FIRE RESISTANCE OF CONCRETE WALLS

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ABSTRACT

A model of heat and moisture transfer in concrete wall is presented. The transport parameters of the model used in the numerical analyses are estimated based on the mix proportion of constituents. The calculated results show the relationship between the mix design and initial water content of concrete and the fire resistance time of concrete wall.

INTRODUCTION

Concrete is a heterogeneous material. It can be treated as a mixture of cement paste, fine and coarse aggregate and pore. The volume fraction of these constituents can be specified by the concrete mix design. Consequently the transport parameters of heat and mass, e.g. thermal conductivity, specific heat, diffusion coefficients of water vapor and liquid water, can be changed in a wide range. Therefore the fire resistance of concrete are to be estimated by its mix design.

Fire resistance of concrete walls are extensively investigated by the standard fire test (ISO834 or its equivalent test methods), but the relationship between the mix design and the fire resistance is not quantitatively clarified by experiments because it requires too much time and manpower.

Zwiers et al.[1] made numerical simulations and showed the difference between normal and lightweight concrete. However, no general relationships are not derived yet. The purpose of this paper is to derive the relationship of mix design and fire resistance, and to make clear the range of modification of fire resistance time caused by the variation of mix design. In order to archive this purpose, heat and mass transfer in concrete slab is mathematically modeled and solved numerically. The transport parameters used in the model are estimated based on the concrete mix design. The relationships are derived from the calculated results in case of 70 and 100mm thick walls.

ANALYSIS

1. A Model of Heat and Mass Transfer

To simulate the heat and mass transfer in concrete during fire, a mathematical model of heat and mass transfer in concrete is used in the following analyses. Concrete is treated as a porous material as shown in Fig. 1. Its skeleton is made from aggregate and hydrated cement paste. Heat is conducted through the skeleton. The pore is partially filled with adsorbed water. The gas phase of the pore contains water vapor, which is in equilibrium with the adsorbed water. When the material is heated intensely, the desorption of adsorbed water takes place. The generated water vapor can diffuse through the pore, and can also flow toward the surface of the material together with the air due to the pressure rise in the pore. At high temperature, the thermal decomposition of crystalline water will take place.

A model to describe these phenomena is already presented by the authors[2]. The model consists of the following five governing equations; heat conservation;

$$\rho c \frac{\partial \theta}{\partial t} = \nabla(\lambda \nabla \theta) - L(R_{sorp} + R_{dcmp}), \tag{1}$$

mixed gas (water vapor + air) conservation;

$$\frac{\partial(\epsilon\rho_g)}{\partial t} + \nabla(\rho_g \mathbf{u}) = R_{sorp} + R_{dcmp}, \tag{2}$$

water vapor conservation;

$$\frac{\partial(\epsilon\rho_v)}{\partial t} + \nabla(\rho_v \mathbf{u}) = \nabla(D_v \nabla \rho_v) + R_{sorp} + R_{dcmp}, \tag{3}$$

adsorbed water conservation;

$$\rho_0 \frac{\partial w}{\partial t} = \nabla(D_w \nabla w) = -R_{sorp}, \tag{4}$$

and crystalline (hydrated) water conservation;

$$\rho_0 \frac{\partial w_c}{\partial t} = -R_{dcmp}. \tag{5}$$

The rate of desorption is expressed by the displacement from the equilibrium water content as

$$R_{sorp} = \gamma(w_{eq} - w). \tag{6}$$

The thermal decomposition of crystalline water takes place in three stages. Their rates are expressed by Arrhenius equations as

$$R_{dcmp} = \sum_{i=1}^{3} \rho_0 w_{c,i} A_{d,i}\, exp(-E_{d,i}/RT). \tag{7}$$

These equations are solved with the Darcy's law for gas filtration and the equations of state of water vapor and mixed gas.

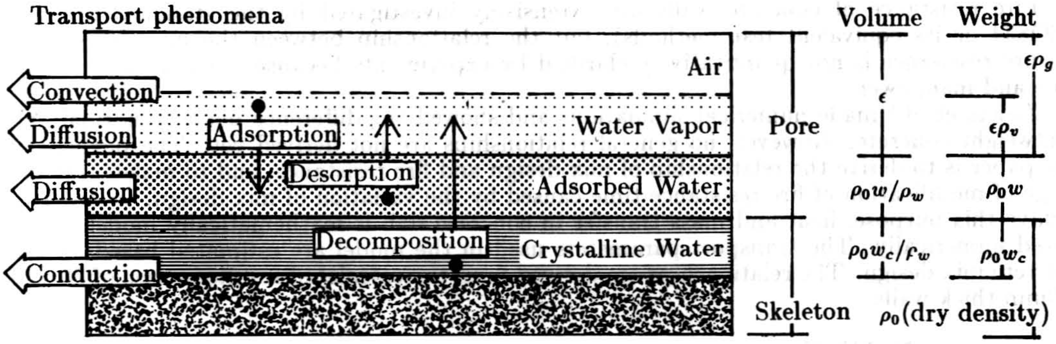

Fig. 1 A model of heat and mass transfer

2. Estimation of the Transport Parameters

In order to investigate the effect of mix design upon transport parameters, the volume fractions of each constituent are calculated from the mix proportions of the concrete, and the transport parameters are estimated using the volume fractions.

The thermal conductivity is estimated by the Maxwell's equation

$$\lambda_{1+2} = \lambda_1 \frac{\lambda_2 + 2\lambda_1 - 2v(\lambda_1 - \lambda_2)}{\lambda_2 + 2\lambda_1 + v(\lambda_1 - \lambda_2)}, \tag{8}$$

where λ_1 and λ_2 are the thermal conductivity of continuous and dispersed phase,respectively, v denote the volume fraction of dispersed phase. The thermal conductivity of each constituent is defined by experiments[3], and used in the equation to estimate the value of concrete. The other paramers are also defined by the volume fractions of constituent[3,4].

A specimen is made for the mix design shown in table 1. The estimated results of transport parameters are shown in Fig. 2.

Table 1. Mix design of concrete

	mix proportions [kg/m^3]	density [kg/m^3]	volume fractions [m^3/m^3]	
coarse aggregate[a)]	973	2690	0.362	
fine aggregate[b)]	792	2650	0.299	
cement	273	3150	0.087	
water	68[c)]	1000	0.068	
sum	2106		0.816	void=0.184

a) sandstone (S1 in Table 2) b) natural sea sand c) excluding excess water

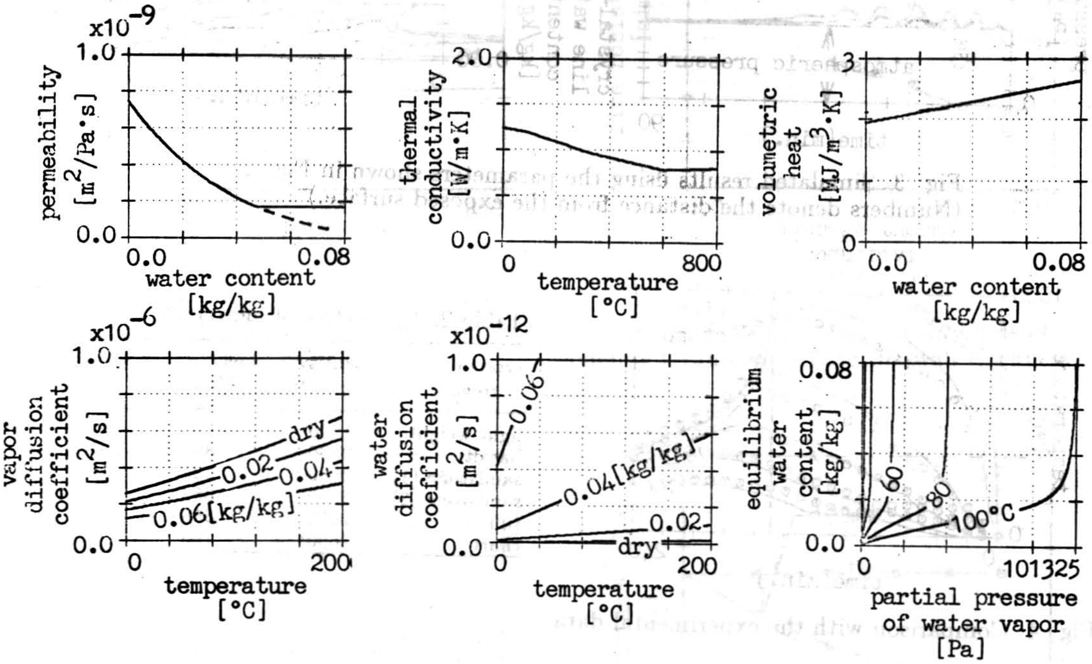

Fig. 2 Transport parameters estimated from the mix proporion in Table 1

RESULTS AND DISCUSSIONS

1. The Results of Calculation

An example is shown for a flat, 70mm thick concrete wall with the transport parameters shown in Fig. 2. The wall is heated from one side by ISO834 fire. Initial water content is 3% by weight. Initial and ambient temperature is 4°C.

The calculated results are shown in Fig. 3. In the temperature history, so-called **creeping of temperature** is clearly reproduced by simulation. During this process, the adsorbed water content shows a typical change. At first it rises up due to the adsorption of water vapor arrived from the hot zone, then it falls down as heat is conducted. The partial pressure of water vapor rises up just before the starting of the creeping of temperature and maintained as long as the wall is heated and water vapor is generated in the wall.

The fire resistance time of this wall, defined by the time required for the unexposed surface temperature to rise 140°C, is 71 minutes as shown in the figure.

The verification with the experimental data is made for 100mm slab heated by JIS A 1304 standard fire for 150min[5]. Initial water content is 4.7% in this case. A part of the results are shown in Fig. 4 in comparison with the measured data. Fair agreements are archived in temperature.

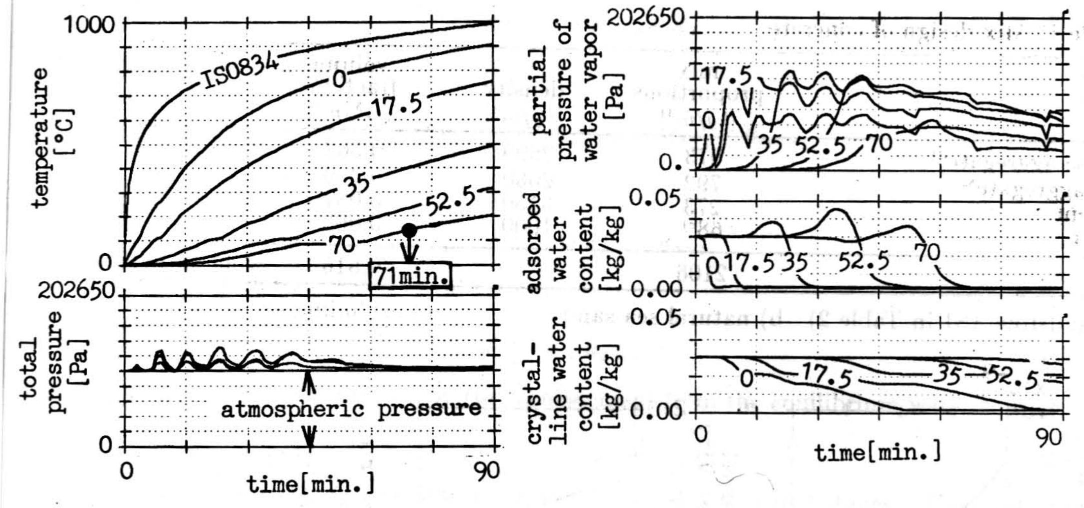

Fig. 3 Simulated results using the parameters shown in Fig. 2. (Numbers denote the distance from the exposed surface.)

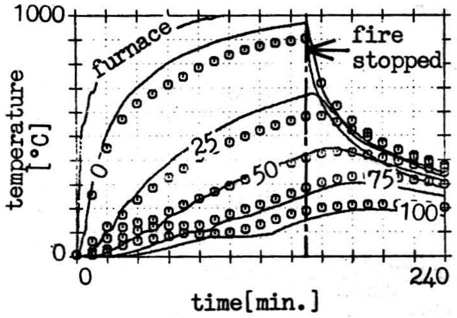

Fig. 4 Comparison with the experimental data

Table 2. Properties of aggregate

type of aggregate	density $[kg/m^3]$	specific heat $[J/kg \cdot K]$	symbol
light weight	1550	795	LW
basalt	2590	896	BA
sandstone (1)	2690	829	S1
sandstone (2)	2690	862	S2
tuff	2620	858	TU
chart	2600	795	CH

2. The Effect of Aggregate Quality on Fire Resistance Time

Coarse aggregate occupies a large volume of concrete. Therefore, the transport parameters, especially the thermal conductivity, depends on the quality of aggregate. In order to examine the effect, six kinds of aggregate shown in Table 2. are used. Other conditions, such as volume fractions of constituents, initial water content, are kept to the same. The estimated thermal conductivity values of the five kinds of concrete are shown in Fig. 5. They show appreciable difference on the quality of coarse aggregate. The maximum value is obtained when using the chart(CH), while the minimum value is for the artificial lightweight aggregate(LW).

Simulations are carried out for these six kinds of concrete wall of 70 and 100mm thickness, respectively. The fire resistance time versus temperature averaged thermal conductivity obtained by calculations are shown in Fig. 6. Fire resistance time is greatly influenced by the quality of aggregate. The degrees of change in fire resistance time are about 41min./(W/m·K) in case of 70mm thickness, and 98min./(W/m·K) in case of 100mm thickness, respectively.

3. The Effect of Aggregate Volume on Fire Resistance Time

In general, natural aggregate tends to increase the thermal conductivity of concrete, thus decreases the fire resistance time. In order to see how the amount of aggregate influences the fire resistance of concrete, the volume fraction of coarse aggregate is changed in the range of 0 to 43.3% by volume for chart(CH) and light weight aggregate(LW). The estimated thermal conductivity is shown in Fig. 7. In case of CH, thermal conductivity increases as the volume fraction increases, contrary, in case of LW, it slightly decreases as the volume fraction increases.

The fire resistance time obtained by simulations are shown in Fig. 8. In case of CH, fire resistance time is considerably reduced by the increase of aggregate. In case of LW, there is no obvious change in fire resistance time because the change in thermal conductivity is small as shown in Fig. 7.

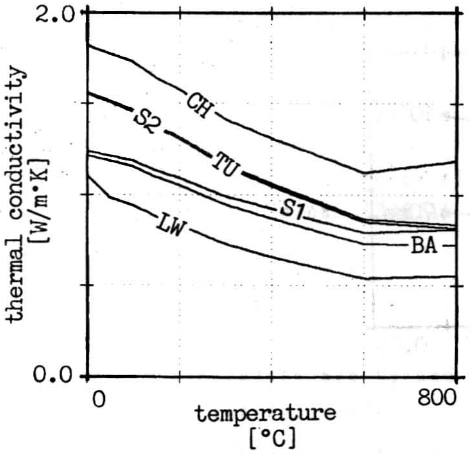

Fig. 5 Estimated thermal conductivity of six kinds of concrete (Volume fraction of coarse aggregate is 36.2%)

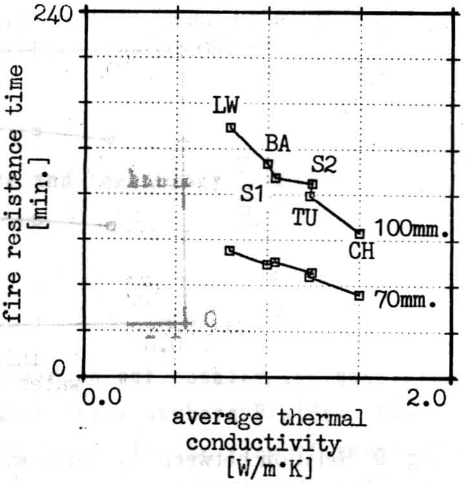

Fig. 6 Fire Resistance time of six kinds of concrete (Numbers denote the wall thickness)

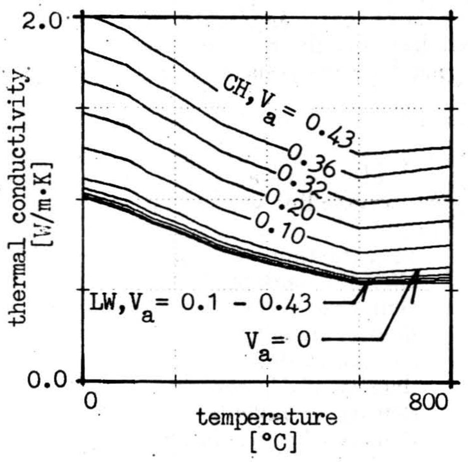

Fig. 7 Estimated thermal conductivity of of Ch and LW for various volume fractions of coarse aggregate

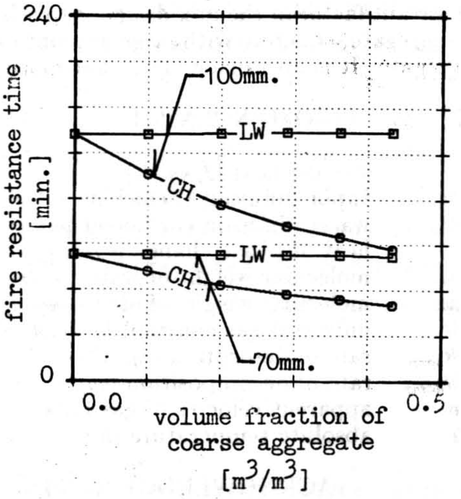

Fig. 8 Relation between the fire resistance time and the volume fractions of aggregate

4. The Effect of Initial Water Content on Fire Resistance Time

It is commonly known that the moist concrete has good fire resistance. In view of heat and mass transfer, moisture makes complicated effects. It increases the volumetric heat capacity and heat of desorption per unit volume. These effects lead to increase fire resistance time. Contrary, it increases the thermal conductivity. This effect leads to decrease fire resistance time.

Simulations are made to in order estimate the effect. The initial water content is changed to 1, 2, 4% by weight corresponding to the calculation as shown in Fig. 3. The results are shown in Fig. 9. The fire resistance time obtained by simulations are plotted versus the initial water content. This figure shows that the moisture in concrete improves the fire resistance. The degree of increase of fire resistance time is about 3.3min./(% by weight) in case of 70mm thick wall, and 5.7min./(% by weight) in case of 100mm thick wall.

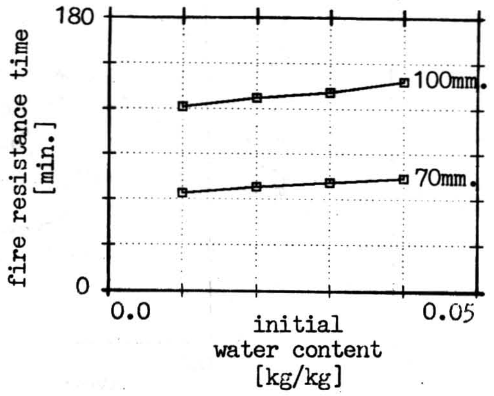

Fig. 9 Relation between the initial water content and the fire resistance time

SUMMARY

Numerical simulations of heat and mass transfer in concrete wall are carried out to investigate the relationship between the concrete mix design and the fire resistance. The most important factor in the mix design is to select the quality of coarse aggregate. As to the amount of aggregate, concrete with large amount of aggregate has poor fire resistance in case of natural aggregate. It is also made clear that moist concrete has long fire resistance time.

NOMENCLATURE

c	specific heat $[J/kg \cdot K]$	w	adsorbed water content $[kg/kg]$
D_v	vapor diffusion coefficient $[m^2/s]$	w_c	crystalline water content $[kg/kg]$
D_w	water diffusion coefficient $[m^2/s]$		
L	heat of phase change $[kg/m^3]$	ϵ	void fraction $[m^3/m^3]$
M_v	molecular weight of water $[kg/kmol]$	λ	thermal conductivity $[W/m \cdot K]$
M_a	molecular weight of air $[kg/kmol]$	θ	temperature $[^\circ C]$
R	universal gas constant $[J/kmol \cdot K]$	ρ	density $[kg/m^3]$
R_{sorp}	rate of desorption $[kg/m^3 \cdot s]$	κ	gas permeability $[m^2/Pa \cdot s]$
R_{dcmp}	rate of decomposition $[kg/m^3 \cdot s]$	ρ_0	density of dry concrete $[kg/m^3]$
$\mathbf{u}$	apparent velocity of gas $[m/s]$	ρ_g	density of mixed gas $[kg/m^3]$
T	absolute temperature $[K]$	ρ_v	density of water vapor $[kg/m^3]$

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