This study aims to evaluate the hygrothermal environment of flooded crawlspaces quantitatively and to establish a drying technique. In addition, moisture desorption characteristics of water-saturated concrete is further clarified by fundamental experiment and numerical simulation.

FUNDAMENTAL EXPERIMENT

Experiment sample

A concrete sample is prepared of more than five according to the water-cement ratio. Three water-cement ratios are absorbed (W/C=35%, 50%, and 65%). Concrete samples are in columnar form (diameter 10cm, height 20cm). Each sample is given 27 days of water curing after concrete casting. Figure 1 shows the samples used for the experiment.

Measurement of pore volume and water content of concrete

Moisture desorption characteristics of concrete are greatly influenced by pore diameter and pore volume (cavity) of materials. Then, pore size distribution and pore volume of the concrete sample are measured by a mercurial indentation technique. Mercurial indentation is a method for specific surface area and pore size distributions of materials (Figure 2). This method consists of letting mercury invade the pores of samples, using the surface tension of mercury.

Pore size distribution is measured using dried samples after the experiment of moisture desorption. Figure 3 shows pore size distribution and the void ratio of concrete samples according to water-cement ratio. Pore size distribution expresses void distribution (pore volume distribution) of a certain pore diameter to occupy materials. Void ratio expresses a value that adds up volume sequentially from a small cavity of a pore diameter. Figure 4 shows water content ratio and unsaturated water potential (ϕ-μ relations) that are calculated based on pore size distribution using a Kelvin equation. The Kelvin equation expresses the adsorption power of a capillary (cavity), and it is given in equation (1). Unsaturated water potential is using thermodynamic energy to express a deviation from the saturation of humid air, and is given in this equation (2).

$$\ln \frac{p}{p_s} = -\frac{2\gamma V_m}{r_{drop} RT} = -\frac{2\gamma V_m}{rRT} \cos\theta \tag{1}$$

$$\mu = R_v T \ln \frac{p}{p_s} = -\frac{2\gamma}{r\rho_w} \cos\theta \tag{2}$$

When water is adsorbed into a cavity of materials, the thinner capillary is, the bigger adsorption power is. Vapor phase water is adsorbed from small pore diameters sequentially and condensed; therefore, water content is given by adding up pore volume according to pore size distribution. In addition, unsaturated water potential is negative thermodynamics energy because it is a deviation from saturation. It is “0” at

decreases until the experiment's fourth day, the outer layer of a sample gradually dries, and it is thought that there is more transmission water than conduction water. The quantity of moisture desorption is proportional to the quantity of evaporation latent heat needed to evaporate from the surface of concrete. Water capacity means the amount of the change of water content for an amount of change of energy (unsaturated water potential). Therefore, the quantity of moisture desorption of each day and the tegmental water capacity have principal proportion relations regardless of the differences of samples (water-cement ratio). Total quantities of moisture desorption over seven days increase so that, as a matter of course, the water-cement ratio of the sample is high. However, transmission water from the surface (quantity of moisture desorption every time) is strongly related with tegmental water capacity.

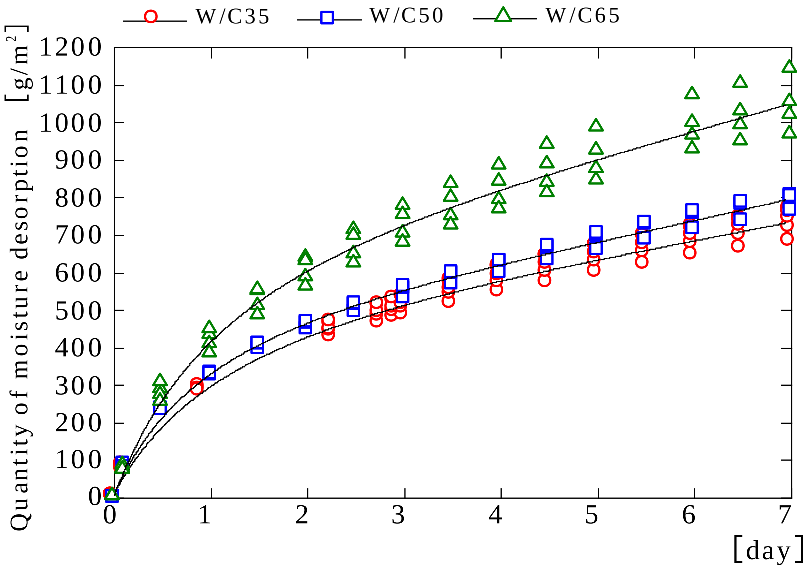


Figure6. *Quantity of Moisture Desorption from Concrete Samples*

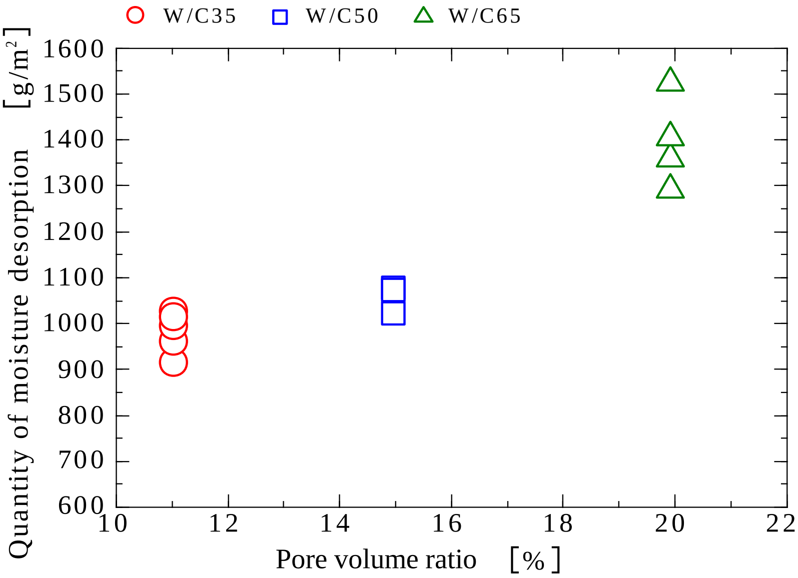


Figure7. *Total Quantities of Moisture Desorption in Seven Days and Pore Volume Ratio*

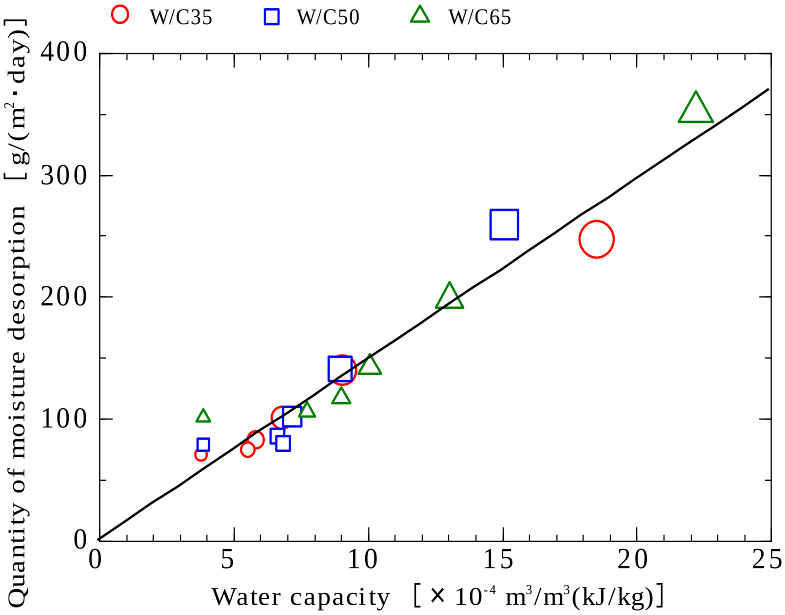


Figure8. Water Capacity and Quantity of Moisture Desorption for Each Day over Seven Days

SIMULATION USING A COMBINED HEAT AND MOISTURE TRANSFER MODEL

Combined Heat and Moisture Transfer Model ‘P-model’

For the experiment of moisture desorption, numerical simulation is performed using combined heat and moisture transfer theory. P-model is used for combined heat and moisture transfer theory. P-model is a nonequilibrium thermodynamics model consisting of the conservation law of energy and water (Figure 9). It uses thermodynamic energy (water potential) in consideration of influences such as external forces and the driving force of water (thermodynamic stress potential). Driving forces such as temperature, density, and pressure to affect water conduction (water transfer in a skeleton) and water transmission (water transfer between space and a skeleton) are unified and are expressed in the same dimension. The basic equation and boundary condition of combined heat and moisture transfer are shown from equation (3) to equation (6).

$$\frac{\partial C\rho T}{\partial t} + (c_{lw} j_{lw})\nabla T = \nabla \lambda \nabla T + r_v \nabla \lambda'_g \nabla \mu_w \qquad (3)$$

$$\rho_w \frac{\partial \phi}{\partial \mu}\frac{\partial \mu}{\partial t} = \nabla \lambda'_g \nabla \mu_w + \nabla \lambda'_l \nabla \mu \qquad (4)$$

$$-\lambda'_g \frac{\partial \mu_w}{\partial n_v} = \alpha'(\mu_{w,a} - \mu_{w,s}) \qquad (5)$$

$$-\lambda \frac{\partial T}{\partial n_v} - r_v \cdot \lambda'_g \frac{\partial \mu_w}{\partial n_v} = \alpha_c (T_a - T_s) + r_v \cdot \alpha'(\mu_{w,a} - \mu_{w,s}) + q_s \qquad (6)$$

The water capacity and water conductivity included in equation (4) are calculated using Φ-μ relations to show in Figure 3 and equation (7). Equation (7) is a calculating formula of water diffusivity which assumes a water content ratio where saturation is a standard (100%) function. Water conductivity is calculated from water diffusivity and water capacity using equation (8). However, this water conductivity is a value that is macro, including both the vapor phase and the liquid phase. Therefore, it is divided into vapor phase water conductivity and liquid phase water conductivity by equation (9) and equation (10).

$$K(\phi_w) = K_0 + \frac{K_s - K_0}{1+\left(\frac{100-\phi_w}{100-C_c}\right)^n} + \frac{K_s - K_0}{1+\left(\frac{100}{100-C_c}\right)^n} \cdot \frac{\phi_w - 100}{100} \tag{7}$$

$$\lambda' = K(\phi_w) \cdot \frac{\partial \phi}{\partial \mu} \tag{8}$$

$$\lambda' = \lambda'_g + \lambda'_l \tag{9}$$

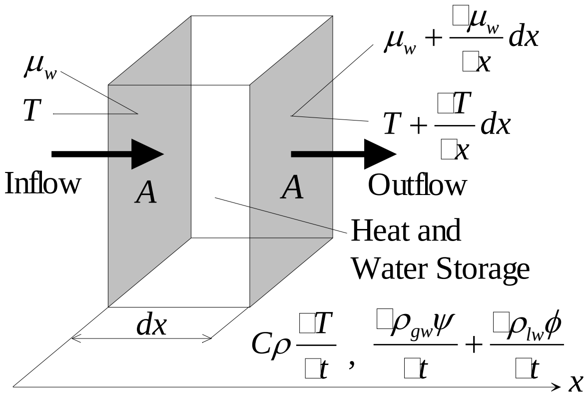
$$\lambda'_g = \lambda'_{g,dry}\left(\frac{\phi_{dry} - \phi}{\phi_{dry}}\right) \tag{10}$$

Table1. *Sign of Equations*

Equation(1)	p	Liquid saturated steam pressure in pores [Pa]	*Equation(4)*	$\partial \phi / \partial \mu$	Water capacity [m^3/(m^3·J/kg)]
	p_S	Saturated steam pressure in a liquid plane [Pa]		λ'_l	Liquid phase water conductivity [kg/(m・s・(J/kg))]
	γ	Surface tension of liquid water [J/m^2]	*Equation(5)*	n_v	Normal vector of Inner direction in boundary surfaces
	V_m	Liquid molar volume [m^3/mol]		α'	Water transmission rate for a water potential
	r_{drop}	Droplet radius [m]			difference [kg/(m2・s・J/kg)]
	R	Molar gas constant [J/(K・mol)]		$\mu_{w,a}$	Water potential of ambient air [J/kg]
	T	Absolute temperature [K]		$\mu_{w,s}$	Water potential of boundary surface [J/kg]
	r	Pore radius [m]	*Equation(6)*	α_c	Convective heat transfer coefficient [W/(m^2・K)]
	θ	Contact angle with a capillary wall of liquid water [°]		T_a	Temperature of ambient air [K]
Equation(2)	μ	Unsaturated water potential [J/kg]		T_s	Temperature of boundary surface [K]
	R_v	Weight gas constant of water molecule [J/(K・kg)]		q_s	Received heat amount by radiation [W/m^2]
	ρ_w	Specific gravity of liquid phase water [kg/m^3]	*Equation(7)*	$K(\phi_w)$	Water diffusivity [cm^2/day]
Equation(3)	C	Specific heat of materials [J/(kg・K)]		K_0	Diffusivity in absolute dry condition [cm^2/day]
	ρ	Specific gravity of a wall [kg/m^3]		K_s	Diffusivity in saturation [cm^2/day]
	t	Time [s]		ϕ_W	Water content on a basis of saturation [m^3/m^3]
	c_{lw}	Specific heat of liquid phase water [J/(kg・K)]		C_c	Water content ratio at a point of inflection of a curve [%]
	j_{lw}	Liquid phase water [kg/m^2・s]		n	Constant
	λ	Thermal conductivity [W/(m・K)]	*Equation(8)*	λ'	Water conductivity [kg/(m・s・(J/kg))]
	r_v	Heat for phase change [J/kg]	*Equation(10)*	$\lambda'_{g,dry}$	Water conductivity in air-dried state [kg/(m・s・(J/kg))]
	λ'_g	Vapor phase water conductivity [kg/(m・s・(J/kg))]		ϕ_{dry}	Void in air-dried state [m^3/m^3]
	μ_w	Water potential [J/kg]		ϕ	Water content in air-dried state [m^3/m^3]

Calculation Accuracy

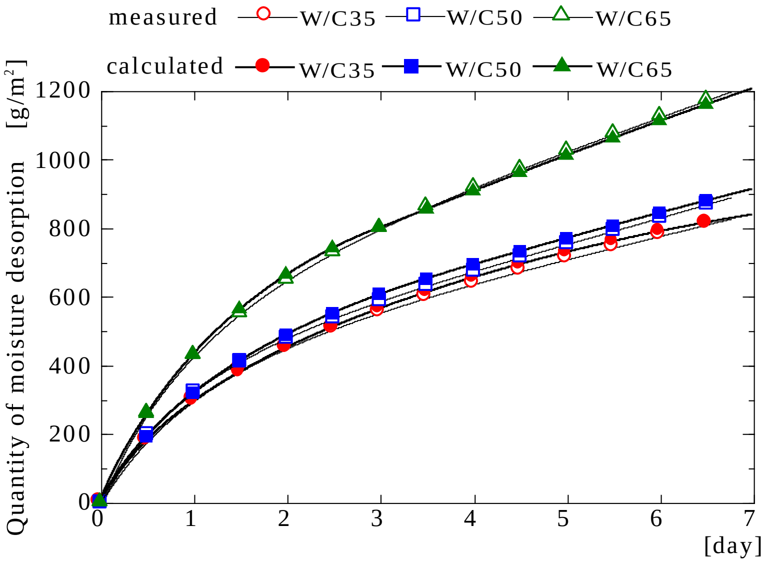
Table 2 shows a calculation condition. Figure 10 shows the quantity of moisture desorption (quantity of transmission water) of concrete samples (W/C=35%, 50%, 65%) by experiments and numerical simulation. As for each sample of the three kinds of water-cement ratios, calculated values accord with measured values well. Therefore, the validity and precision of the method of analysis are confirmed.



Fiqure9. *Conductive Heat and Moisture Transfer*

Table2. *Calculation Condition*

Specimen	Concrete
Surrounding temperature	20 degree C constant
Initial condition	saturated
Peliod	7 days
Calculation interval	1 minutes
Water cement ratio	35%
	50%
	65%



Fiqure10. *Verification of Precision*

CONCLUSIONS

The purpose of this study was to evaluate quantitatively both the hygrothermal environment of a house which has encountered flood damage and a drying method for flooded crawlspaces. Moisture desorption characteristics of water-saturated concrete are clarified by experiments and numerical simulation. The following presents the results.

1) Quantity of moisture desorption (transmission water) from concrete is principal in proportion to tegmental water capacity regardless of the water-cement ratio (W/C=35%, 50%, 65%).
2) Calculated values by combined heat and moisture transfer model ‘P-model’ accord with experimental values well. Therefore, the high precision of this model is confirmed.

REFERENCES

Ozaki A., Watanabe T. et al. 2001, Systematic Analysis on Combined Heat and Water Transfer through Porous Materials Based on Thermodynamic Energy, Journal of Energy and Buildings, Vol.33, No.4, p.341-350