475 contraction, and the anisotropy of the Biot coefficients should be adequately considered.

- 476
- 477 [insert Figure 11]
- 478

479 **5.** Conclusion

480 In this study, the effects of anisotropy of the material properties on the deformation during freezing and thawing processes and proper numerical modeling of it are investigated. The strain measurement 481 using two fired clay materials confirmed the strongly anisotropic deformation during the freezing. 482 483 Notably, the plate-shaped simulated roof tile contracted in the direction normal to the thickness while 484 it expanded significantly in the thickness direction. The freeze-thaw process is then simulated based on theory of poromechanics and anisotropic poroelasticity. The comparison between the measured and 485 486 calculated results reveals that applying only the anisotropy of mechanical properties is insufficient for 487 reproducing the anisotropic deformation of the material; moreover, the contraction in the direction 488 normal to the thickness can be reproduced only when the anisotropies of the Biot coefficient and 489 general mechanical properties are considered. Analysis of the causes of the deformation reveals that 490 the expansion in the direction normal to the thickness due to the pressure development during the 491 freezing is suppressed by the large Young's modulus and small Biot coefficient and the contraction 492 due to the Poisson's effects accompanied by the large expansion in the thickness direction can be a 493 dominant factor of the deformation in the direction normal to the thickness. Therefore, considering the 494 anisotropy of the Biot coefficient is recommended when materials with laminated structures, such as 495 types of stones and fired clay materials, are considered.

496 In this study, we chose the simulated roof tile as the target of the calculations considering its 497 relatively simple dimensions, small heterogeneity, and strong anisotropy in the mechanical properties due to the laminated structure or orientation of particles compared with bricks, which allowed us to 498 499 predict the poroelastic properties under simple assumptions of parallel pore structure. In the future, 500 the deformation of bricks, which also exhibited the anisotropy in the strain measurement will be further 501 explored for the practical application. In addition, the validity of such assumptions for other types of 502 building materials needs further investigation for a wider application of anisotropic poroelasticity to 503 various building materials

504 Appendix

505 The components in equation (21) are defined as

506
$$\mathbf{C}_{\mathrm{TT}} = \int_{\Omega} \frac{\partial}{\partial T} (CT - H_{li} m_i) \mathbf{N}^T \mathbf{N} d\Omega$$
(A.1)

507
$$\mathbf{C}_{\mathbf{T}\mathbf{p}} = \int_{\Omega} \frac{\partial}{\partial p_i} (CT - Hm_i) \mathbf{N}^T \mathbf{N} d\Omega$$
(A.2)

508
$$\mathbf{C}_{\mathbf{T}\mathbf{u}} = \int_{\Omega} \frac{\partial}{\partial \mathcal{E}_{\nu}} (CT - Hm_{i}) \mathbf{N}^{T} \mathbf{m}^{T} \mathbf{B} d\Omega$$
(A.3)

509
$$\mathbf{C}_{\mathbf{p}T} = \int_{\Omega} \frac{\partial}{\partial T} (m_i + m_l) \mathbf{N}^T \mathbf{N} d\Omega$$
(A.4)

510
$$\mathbf{C}_{\mathbf{pp}} = \int_{\Omega} \frac{\partial}{\partial p_l} (m_l + m_l) \mathbf{N}^T \mathbf{N} d\Omega$$
(A.5)

511
$$\mathbf{C}_{\mathbf{pu}} = \int_{\Omega} \frac{\partial}{\partial \mathcal{E}_{v}} (m_{i} + m_{i}) \mathbf{N}^{T} \mathbf{m}^{T} \mathbf{B} d\Omega$$
(A.6)

512
$$\mathbf{C}_{\mathbf{uT}} = -\int_{\Omega} \left[\alpha \mathbf{B}^{\mathrm{T}} \mathbf{D} + b \frac{\partial}{\partial T} (S_{i} p_{i} + S_{l} p_{l}) \mathbf{B}^{\mathrm{T}} \right] \mathbf{mN} d\Omega$$
(A.7)

$$\mathbf{C}_{up} = -\int_{\Omega} b \frac{\partial}{\partial p_l} (S_l p_l + S_l p_l) \mathbf{B}^{\mathrm{T}} \mathbf{m} \mathbf{N} d\Omega$$
513 (A.8)

514
$$\mathbf{C}_{uu} = \int_{\Omega} \mathbf{B}^{\mathrm{T}} \mathbf{D} \mathbf{B} d\Omega$$
(A.9)

515
$$\mathbf{K}_{\mathrm{TT}} = \int_{\Omega} \nabla \mathbf{N}^{T} \lambda \nabla \mathbf{N} d\Omega + \int_{\Gamma} h \mathbf{N}^{T} d\Gamma$$
(A.10)

516
$$\mathbf{K}_{pp} = \int_{\Omega} \nabla \mathbf{N}^T \boldsymbol{\lambda}' \nabla \mathbf{N} d\Omega$$
(A.11)

517
$$\mathbf{f}_{\mathrm{T}} = -\int_{\Gamma} (Q - hT_{out}) \mathbf{N}^{T} d\Gamma$$
(A.12)

518
$$\mathbf{f}_{\mathbf{P}} = -\int_{\Gamma} J \mathbf{N}^{T} d\Gamma$$
(A.13)

519
$$\frac{\partial \mathbf{f}_{\mathbf{u}}}{\partial t} = \frac{\partial}{\partial t} \int_{\Gamma} \mathbf{N}_{\mathbf{u}}^{T} t d\Gamma$$
(A.14)

520 where Ω and Γ are the domains of an element and its boundary, respectively; moreover,

521
$$\mathbf{m} = \begin{bmatrix} 1 & 1 & 0 \end{bmatrix}^T$$
(A.15)

522
$$\mathbf{B} = \begin{bmatrix} \frac{\partial N_1}{\partial x_1} & 0 & \frac{\partial N_2}{\partial x_1} & 0 & \frac{\partial N_3}{\partial x_1} & 0 & \frac{\partial N_4}{\partial x_1} & 0 \\ 0 & \frac{\partial N_1}{\partial x_2} & 0 & \frac{\partial N_2}{\partial x_2} & 0 & \frac{\partial N_3}{\partial x_2} & 0 & \frac{\partial N_4}{\partial x_2} \\ \frac{\partial N_1}{\partial x_2} & \frac{\partial N_1}{\partial x_1} & \frac{\partial N_2}{\partial x_2} & \frac{\partial N_2}{\partial x_1} & \frac{\partial N_3}{\partial x_2} & \frac{\partial N_4}{\partial x_1} & \frac{\partial N_4}{\partial x_2} \end{bmatrix}$$
(A.16)

523

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- 639

















(a)





Solid lines: experiment; Dotted lines: calculation



Solid lines: experiment; Dotted lines: calculation



Solid lines: experiment; Dotted lines: calculation





(a)

⁽b)