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Heat and Mass Transfer in the Walls Subjected to Fire

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ABSTRACT

The physical process of heat and mass transfer in concrete walls was described by a model. The model consist of heat conduction in the skeleton, mass (air, water vapor and adsorbed water) transfer in the pore. The desorption of the adsorbed water and the decomposition of the water of crystallization were included explicitly. The model was applied to two practical problems. The first application was to investigate the variation of insulation performance of flat wall by the change in initial water content. The range of variation was quantified and compared with the variation caused by mix design. From the calculated results, a methodology was proposed to carry out the mix design of concrete for arbitrate required insulation performance taking into account of the variation caused by uncertainty in initial water content. The second application was to define the optimum cross sectional shapes of composite floor of profiled steel sheet and concrete. The model was extensively used to analyze the dependence of the insulation performance upon the cross sectional shape. Simple but useful concept of "thermally optimum" was proposed to assure sufficient insulation performance.

1. INTRODUCTION

Concrete is a wet porous material. When concrete members are intensely heated, water in the pore evaporates to vapor. As a consequence, temperature rise is delayed in the temperature range of 100 and 150℃. This phenomenon is called "creeping of temperature". To predict the temperature histories of concrete members, this phenomenon should be modeled appropriately.

In the early 1960's, simple models were proposed by Kawagoe[1)], Wakamatsu[2)], Pettersson *et al*[3)], Wickstrom[4)], Lie[5)] and others. They assumed that the temperature is sustained at 100℃ as long as liquid water remains in the pore. This method gives reasonable results of temperature rise. Thus it is widely used in many applications up to today. However the model is not enough when we needs information other than temperature. More sophisticated models treats the problem as a drying process of wet porous material. Desorption (evaporation) of physically adsorbed water, and corresponding mass transfer in the pore are described. Harmathy[6)] proposed a model for brick walls. Similar approaches were proposed by Huang *et al*[7)], Sahota *et al*[8)] for concrete.

When we focus on concrete, two types of water, physically adsorbed water and the water of crystallization, exist. Physically adsorbed water evaporates in the temperature range of 100 to 150℃, which results in the creeping of temperature and the pore pressure rise. The water of crystallization are decomposed into vapor at higher temperature. This process corresponds with the deterioration of the material. In order to know the behavior of concrete during fire, it is important to take the both phenomena into account.

A model of heat and mass transfer in concrete was developed by the authors[9] to take into account of both desorption and decomposition. In this paper, the physical and mathematical basis of the model is briefly described. Then the model is applied to two practical problems. The first application is to analyze the variation of the insulation performance of flat walls heated by ISO fire. The effect of initial water content and mix design is quantified, which enables the rational mix design of concrete walls for insulation performance. The second application is a problem of finding the optimum cross sectional shape of composite floor. So far these applications deals with only the insulation performance (temperature rise of unexposed surface). The correlation with material integrity and deterioration is under investigations. A preliminary idea will be briefly mentioned as a plan of future investigations.

2. PHYSICAL PROCESS OF HEAT AND MASS TRANSFER IN CONCRETE

2.1 Experimental Investigation

The process of heat and mass transfer was investigated by small scale experiments. The specimen was a flat mortar wall of 40 mm thickness. As shown in Figure 1, the wall was heated by an electric furnace. Temperature, water content and pore pressure were measured at the locations shown in the figure. Temperature was measured by type K thermocouples. Water content was measured by hand made probes. Pore pressure was measured indirectly via a oil pressure in a pipe embedded in the mid thickness of the specimen.

An example of the results is shown Figure 2 by symbols. Among the data, the data at the mid thickness point (point 3) is analyzed in the following. Temperature gradually rose until 100℃. Then the creeping of temperature began at 15 minutes. Until temperature reached 140℃ at 25 minutes, the temperature rise was very slow. In the early stage, the water content increased because of the re- adsorption of water vapor that came from the zone closer to the exposed surface. During the period of creeping of temperature, water content decreases monotonously. The pore pressure increased during the same period. The peak value appeared at 26 minutes. At almost the same time, the creeping of temperature is finished. As described above, complex transport phenomena take place in the material during the period of creeping of temperature.

2.2. A Model of Heat and Mass Transfer

The above described physical process could be modeled by a system shown in Figure 3. Water is physically adsorbed in the pore. The rest of the pore is occupied by a gaseous mixture of air and water vapor. Water vapor and adsorbed water are in equilibrium. When the temperature and/or the partial pressure of water vapor changes, desorption or adsorption takes place to sustain the equilibrium. Skeleton is made of thermally stable material and water of crystallization. At high temperature, the water of crystallization is removed from skeleton to pore. Heat is conducted in skeleton. Water vapor and air move through pore by diffusion and convection. Adsorbed water diffuses through the pore by capillary actions.

To consider these phenomena, conservation of heat, gaseous mixture (air and water vapor), water vapor, physically adsorbed water and water of crystallization were applied.,

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

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

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

$$\rho_0\frac{\partial w}{\partial t}=\nabla(\rho_0D_w\nabla w)-R_{sorp}, \tag{4}$$

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

To close the system, Darcy's law for gas filtration, rates of desorption and decomposition, ideal gas laws were coupled.

Gas Filtration through the Pore : The pore structure of concrete is usually fine so that the flow in the pore is laminar. Therefore the Darcy's law for gas filtration can be applied for gas velocity,

$$\mathbf{u}=-\kappa_D\nabla P_g\ , \tag{6}$$

Rate of desorption :Normally the condition of water vapor and the adsorbed water is close to equilibrium state. Thus, the rate of desorption was described by the Langmuir's equation,

$$R_{sorp}=\gamma(w-w_{eq}), \tag{7}$$

where $w_{eq}(=f(\theta,P_v))$ is the equilibrium water content.

Rate of Decomposition : The water of crystallization is decomposed gradually as the temperature is increased. There are many kinds of water of crystallization in concrete[10]. However, for simplicity, they were classified into three groups: (1) gel water (decomposition temperature 100 - 400℃), (2) calcium hydroxide (450 - 550℃) and (3) calcium silicate hydrated (600℃ -). The rates of decomposition of the three groups were described by Arrhenius type rate equations,

$$R_{dcmp}=\rho_0\sum_{k=1}^{3}w_{c,k}A_k\exp(-E_k/RT), \tag{8}$$

where subscript k (=1,2,3) corresponds with the above three groups.

Equations of State :The ideal gas law for water vapor and gaseous mixture are

$$\rho_v=M_vP_v/RT, \qquad \rho_g=\rho_v+\rho_a=[(M_v-M_a)P_v+M_aP_g]/RT. \tag{9}(10)$$

2.3. Numerical Implementation

The governing equations are non liner and stiff because of the non liner source term, and because of the difference in characteristic time for diffusion (Fourier number) between heat and water. To avoid the numerical difficulty, integral equation method developed by Terai was applied [11]. After descritization, we get a set of simultaneous ordinary differential equations of temperature, total pressure of gaseous mixture (pore pressure), partial pressure of water vapor, content of physically adsorbed water and water of crystallization,

$$\frac{d\mathbf{x}}{dt} = f(t,\mathbf{x}) , \quad (11)$$

where $\mathbf{x} = \{\theta_1, \theta_2, \ldots; P_{g,1}, P_{g,2}, \ldots; P_{v,1}, P_{v,2}, \ldots; w_1, w_2, \ldots; w_{c,1}, w_{c,2}, \ldots\}^T$ is a vector of nodal variables. The diagonally implicit Runge- Kutta method was applied to integrate equation (11).

2.4. the Computer Code FRECS

The model was implemented in a Fortran 77 program named FRECS (Fire REsistance of Concrete Structures). The source code consists of about 4200 lines. It was developed on a super computer, however now it is available on UNIX workstation. A typical CPU time is about three hours to solve a problem with 40 elements for four hours of simulation time. The code was verified by comparison with several experiments. In most cases, the agreement is good. An example is shown in Figure 2 by solid lines[9].

3. VARIATION OF THE INSULATION PERFORMANCE OF WALLS BY INITIAL WATER CONTENT AND MIX DESIGN

In this chapter, a methodology for rational mix design of concrete walls for insulation performance is discussed. Insulation performance of concrete walls depends on initial water content. Moist concrete has better insulation performance than dry concrete. However the initial water content depends on the surrounding environment before fire. Thus it is hardly controllable. Due to the uncertainty in initial water content, rational design of concrete is difficult. On the other hand, the hygro-thermal properties (thermal conductivity, specific heat, permeability and so on) depend upon the mix design (type of aggregate and mix fraction). Mix design is controllable to a certain extent.

If the uncertainty by initial water content is smaller than the variation caused by mix design, it is possible to specify an acceptable range of mix design of concrete in order to assure the required insulation performance. To investigate the relative importance of initial water content and mix design , the code FRECS was applied to a flat wall with 70 mm thickness heated by ISO fire. The analysis consists of two stages. In the first step, the hygro- thermal properties were estimated for a variety of mix design and water content. Six kinds of aggregate, lightweight (LW), basalt (BA), sandstone (S1, S2), tuff (TU), and chart (CH), were selected to account for commonly used aggregates. Initial water content was varied in the range of 1 to 4 % by weight. Then, in the second step, the insulation performance was calculated using the estimated hygro- thermal properties.

3.1. Relationship between the Mix Design of Concrete and Hygro- Thermal Properties

A simple relationship between the mix design of concrete and hygro- thermal properties were developed by the authors[12]. Let the volume fraction of coarse and fine aggregate, cement paste be V_{ag}, V_s, V_p, respectively. Simple additive rule can be applied to estimate the density, volumetric heat capacity and void fraction as

$$\rho = \sum_i \rho_i V_i, \quad \rho c = \sum_i \rho_i c_i V_i, \quad \varepsilon_0 = 1 - \sum_i V_i . \qquad (12)\,(13)\,(14)$$

As to the thermal conductivity, Maxwell's formula for the two phases mixture of dispersed phase and continuous phase

$$\lambda_{i+j} = \lambda_i \frac{\lambda_j + 2\lambda_i - 2v_i(\lambda_i - \lambda_j)}{\lambda_j + 2\lambda_i + v_i(\lambda_i - \lambda_j)}, \qquad (15)$$

was applied to the mixing of cement paste and sand, then to the mixing of cement mortar and coarse aggregate, where λ_i and λ_j are the thermal conductivity of continuous and dispersed phase, v is the ratio of volume fraction of dispersed phase. Variation of the thermal conductivity is shown in Figure 4 for the six kinds of aggregate in case of V_{ag}= 0.362, V_s= 0.299 and V_p= 0.155.

3.2. Variation of the Insulation Performance of 70 mm Walls by the Change in Initial Water Content and Mix Design [13]

(1) Initial Water Content :

The effect of initial water content was analyzed in case of sandstone concrete (S1). The initial water content was varied in the range of 1 and 4 % by weight. Using the value S1 in Figure 4, the temperature rise of the 70 mm thick wall was calculated. The results are shown in figure 5. In case of 1% of initial water content, the duration of the creeping of temperature is only 4 minutes. As the initial water content is increased, the duration is increased to 12 minutes. The critical time for insulation performance (as defined by ISO 834) varies in the range of 64 to 74 minutes. The magnitude of variation in critical time is almost the same as in the duration of the creeping of temperature. The sensitivity is 3.3 minutes per 1% change in initial water content.

(2) Mix Design

The effect of mix design was analyzed in a similar way. While the initial water content was kept 3% wt., the type of aggregate was changed to the other five kinds in figure 4. The calculated results are shown in Figure 6. Here, the temperature rise is greatly altered. The lightweight concrete has the best insulation performance, while the worst one is chart concrete. The critical time varies between 54 and 83 minutes.

Similar analysis was carried out changing the mix proportion of coarse aggregate. The critical time was calculated for each case. The results are summarized in Figure 7 as a function of the volume fraction of coarse aggregate V_{ag} and the temperature averaged thermal conductivity of coarse aggregate,

$$\overline{\lambda_{ag}} = \int_{RT}^{800} \lambda_{ag}(\theta) d\theta / (800 - RT) \quad (16)$$

The worst case is again the chart concrete when the volume fraction of coarse aggregate is increased. The best case is the lightweight concrete. The total variation is between 50 and 83 minutes.

Comparing the variation caused by initial water content and mix design, the effect of mix design is dominant. Thus, in the purpose of design, the variation of initial water content is relatively unimportant. Approximately the effect could be added linearly. For example, to assure the 60 minutes of fire resistance time, mix design should be selected in the non hatched region in Figure 7 where the critical time is greater than 67 (=60 +3.3 $\times$ 2) minutes.

4. OPTIMUM CROSS SECTIONAL SHAPE OF COMPOSITE FLOOR [14)]

In this chapter, a methodology to design the optimum cross sectional shape of composite floor is discussed. When we consider the load bearing capacity of the slab, the lib should be as large as possible. However, when the concrete volume is limited, minimum thickness of the slab is decreased as the rib size is increased. This results in poor insulation performance. Therefore, it is expected that there is a certain limit of lib size in order to assure the insulation performance of the composite floor.

To find the limit, code FRECS was applied to various cross sectional shape. The examined cross sectional shapes are shown in figure 8. The average thickness of all these cross sectional shapes are 115 mm. From the calculated results, the critical time for insulation performance was defined by,

$$t_{fr} = \min(t_{ave}, t_{max}) \quad (17)$$

where, t_{ave} is the critical time for average temperature rise (140℃) of unexposed surface, t_{max} is the critical time for maximum temperature rise (180℃) of unexposed surface.

4.1 Examples of Results

As examples, the time- dependent temperature distributions at the unexposed surface of series A, are shown in figure 9(above). In the same figure (below), the isothermal lines at the critical time, t_{fr}, are drawn. In case of type H, the isothermal lines are considerably curved, thus the insulation criterion for the maximum temperature rise was exceeded ($t_{fr}= t_{max}$). On the contrary, in case of type L, the isothermal lines were similar to horizontal lines, therefore the insulation criterion for the average temperature rise was exceeded ($t_{fr}= t_{ave}$).. In case of type S, both criteria for average and maximum temperature rise were exceeded at the same time ($t_{fr}= t_{max}= t_{ave}$).

4.2 Concept of Thermally Optimum

The variation of two critical times are shown in figures 10 and 11 as functions of rib width and height. The critical time for average temperature rise, t_{ave}, is not significantly changed by the cross sectional shapes, whereas the critical time for maximum temperature rise,

t_{max}, is strongly influenced. It drastically decreases as the rib width and/or height is increased.

The resulting critical time t_{fr} is shown in Figure 12. It is clear that the critical time is considerably reduced if the rib size is greater than a certain limit. The bold line indicates the cross sectional shapes where the both criteria are exceeded at the same time ($t_{ave}= t_{max}$). In these cross sectional shapes, there is no redundancy of the concrete location. Thus we name this feature as "thermally optimum". The line of thermally optimum shape is a good indicator of the limit of rib size acceptable to assure the insulation performance.

5. SUMMARY AND FUTURE DEVELOPMENTS

5.1. Summary

A model of heat and mass transfer was applied to analyze the insulation performance of 1) flat walls and 2) composite floor of profiled steel plate and concrete.

Through the investigation of the flat walls, the effect of initial water content and the mix design of concrete was examined. The calculated results show that the variation by initial water content is much smaller than that by mix design of concrete. Thus the mix design for insulation performance is possible including the variation caused by initial water content.

The analysis on composite floor demonstrated that the insulation performance of composite floor depends on its cross sectional shapes. When the available concrete volume is limited, there is a certain limit of rib size in order to assure the insulation performance. From the results of calculations, the limit was derived as thermally optimum shapes, where the two insulation criteria are exceeded at the same time.

From the two applications, it was revealed that the analytical model is an effective tool to derive a design methodology for insulation performance of concrete members.

5.2. Future Developments

The present model assumes no significant change of material structure. However, material integrity is one of the important aspect of fire resistance. Heat and mass transfer process is concerned with this problem. Especially, the pore pressure rise and the temperature gradient are closely related to spalling and/or separation of surface layers, which would drastically decrease the fire resistance of concrete members.

To investigate the correlation between material integrity and heat and mass transfer, small scale experiments are being conducted. Cement mortar slab is intensely heated under sustained load. Interaction between heat and mass transfer and deformation will be analyzed.

NOTATIONS

Alphabets

A^*	pre-exponential factor	[1/s]
c	specific heat	[J/kg·K]
D_v	vapor diffusion coefficient	[m²/s]
D_w	water diffusion coefficient	[m²/s]
E^*	apparent activation energy	[J/kmol]
$f(...)$	function of ...	
H_{ave}	average height of composite floor	[mm]
H_{min}	minimum height of composite floor	[mm]
H_r	rib height of composite floor	[mm]
L_s	latent heat of desorption	[J/kg]
L_d	latent heat of decomposition	[J/kg]
P	pressure	[Pa]
R_{sorp}	rate of desorption	[kg/m³·s]
R_{dcmp}	rate of decomposition	[kg/m³·s]
t	time	[s]

t_{ave}	critical time for average temperature rise of unexposed surface	[min.]	Greek Letters			
t_{fr}	critical time for insulation performance defined by ISO 834	[min.]	γ	rate constant of desorption	[kg/m^3.s]
t_{max}	critical time for maximum temperature rise of unexposed surface	[min.]	ε	void fraction	[m^3/m^3]
T	absolute temperature	[K]	θ	temperature	[°C]
u	apparent velocity of gas	[m/s]	ρ	density	[kg/m^3]
V	volume fraction	[m^3/m^3]	λ	thermal conductivity	[W/m·K]
w	content of physically adsorbed water	[kg/kg]	κ_D	permeability	[m^2/Pa·s]
w_{eq}	equilibrium water content	[kg/kg]	Subscripts		
w_c	content of water of crystallization	[kg/kg]	a	air	
W_r	rib width of composite floor	[mm]	ag	aggregate	
			v	water vapor	
			g	gaseous mixture	
			0	dry concrete	

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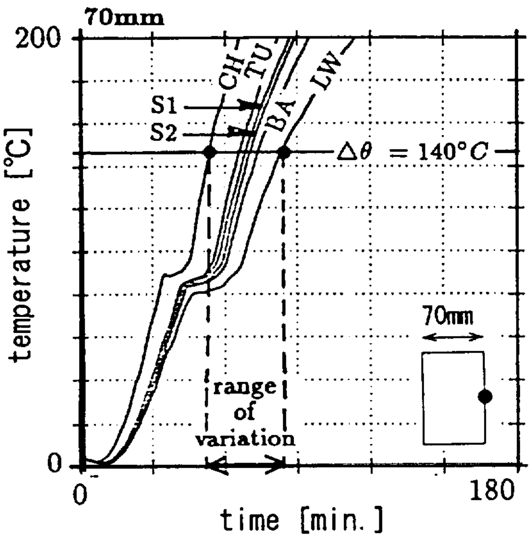


Figure. 6 calculated unexposed surface temperature for different kind of aggregate. ISO 834 standard fire. Volume fraction of coarse aggregate is 0.362. Initial water content is 3 % by weight.

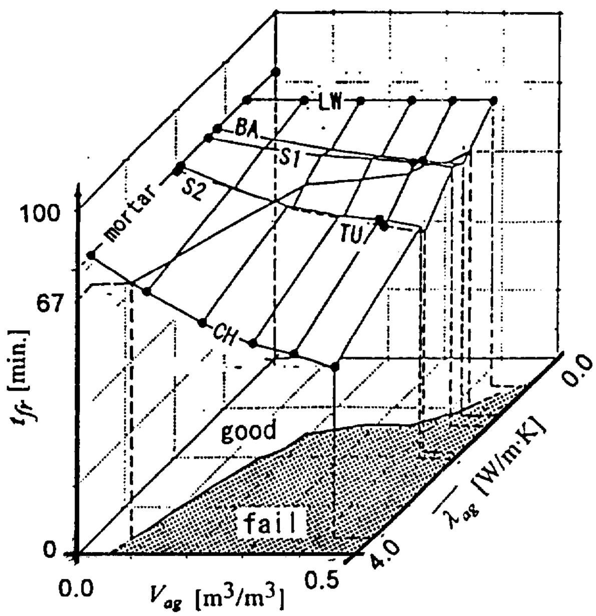
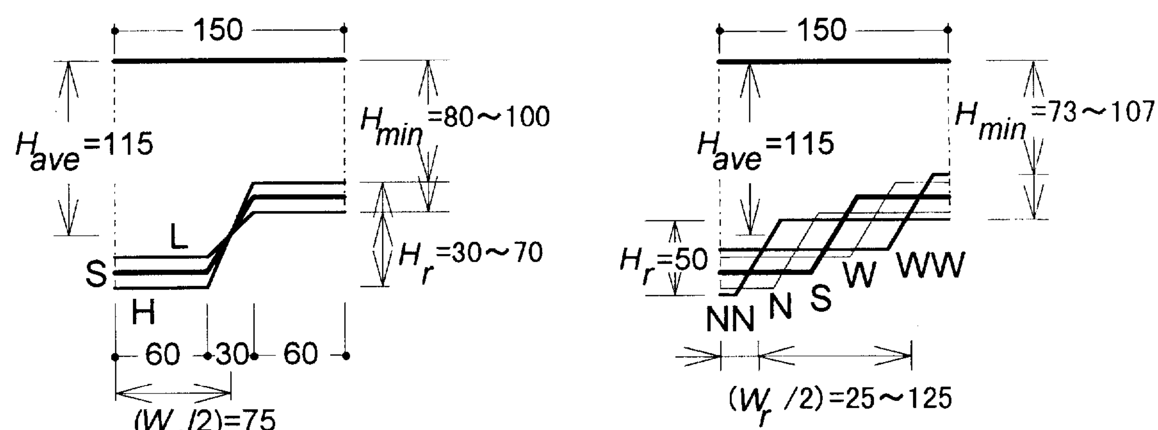


Figure 7 critical time for insulation performance as a function of volume fraction of coarse aggregate V_{ag} and temperature-averaged thermal conductivity of coarse aggregate $\overline{\lambda_{ag}}$. Initial water content is 3%.



series A: variations of rib height H_r series B: variations of rib width W_r

Figure 8 Variations of the cross sectional shapes (unit in mm)

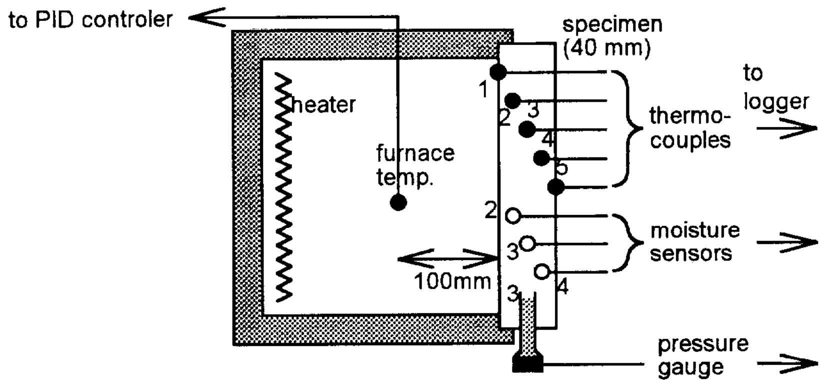


Figure 1 Schematics of experiment. A 40 mm thick specimen is equipped to a electric furnace. Temperature, water content and pore pressure are measured. (Drawing is not to scale.)

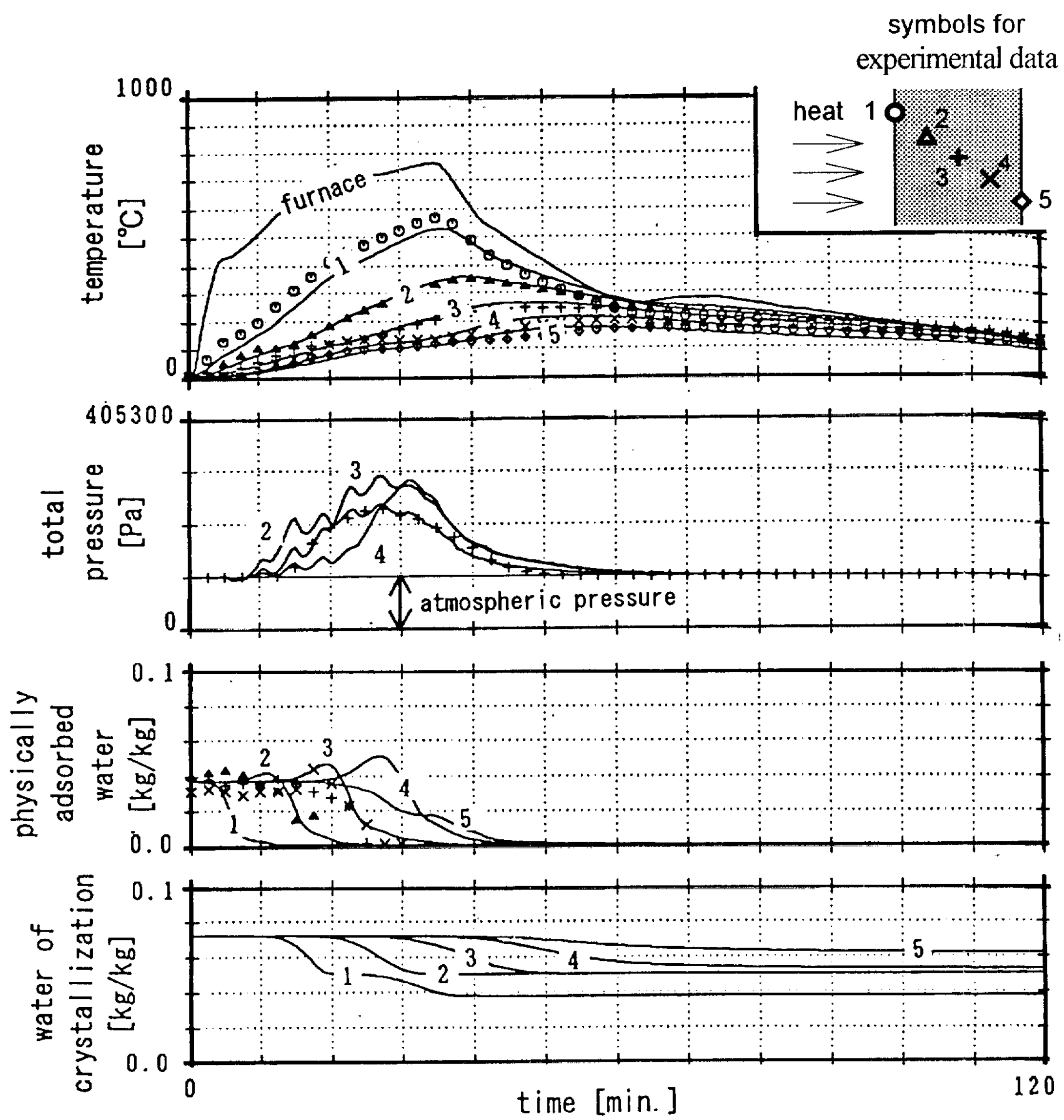


Figure 2 results of an experiment with 40 mm thick mortar wall. (symbols : measured data, solid lines : calculated results)

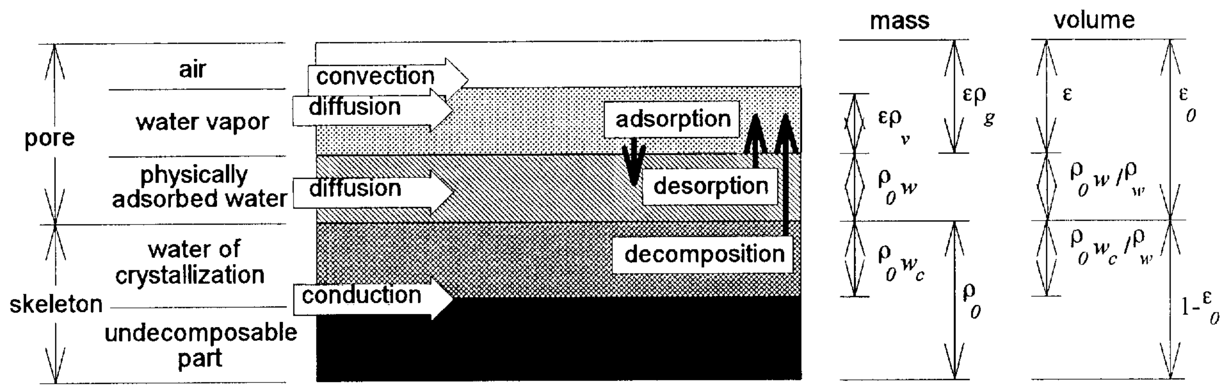


Figure 3 A model of heat and mass transfer in concrete during fire, considering the heat conduction, filtration of gaseous mixture, diffusion of water vapor and physically adsorbed water. These phenomena are coupled by sorption and decomposition

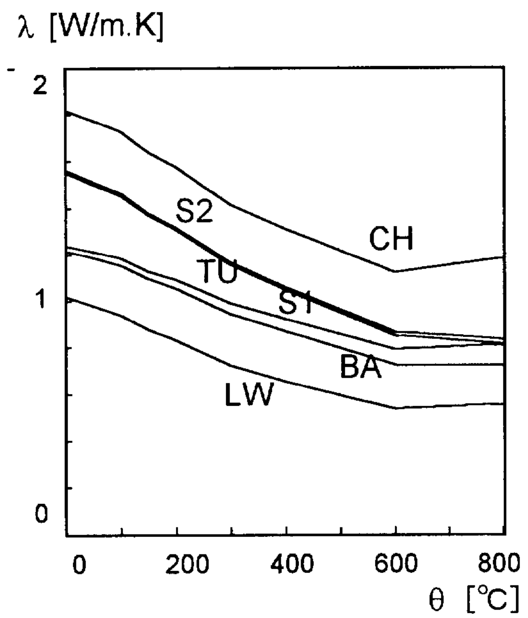


Figure 4 estimated thermal conductivity of six kinds of concrete where V_{ag}= 0.362, V_s= 0.299 and V_p= 0.155 (LW = light-weight aggregate, BA = basalt, S1, S2= sandstone, TU = tuff, CH = chart)

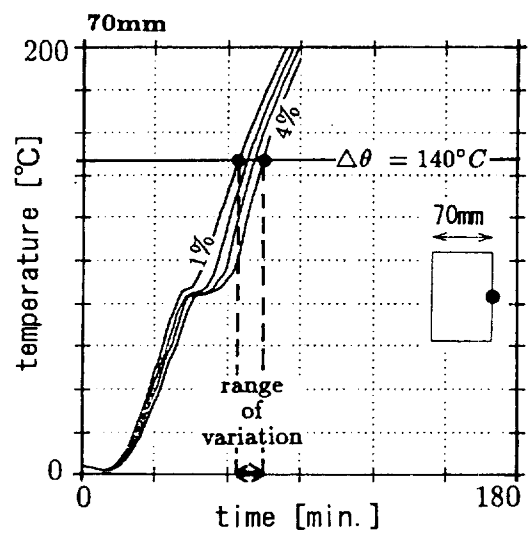


Figure. 5 calculated unexposed surface temperature rise under ISO fire for different initial water content in case of sandstone concrete (S1).

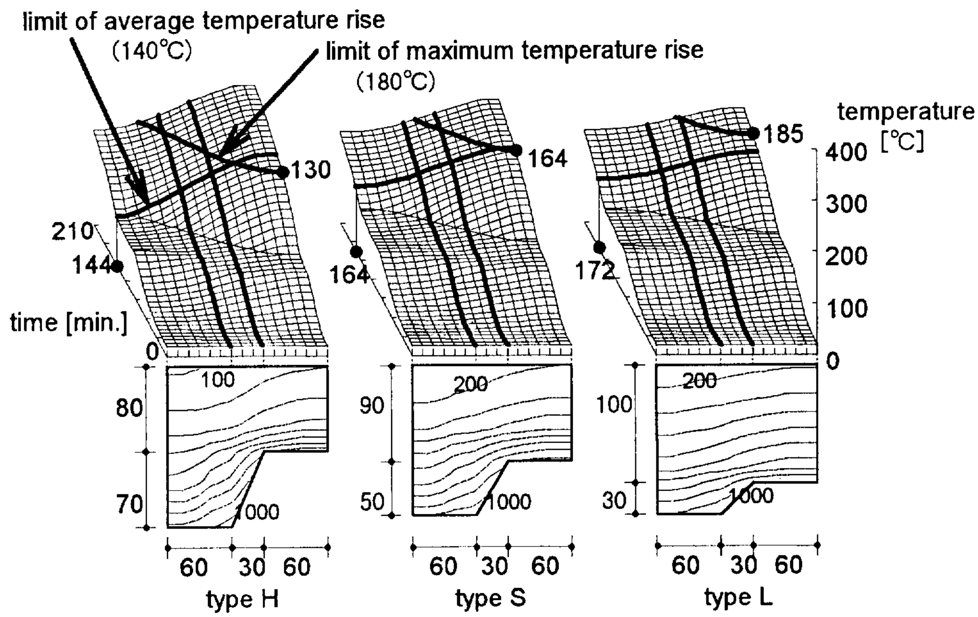


Figure 9 Change of temperature distribution of the unexposed surface with time (above) and isothermal lines at critical time for insulation criteria, t_{fr} (below)

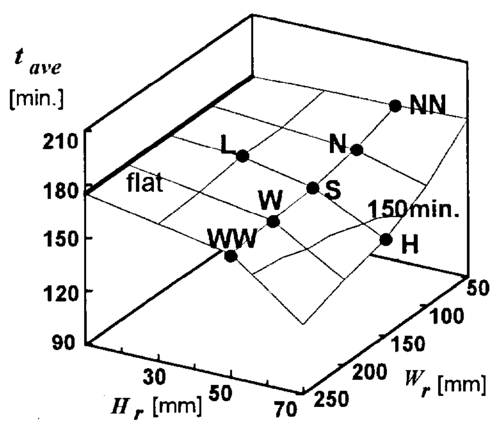


Figure 10 critical time for average temperature rise

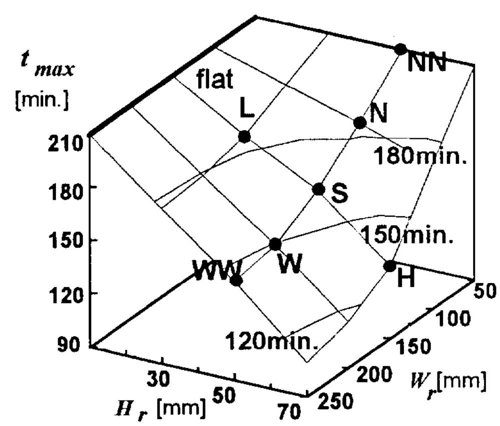


Figure 11 critical time for maximum temperature rise

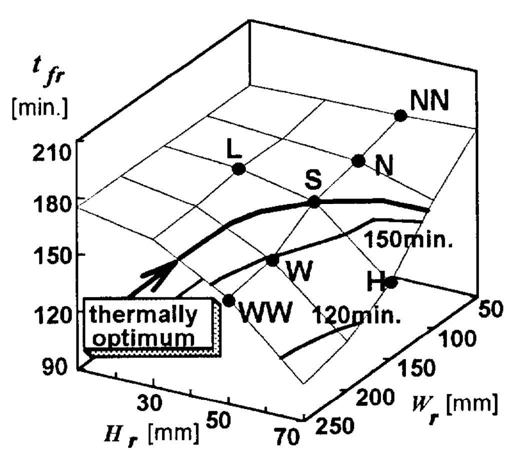


Figure 12 critical time for insulation performance as a function of rib height and width.

Discussion

Takashi Kashiwagi: I have two questions. First, did you include migration of the water in both directions. One is to the heated surface side, the other one is to a cooler side. On the cooler side, condensation is happening.

Kazunori Harada: Yes. This has been taken into consideration. We gradually heat from the left hand side and as we heat, steam will be generated. The steam would then migrate to both sides, and condensation occurs on the cooler side. That is the reason why such a peak is shown in the graph.

Takashi Kashiwagi: My second question is that there are many constants, such as a degradation constant to the absorption, and a dependency of the temperature of conductivity. Are these all measured directly for each sample?

Kazunori Harada: Yes. First of all, with respect to absorption coefficient, it is difficult to measure it, so we didn't. However, if we use a coefficient which is larger, then we found out that we could get good results. The reason is that the local absorption speed is faster than diffusion or migration, that is the reason why we can obtain good results.

Patrick Pagni: Your fire resistance of concrete structure is a very valuable and useful program. Do you think it would be possible to add the internal stress equations to model microcrack changes in properties and eventually, perhaps even spalling phenomena?

Kazunori Harada: Yes and we are doing experiments using small samples. The purpose of these is to find out the relationship between the heat moisture migration and the spalling of materials.