Thermo-Mechanistic Multi-Scale Modeling of Structural Concrete at High Temperature

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Abstract

A multi-scale model for significant characteristics of cementitious composite and structural concrete at high temperatures is presented and the experimental verification at micro, meso and macro-scales is conducted. Deterioration of cement hydrates, reduced stiffness of concrete composite and their rehydration are modeled at high temperature of 100 – 1000°C and integrated up to the multi-scale simulation platform. This framework enables us to reproduce some meso-scale chemo-physics such as progressive spalling of concrete cover and exposure of reinforcing bars. The temperature-dependent thermal characteristics of both aggregates and cement matrix are also considered to track the rising temperature inside RC members. The behavioral simulation of columns, slabs and beams, which are subjected to axial compression and out-of-plane flexural shear, is conducted to be ready for fire.

1. Introduction

The maintenance of urban infrastructures has become a serious issue, and their collapse risk assessment at fire is required as well as the degradation of serviceability under long-term actions. In the past decades, we experienced fire accidents which happened to urban infrastructures (Hoj et al. 1999; Hedden et al. 2010; JCI 2017). It is of importance to identify the structural limit states at accidents and to prepare for some restoring countermeasures.

The fire damage to structural concrete is associated with thermo-chemo-mechanistic events (e.g. Phan et al. 2001; Hertz 2003; Liu et al. 2018). There are innumerable experiences of concrete exposed to high temperature which focused on changed pore structures (e.g. Lin et al. 1996; Pavani et al. 2019), strength decay (e.g. Chan et al. 1999; Arioz 2007), vapor pressure and spalling (e.g. Kalifa 2000; Phan 2008), and properties of fiber concrete (e.g. Kalifa et al. 2001; Liu and Tan 2018). Previous researches (e.g. Gawin et al. 2006; Zhang and Davie 2013; Zhang et al. 2017; Gawin et al. 2019) challenged to predict and control spalling of concrete, which is one of significant deteriorations related to both thermal stresses and rising vapor pressure inside structures.

In these predictive models of concrete at high temperatures (e.g. Gawin et al. 2003; Capua and Mari 2007; Sun et al. 2019), the impact of dehydrated crystallized water on the overall structural safety was empirically taken into account in practice, but the heat deterioration and the following solidification processes at micro-scales of cementitious composites were not explicitly linked with behavioral structural simulation with cracks and yield of reinforcement. Thus, the safety assessment has been performed by setting up the scope of structural types and their applicability (Chen et al. 2009; Tan and Nguyen 2013; Monte and Felicetti 2017). Under this background, the authors tried to upgrade the multi-scale modeling which has been applied to structural concrete under ambient temperatures, and to extend its applicability up to 1000°C. The structural safety and risk assessment beyond the design conditions and/or after the fire is required for urban infra-management and resilience from unexpected events. To meet these challenges, the knowledge of constituent materials and structural mechanics is to be integrated. Thus, the multi-scale scheme is expected as a useful tool.

On the basis of multi-scale platform (Ishida and Maekawa 1999; Maekawa et al. 2003, 2008) of cementitious composites as illustrated in Fig. 1, deterioration of both calcium silicate hydrate (CSH) and calcium hydroxide (CH) solids accompanying varying micro-pores was recently challenged (Iwama et al. 2018, 2019). In this updated version of high temperature, the micro-pore structural modeling was extended in consideration of the released chemically bound water, and rehydration of CH crystals was integrated under cyclic fire and wetting. This modeling of microscopic porous solid was combined with meso-scale thermodynamics of moisture. To integrate the micro-scale structure of cement hydrates with meso-scale structure as shown in Fig. 1, concrete is assumed as two-phase (aggregates and cement hydrates) composite. Here, the hydration progress and formation
of solid with micro-pores are considered by the solidification model (Asamoto et al. 2006). The deformation and fracture of solid skeletons are integrated with the macroscopic constitutive models of cracked concrete (Maekawa et al. 2003) according to the original framework by Ishida and Maekawa (1999).

In this paper, as shown in Fig. 2, the authors attempt to further improve this multi-scale modeling for structural risk assessment of existing reinforced concrete (RC) and verify the model framework to clarify its applicability. In this scheme, dehydration of cement hydrates at high temperatures and the following micro-pore structure changes are taken into account. Here, the associated moisture transfer characteristics, which have
much to do with vapor pressure, are coherently amended time by time. At the same time, the decay of strength and stiffness of concrete are considered by using the smeared crack modeling (Maekawa et al. 2003).

One of the highlights is the post-failure simulation after progressive spalling which may have some impact to bond of reinforcement and subsequent shear failure. In this framework, if the arbitrary mixture of concrete and curing conditions are determined, the pore structure of the hardened cement and the strength and strain of the concrete are calculated, and it is possible to predict long-term deformation for various types of structures and load conditions.

The first stage of experimental verification and validation of the models is on the micro-scale by means of the thermo-gravimetry (TG) and the nano-indentation. The second stage is on meso-scale in reference to the stress-strain relation and the compressive strength of damaged concrete of 10⁻¹ m scale. Finally, the third stage is on 10⁻¹⁰ m scale of structural reinforced concrete which has much to do with heat conductivity, vapor pressure, fracture energy, deformation and failure mode.

2. Decomposition of cement hydrates at high temperature and rehydration

2.1 Dehydrated AFm, CSH and CH and rehydrated CH

After exposed to fire, three kinds of cement hydrates - Al₂O₃–Fe₂O₃–mono (AFm), calcium silicate hydrate (CSH) and calcium hydroxide (CH) - play a primary role on their mechanical change as shown in Fig. 3. The spalling of concrete has been fairly discussed by intensive researches (e.g. Kalifa 2000; Gawin et al. 2006; Zhang and Davie 2013; Zhang et al. 2017; Sun et al. 2019). The discussion on the chemically varying cement hydrates with deteriorated micro-pores is still going on and it is necessary especially for ultra-high strength concrete whose chemically bound water will be much released inside nano-scale pores. In this section, the chemo-physics-mechanistic change of cement hydrates is simply modeled so that we may install the dehydration and transient micro-pores into the macroscopic structural behaviors.

Although it is not easy to identify degradation of individual cement hydrate’s compound, the weight loss of mixed minerals can be precisely measured at rising temperature by the thermo-gravimetry (TG) curve of cement paste. Then, we have regression of each hydrate in reference to the pure crystal’s activity and inversely reproduce the macroscopic regression of crystal’s assembly for validation in regard to the TG curve of cement paste (Iwama et al. 2018). The overall micro porosity distribution is statically expressed (Maekawa et al. 2008) by

$$\varphi(r) = \varphi_{lr} + \varphi_{gl} \left[1 - \exp\left(-B_{gl} \cdot r\right)\right] + \varphi_{cp} \left[1 - \exp\left(-B_{cp} \cdot r\right)\right]$$

where, \(\varphi(r)\) is the pore size distribution to indicate the specific total pore volume whose size is less than the pore radius denoted by "r". \(\varphi_{lr}, \varphi_{gl}\) and \(\varphi_{cp}\) are respectively total porosity of interlayer, gel and capillary pores. \(B_{gl}\) and \(B_{cp}\) are the specific distribution parameters of gel and capillary pores, the inverse of which are geographical representative of pore sizes. These values are formulated with respect to the specific surface area, which empirically derives from the hydration degree of cement computed by the multi-mineral heat generation model (Maekawa et al. 2008).

Here, \(B_{gl}\) is kept unchanged when the decomposition of crystallized water proceeds and the gel grains disap-
pear. Consequently, the volume which was occupied by the lost gels tunes to the capillary spaces. Then, the progress in capillary pore porosity and its increasing pore size are computed by the original micro-pore structure formation model. These open spaces caused by high temperature can be filled up again when rehydration proceeds. Then, we have the total porosity as a simple summation of each pore which is varying with dehydration and rehydration of cement hydrates. The transient diffusion of vapor, penetration of liquid condensed water and the strength development of concrete (Otabe and Kishi 2005) are consistently calculated since these are directly connected to the varying micro-pore structures.

The degradation accompanying the dehydration of AFm and CSH proceeds at the lower temperature than that of CH. The crystallized water of AFm is released about at 100°C, and 200°C for the case of CSH. Thus, for the numerical modeling, we have,

\[
W_d(AFm) = W_{AFm} \left[ 1 - \left( \frac{100}{T_{\text{max}(AFm)}} \right)^{1.5} \right]
\]

(2)

\[
W_d(CSH) = W_{CSH} \left[ 1 - \left( \frac{200}{T_{\text{max}(CSH)}} \right)^{0.6} \right]
\]

(3)

where, \( W_d(AFm) \) and \( W_d(CSH) \) are the weight loss of crystallized water of AFm and CSH (kg/m³), \( W_{AFm} \) and \( W_{CSH} \) are crystallized water of AFm and CSH (kg/m³), \( T_{\text{max}(AFm)} \) and \( T_{\text{max}(CSH)} \) are the maximum temperature of the past ambient history to AFm (≥ 100°C) and CSH (≥ 200°C), respectively.

By adding the weight loss of crystallized water estimated by Eqs. (2) and (3), we have the absolute weight loss (kg/m³). Finally, we have the total amount of crystallized water by integrating the rate of the cement hydration (Maekawa et al. 2008) and the released crystal-

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**Fig. 3 Scheme of dehydration, rehydration linked with microstructure development.**
lized water (Fig. 3). According to the mass loss of each component, porosity of capillary pores changes as the cement hydrates are partially broken and the space occupied by the chemically bound water becomes vacant as shown in Fig. 3.

The porosity owing to released crystallized water is logically the same as the one calculated from the microstructure development model (Maekawa et al. 2008), since the hydrates whose crystallized water was lost are converted to capillary pores as illustrated in Fig. 3. The consistency of mass balance was analytically experimentally confirmed (Iwama et al. 2018).

It is well known that pure CH solid is degraded over 400°C (Vance et al. 2015). With the same manner as AFm and CSH, we assume a rapid drop-off of the bound water when temperature rises from 400°C to 450°C as,

\[ W_{d(CH)} = W_{CH} \left( \frac{T_{\text{max}} - 400}{50} \right) \]  

(4)

where, \( W_{d(CH)} \) is the weight loss of crystallized water of CH (kg/m³), \( W_{CH} \) is the weight of crystallized water of CH which is associated with the degree of cement hydration (kg/m³), and \( T_{\text{max}} \) is the past maximum temperature (400°C ≤ \( T_{\text{max}} \)). Over 450°C, we assume no further loss as,

\[ W_{d(CH)} = W_{CH} \]  

(5)

Then, the calculated porosity of capillary pores is idealized as stated above on AFm and CSH.

Generally speaking, it is not easy to repair or upgrade urban underground structures which are hardly replaceable after accidents. Thus, remaining serviceability of post-damaged structures shall be estimated for risk assessment. In a practical viewpoint, the rehydration of damaged concrete shall be incorporated in the predictive method (Poon et al. 2001; Alonso and Fernandez 2004; Park et al. 2015). Then, we consider thermodynamic water-sorption processes in line with the pore evolution and degradation as shown in Fig. 3. As calcium oxide (CaO) is highly reactive, we assume quick rehydration numerically without delay as,

\[ W_{r(CH)} = \int C_{\text{ak}} \cdot W_{d(CH)} \cdot W_{\text{free}} \cdot dt \]  

(6)

where, \( W_{r(CH)} \) is the weight of rehydrated crystallized water of CH (kg/m³), \( C_{\text{ak}} \) denotes the rate of the reaction, and \( W_{\text{free}} \) is the weight of free water to react with CaO. It should be noted again that the degraded AFm and CSH may not revive even though the vacant pore-spaces and un-hydrated cement would exist in the mixture. This is assumed to be an irrecoverable process.

2.2 Re-clinker process of dehydrated CSH

The re-clinker process (Lin et al. 1996; Alonso and Fernandez 2004) which is defined as the revival process of dehydrated CSH is included in the proposed model for estimating the possible revival of damaged structures.

We assume that a) revived CSH to the new clinker is those which had been already decomposed after release of the chemically bound water, b) re-clinker may begin over 800°C, and c) any damaged CSH revives to clinker when temperature is over 800°C with two hours or more. Here, mass conservation is satisfied so that the amount of revived CSH never exceed the amount of decomposed CSH. Then, this re-clinker event is described such that the hydration degree of the constituent mineral is “rewound” as,

\[ \frac{d\alpha}{dt} = -C_{\alpha}(W_{d(AFm)} + W_{d(CSH)}) \]  

(7)

where, \( \alpha \) is the hydration degree (0 ≤ \( \alpha \) ≤ 1), \( C_{\alpha} \) specifies the rate factor of the reaction and its inverse means the representative half time (day⁻¹).

3. Modeling of mechanical damage of concrete

3.1 Vapor pressure inside micro-pores before and after spalling

Major factors for fire damages of structural concrete are the thermal stress and the vapor pressure caused by vaporization of moisture inside micro-pores and the release of crystallized bound water (e.g. Kalifa 2000; Phan et al. 2001; Hertz 2003; Phan 2008; Liu et al. 2018). In this study, we understand that it is not the matter of choice. In fact, the multi-scale modeling may consider both factors automatically. Here, we have the total stresses of concrete solids and pore media as,

\[ \sigma_{ij} = \sigma'_{ij} + \delta p_{\text{vap}} \]  

(8)

where, \( \sigma_{ij} \) and \( \sigma'_{ij} \) are total stress tensors and the effective ones defined on the concrete skeleton (Pa), and \( p_{\text{vap}} \) denotes the vapor pressure developing inside both micro pores and crack gaps (Pa). We have the thermodynamic phase equilibrium of the idealized gas as,

\[ p_{\text{vap}} = P_{\text{sat}} \exp \left( \frac{PM_{w}}{RT} \right) \]  

(9)

where, \( P_{\text{sat}} \) is the saturated vapor pressure (Pa), \( P_{l} \) is the pore water pressure (Pa), \( M_{w} \) and \( p_{l} \) are molar volume of liquid water (kg/mol) and its density (kg/m³), \( R \) is gas constant (J/(mol·K)) and \( T \) is absolute temperature (K).

This proposed model computes the vapor pressure by considering vaporization of dehydrated crystallized water from the cement hydrates as well as condensed free water automatically, since the decomposition models of cement hydrate solids (Iwama et al. 2018, 2019) are applied, simultaneously. This is important especially for ultra-high strength concrete having less free condensed water but much chemically bound one. As a matter of fact, it is empirically known that the risk of spalling is generally great for high strength concrete (e.g. Kalifa 2000; Tan and Nguyen 2013; Li et al. 2019).
As shown in Fig. 4, based on the micro-pore structures formulated by Eq. (1), moisture transfer is driven by both pressure and temperature gradients. The moisture transfer between cement paste and aggregates is also considered, and according to moisture and temperature conditions, aggregates can shrink and expand in this platform (Maekawa et al. 2008). In this proposed model, the liquid and vapor conductivities calculated in the multi-scale platform (Ishida and Maekawa 1999) are utilized at high temperatures as,

\[
K_l = \left( \frac{\phi \rho_l}{250 \eta} \right)^2 \left[ \frac{M h}{\rho_l \rho_v \rho \phi} \right] \tag{10}
\]

\[
K_v = \left( \frac{\rho_c D_0}{2.5} \right) \left[ (1 - S) K(h) \right] \tag{11}
\]

where, \(K_l\) is liquid conductivity (kg/(Pa·m·s)), \(\phi\) is bulk porosity of concrete, \(\rho_l\) is density of liquid water (kg/m³), \(\eta\) is actual viscosity of a fluid under non-ideal conditions (Pa·s), \(r_c\) is pore radius at interface of liquid and vapor (m), \(r\) is pore radius (m), \(K_v\) is vapor conductivity (kg/(Pa·m·s)), \(\rho_v\) is density of vapor (kg/m³), \(D_0\) is vapor diffusivity in a free atmosphere, \(S\) is saturation of the porous media, \(K(h)\) is Knudsen effect, \(M\) is molecular weight of water (kg/mol), \(h\) is relative humidity in the micro-pore, \(R\) is gas constant (J/(mol·K)).

The thermodynamic equilibrium of liquid and vapor holds with both vaporization of heated liquid and the condensation of high pressurized and/or cooled vapor. The total stress is obtained by solving the equilibrium of solid and pore media together with the deformational compatibility and boundary conditions. If computed tensile stress exceeds its strength, cracks are assumed to occur normal to the principal stress direction. The larger the crack is open, the easily the moisture migrates along the crack surface (Bazant et al. 1987; Ishida and Maekawa 1999; Maekawa et al. 2008).

The vapor pressure drops when crack or large volume expansion happens. Then, we simply apply the equation of state of ideal gas by assuming that capillary pores and the space in between crack share the same pressure. When the pressure drop by volumetric change is less at the time of crack occurrence with less increment of strains, cracked concrete is thought to still remain as a part of the whole structure. But, when the sudden drop of vapor pressure and increase of volumetric change (strain) takes place simultaneously, the authors define that it is the spalling in consideration of the kinetics of observed behaviors. This event will be discussed in the following section as a highlight of this study.

### 3.2 Progressive spalling

On the occasion of fire, a long-lasting high temperature is concerned. Underground utility ducts made by concrete are requested to resist the high temperature and the soil pressure during the fire, too. Then, the progressive spalling of concrete after another should be numerically simulated for risk assessment. As shown in Fig. 5, a piece of concrete volume falls from the structural surface when spalling occurs. As the finite element scheme generally assume continuum fields, it has been hard to reproduce geometrically vanishing elements of progressive spalling. In order to overcome this issue, the spalled-off elements are computationally replaced with the equivalent boundary transfer elements to link the ambient states and the elements so that we may have a quick release of entropy and the mass of moisture after spalling. Then, within the scheme of finite element analysis, we have a smeared heat transfer which is im-

![Fig. 4 Two phase model for integrated solid and vapor in motion.](image-url)
planted into the solid finite element as,

\[ Q_{eq} = \frac{1}{V_{element}} \int k(T_{fire} - T) ds \]  

(12)

where, \( Q_{eq} \) is the equivalent heat generation rate, \( k \) is the heat transfer coefficient, \( V_{element} \) is the volume of the spall-off finite element, \( T_{fire} \) is the ambient temperature of fire, and \( A \) is the surface area exposed to the fire.

When an element would turn to the spall-off, fictitious specific heat generation rate is defined as such the volume-integrated heat rate over the element gets equal to the surface integrated rate of heat and mass transfer. Actually, enthalpy and the hygro-potential rates of spalling elements are set up as zero. Then, the inside element is computationally exposed to the environment of high temperature and the vapor pressure. As the crack strain of spall-off elements is so large (1%) as to bear almost zero stresses in compression and tension, these elements are mechanically killed without load-carrying capacity if the elements are forced to leave the original position as shown in Fig. 5. These exemplified procedures as stated above are computationally realized by the scheme of the finite element discretization and their computed results are shown in Fig. 6.

The upper part of Fig. 6 illustrates the principal strain profiles of concrete including progressive damaging (25% of water to cement ratio) by one dimensional analysis at rapid heating. Cracking of concrete occurs progressively into the core of members deeply and results in laminated failure, that is to say, spalling. The lower part of Fig. 6 shows the corresponding transition of relative humidity (RH) and the computed vapor pressure in micro-pores at each depth from the heating surface after 40, 100 and 180 minutes from the beginning of heating.

Let us pay attention to the transition of relative humidity inside micro-pores. The relative humidity decreases from the surface as time passes quickly, because the liquid water evaporates under high temperature and changes to vapor close to the surface and is quickly discharged to the outside air. In contrast, the internal rela-
tive humidity increases and finally comes up to 100%. This is condensation of the vapor into the liquid water. At the same time, the rising pressure of inside vapor becomes the driving force to push the moisture back inside the structure, and the further phase change is provoked. In computation, the highest vapor pressure develops at the depth of 30 mm (40 minutes from the beginning), 70 mm (100 minutes from the beginning) and 100 mm (180 minutes from the beginning), progressively.

The vapor pressure profile gradually moves and shifts into the deeper part far from the surface as shown in Fig. 6. Just before spalling, the spatial distribution of vapor pressure is rather smooth as shown in Fig. 5, but when the maximum pressure produces the stress which exceeds the tensile strength, cracking is computationally made in concrete domain close to the point of the maximum pressure. Just after cracking, the sudden pressure drop takes place owing to the volumetric expansion of damaged elements, and the vapor pressure is released from the elements of spalling. The zone of zero-pressure is regarded as the lost volume by spalling and the front of fire is computationally shifted inward. Reproduction of progressive spalling-off of concrete makes it possible to simulate the behavioral simulation of the whole structures.

Up to this section, the overall framework of multi-scale analysis, which was originally developed for normal temperature and whose applicability is to be extended to high temperature in this paper, was summarized as shown in Fig. 1 to Fig. 5. Then, in the following sections, the authors will present models of components to support the overall system, i.e., mechanical constitutive model and thermal characteristics of macro-scale.

### 3.3 Micro-elasticity of decomposed cement hydrates

The macroscopic stiffness of concrete element (10^{-1} - 0 m) is expressed as the integration of the intrinsic microscopic elasticity of each cement hydrate (10^{-6} - 3 m). As shown in Fig. 7, concrete is idealized as combination of

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**Fig. 6 Varying profiles of relative humidity and vapor pressure related to progressive spalling.**
the cement paste and aggregate and the solidification model (Asamoto et al. 2006) is applied for cement binders and concrete composites. The stiffness of cement paste is computed to be an integrated solidified cluster, which is produced one after another as the hydration progresses. The intrinsic stress and strain of each cluster are not unique since the birth time of cluster is different. Based on this approach, the averaged stiffness, the strain and the stress of cement paste are calculated as the total of each cluster.

There are some investigations of micro-stiffness of cement clinker and hydrates by means of the nano-indentation (Velez et al. 2001; Constantinides and Ulm 2004; Dejong 2005). The properties of each cluster are not common because solidified times of each cluster are different as stated before. However, the impact of high temperature at fire is thought to reach all clusters simultaneously. Then as shown in Fig. 7, the authors install the reduced intrinsic stiffness of cement hydrates on the multi-scale modeling. Here, it is assumed that the decreased stiffness of cement hydrates may attribute to the increased porosity of cement binders caused by dehydration as well as the strength. If all cement hydrates are decomposed, the shear stiffness will be almost lost although the volumetric stiffness may remain to some extent. Then, the reduction of the stiffness of cement hydrates is simply expressed by using the dehydration level as,

$$E_{\text{e,damage}} = E_e \times \exp(R_{\text{water}} - 1)^{1.5}$$ (13)

$$G_{\text{e,damage}} = G_e \times \exp(R_{\text{water}} - 1)^{3.0}$$ (14)

$$R_{\text{water}} = \frac{(W_{\text{AFm}} + W_{\text{CSH}}) - (W_{\text{AFm}} + W_{\text{AFm,CSH}})}{W_{\text{AFm}} + W_{\text{CSH}}}$$ (15)

where, $E_{\text{e,damage}}$ is reduced volumetric stiffness of each cluster (N/mm$^2$), $E_e$ is the intrinsic volumetric stiffness (N/mm$^2$) which was originally proposed under room temperature (Asamoto et al. 2006; Maekawa et al. 2008), $R_{\text{water}}$ is remaining crystallized water ratio based on Eqs. (2) and (3), $G_{\text{e,damage}}$ is reduced shear stiffness of each cluster (N/mm$^2$) and $G_e$ is the intrinsic shear stiffness (Asamoto et al. 2006; Maekawa et al. 2008).

The originally proposed $E_e$ and $G_e$ are made generalized as $E_{\text{e,damage}}$ and $G_{\text{e,damage}}$. The other parameters linked with the intrinsic stiffness of each cluster (see Fig. 7) are calculated automatically with regard to the generalized $E_{\text{e,damage}}$ and $G_{\text{e,damage}}$ in the multi-scale platform (Asamoto et al. 2006; Maekawa et al. 2008). Thus, the overall stiffness of cement hydrates at about 700°C results in approximately 1/4 of the one under normal temperature as verified in later section.

In the multi-scale platform, the smeared crack consti-
tutive model (Maekawa et al. 2003) is used after cracking. Here, the reduction of space-averaged compressive strength and the stiffness of concrete element containing cracks are taken into account (Vecchio and Collins 1986; Miyahara et al. 1987; Fukaura and Maekawa 2009) (see Fig. 8). This reduction is expressed in terms of the transverse strain normal to cracks. When we install the fire-damaged micro-structure (Fig. 3) and the solidification model (Fig. 7) for cement hydrates into this smeared crack model, we have the space-averaged stress-strain relation of the reduced compressive strength and the stiffness of concrete element as shown in Fig. 8.

This simple integration may not take into account micro-cracking around aggregates caused by high temperature history. As this meso-scale damage is not covered by the simple summation of the micro-scale modeling of Figs. 3 and 7, the integrated constitutive model (Fig. 8) shall indicate the stiffer stress-strain relation (e.g. Castillo and Durrani 1990; Miyamoto and Abe 2003; Kakae et al. 2017) of finite volume of concrete. In order to consider this meso-scale damage, we tentatively have,

\[
\varepsilon_{\text{peak},h} = \left( \frac{\varepsilon_{\text{peak}}}{R_{\text{water}}} \right)
\]

(16)

where, \(\varepsilon_{\text{peak},h}\) is the peak strain at high temperature, \(\varepsilon_{\text{peak}}\) is the peak strain of the smeared crack modeling (Maekawa et al. 2003) in which the reduced compressive strength and the stiffness of cement hydrates are solely used as discussed above. Here, let us consider the same lateral average strain of cracked concrete element at the room and the high temperature. The latter case may have the large continuum strain of concrete in between cracks owing to fire. Then, the strain component must be smaller than the former case. The impact of smaller crack strain and that of the larger continuum strain are opposite in terms of the compressive strength of cracked concrete element (Vecchio and Collins 1986; Miyahara et al. 1987; Fukaura and Maekawa 2009). Thus, the authors simply assume that these factors be cancelled. (see Fig. 8).

The derived macroscopic stress-strain relation at 700°C shows about 1/4 of the stiffness at room temperature, and it may compute the rehydrated cement concrete (Poon et al. 2001; Alonso and Fernandez 2004; Park et al. 2015) by post-fire curing where new hydration clusters develop. The experimental validation of these is presented in later section.

4. Modeling of thermal property change of concrete at high temperature

4.1 Heat capacity and conductivity

The heat capacity and conductivity of cement concrete composites are modeled as integrated intrinsic characteristics of each constituent component (see Fig. 9), that is to say, cement hydrates, un-hydrated cementitious powders, aggregates and condensed water. Then, these macroscopic thermal characteristics are not constant but are varying in accordance with the mixture of concrete, the hydration degree and drying states (Maekawa et al. 2008). In this scheme as shown in Fig 9, the authors newly installed the varying thermal characteristics of aggregates under high temperature in reference to the temperature dependency of rocks (Shimooka et al. 1983) and concrete composites (Schneider 1982) as,

\[
c_{\text{agg},h} = c_{\text{agg}} \left\{ 1 + \frac{0.5}{3} (0.01 T - 1) \right\}
\]

(17)

\[
k_{\text{agg},h} = k_{\text{agg}} \left\{ 1 - \frac{0.2}{3} (0.01 T - 1) \right\}
\]

(18)

where, \(c_{\text{agg},h}\) is specific heat of aggregate at high temperature (J/(kg·K)), \(c_{\text{agg}}\) is specific heat of aggregate less than 100°C (J/(kg·K)), \(k_{\text{agg},h}\) is heat conductivity of aggregate at high temperature (W/(m·K)), \(k_{\text{agg}}\) is heat conductivity of aggregate less than 100°C (W/(m·K)) and \(T\) is temperature history in the element (100°C ≤ \(T\) ≤ 400°C). In the previous research by Shimooka et al. (1983), increased \(c_{\text{agg},h}\) and decayed \(k_{\text{agg},h}\) tend to con-

![Fig. 8 The meso-stiffness of concrete with cracks (the tentative expansion to high temperatures).](image-url)
verge at more than 400°C. Thus, $c_{agg,A}$ and $k_{agg,h}$ are assumed to be kept constant when the temperature is beyond 400°C in this proposed model.

$$c_{agg,A} = 1.5 \cdot c_{agg}$$

$$k_{agg,h} = 0.8 \cdot k_{agg}$$

(19) (20)

4.2 Heat conductivity of cracked concrete

As discussed in the previous section, the heat conductivity of concrete is declined as temperature rises (Schneider 1982). Furthermore, the macroscopic conductivity is reduced after cracking, since air of low conductivity in between cracks works like thermal isolator. In order to build the macroscopic thermal conductivity with cracking, we combine the intrinsic model as shown in Fig. 9 with the meso-scale crack space occupied by air as shown in Fig. 10. As the heat flux develops through the concrete continuum and the discrete crack gap, we have,

$$\frac{1}{K_{ave}(x,y,z)} = \frac{1}{K_C} + \frac{\epsilon_{max(x,y,z)}^2}{K_{air}}$$

(21)

$$K_{air} = 0.0011T + 0.513$$

(22)

where, $K_{ave(x,y,z)}$ is average heat conductivity of cracked element for each direction (W/(m·K)), $K_C$ is heat conductivity of non-cracked concrete (W/(m·K)), $K_{air}$ is heat conductivity of air (W/(m·K)) (NAOJ 2018), $\epsilon_{max(x,y,z)}$ is the maximum effective strain of each direction experienced in the past. As shown in Fig. 10, the heat conductivity of concrete is uniform before cracking. After cracking, the heat conductivity of concrete continuum is combined with the one of air sandwiched by

$C_{con} = W_C \sum c_i \times W_i$

$K_A = \sum k_i \times V_i$

$W_C$: Weight of concrete  
$C_i$: Specific heat capacity of each components  
$k_i$: Heat conductivity of each components  
$W_i$: Volume ratio of each components in concrete

$C_{con}$: Heat capacity of concrete  
$W_i$: Weight of each components in concrete  
$K_A$: Heat conductivity of concrete  
$K_C$: Heat conductivity of non-cracked concrete  
$K_{air}$: Heat conductivity of air  
$\epsilon_{max(x,y,z)}$: Maximum effective strain of each direction

**Fig. 9 Heat characteristics change of aggregates: heat capacity and heat conductivity.**
crack planes. Then, the heat conductivity of cracked concrete is reduced, and expressed by $K_{\text{ave}(x,y,z)}$ in this model.

5. Experimental validation

5.1 Micro-scale validation - weight loss (TG) and stiffness (nano-indentation) -

The weight loss of crystallized water of AFm, CSH and CH is calculated by Eqs. (2), (3), (4) and (5) and then, the volumetric change of the gel in the hydrates is computed by simultaneously solving these equations in the microstructure development model of the multi-scale hygro-chemo-physics. Accordingly, the capillary pore porosity increases because the hydrates are broken as shown in Fig. 3. Then, the stiffness is reduced by the dehydration of cement hydrates as shown in Fig. 7 and Fig. 8.

The weight loss of cement paste (water cement ratio = 40%) of both experiment (Iwama et al. 2018) and analysis is shown in the left side of Fig. 11, where both weight losses fairly match, but there exists some difference around 100°C to 200°C. It might attribute to simplicity for formulae and of the dehydration of AFm and CSH and/or a probable variation of mineral compounds in cement used. More detail investigation is thought to be made.

The comparison of stiffness reduction of CSH cluster with the result of nano-indentation experiment (Dejong 2005) is shown in the right side of Fig. 11. Since simple assumption is attempted in this proposed model, the stiffness of CSH is underestimated from 200°C to 400°C. However, it is considered that the stiffness reduction of CSH is appropriately evaluated above 500°C where the damage of concrete structures will begin to develop significantly. Also, according to the previous research (Dejong 2005), the experiment of nano-indentation at high temperatures has a large variation. Therefore, this proposed model, which can evaluate the stiffness reduction on the safety side, is appropriate in terms of risk assessment in the event of fire.

5.2 Meso-scale validation - stress-strain relation at high temperature -

The proposed model for the reduction of concrete stiffness at high temperature is validated by using the previous experimental results (Abe et al. 1999). The reduction of stiffness is confirmed by the compressive stress-strain relationship at high temperature. Therefore, as shown in Fig. 12, the specimens are slowly heated and compressed after the temperature of specimen becoming uniform.

The compressive test at high temperature was performed on φ50 × 100 mm concrete cylinders. There were three mix proportions of 32%, 41% and 58% water to cement ratio (W/C) as shown in Fig. 12. The maximum size of course aggregates is 15 mm. The specimens were demolded after 24 hours of casting and wet curing was executed. Then, they were kept in a thermostatic chamber under the controlled temperature of 20°C.
Afterwards, the specimens were heated in an electric furnace and kept under constant temperature for 1.5 hours. As shown in Fig. 12, the heating rate were 0.8°C/min till 100°C, and 1.25°C/min over 100°C.

Figure 12 shows the averaged stress-strain relation of the specimen at 300°C when the porosity of cement hydrates begins to increase due to dehydration of CSH and the case of 700°C when the structural deformation becomes large due to decreased strength and increase in temperature of reinforcing bars. The simulation may fairly correspond to the experimental facts.

5.3 Meso-scale validation - compressive strength by post-fire-curing -

The built model was also experimentally validated with the averaged compressive strength of 10⁻³ m scale test pieces after heating (Poon et al. 2001). It must be noted that the compressive strength simulation is not for validation of the micro-meso scale modeling of cement hydrates but for the macroscopic behavioral validation where stress and crack damage is not uniform, because the fire damage develops non-uniformly. Then, the volume of the test specimen consists of a group of finite elements and the compression test is treated as the structural behaviors as shown in Fig. 13.

The compression test of material was conducted by 100mm concrete cubes. Here, we have two mixtures; 30% and 50% water to cement ratio (W/C). The specimens were demolded after 24 hours of casting and soaked in water of 20°C. After 28 days of this curing, the specimens were stored into a chamber where temperature and relative humidity were kept 20°C and 75% relative humidity in reference to the annual averaged ambient condition of Hong Kong (Poon et al. 2001). At the age of 60 days, we heated the specimens in an electric furnace up to 600°C and 800°C and sustained in one hour. The heating and cooling rates were 2.5°C/min as constant. The specimens were under natural cooling to 20°C after the completion of heating cycle. Then, the specimens were kept in 20°C for 12 hours.

As shown in Fig. 13, the compression tests were executed before (Before Fire) and after fire (After Fire) at 7, 28 and 56 days of post-fire-curing, respectively. Figure 13 shows the comparison of the experiment and the simulation. We can see the decreased compressive strength as well as the recovery after post-fire-curing. Thus, the modeling is functional qualitatively and quantitatively.

5.4 Macro-scale validation - vapor pressure of concrete wall -

Previous researches (e.g. Kalifa 2000; Gawin et al. 2006; Zhang and Davie 2013; Zhang et al. 2017; Sun et al. 2019) try to predict the spalling of concrete cover which is one of significant factors of structural deterioration at fire in consideration of both thermal stresses and rising vapor pressure inside concrete body. Thus, the vapor pressure is an indispensable factor to be focused on. The
Fig. 13 Comparison of compressive strength with experiment about post-fire-curing by cube model.

Fig. 14 Comparison of temperature and vapor pressure with the experiment by the concrete wall.
validation is conducted by using experimental results (Lee 2016) of the plane concrete wall which is not restrained by reinforcing bars.

As shown in Fig. 14, the center face of the wall is heated by the specified ISO834 heating curve in 30 minutes long (Lee 2016). The temperature and vapor pressure of the points I and II as shown in Fig. 14 at 25mm, 50mm and 75mm from the heated surface is compared with the experiment. Concrete is high strength whose water to binder ratio is 20%. It was cured in 28 days by seal curing.

There are two cases of heating (e.g. Kodur et al. 2004; Haddad et al. 2011; Felicetti et al. 2017; Ozawa et al. 2018). One uses the electric furnace (Haddad et al. 2011; Felicetti et al. 2017) and heats the specimens mainly by air. The other uses direct fire (Kodur et al. 2004; Ozawa et al. 2018). In the former case, air in the furnace is heated followed by heating concrete surface. Then, the normal heat transfer coefficient which is used in thermal stress analysis (JCI 2016) may be utilized. But in the latter case, the heated air strongly circulates in the furnace and the radiation from the fire directly heats the concrete surface. Then, the apparent heat transfer coefficient gets large. In this validation, the heat transfer of the direct fire with air circulation is set up as 116 W/m²K, which is 10 times the normal heat transfer coefficient under no wind (JCI 2016).

As shown in Fig. 14, the simulation results are close to the experiments as a whole. In particular, at 50 mm and 75 mm, both the temperature and water vapor pressure are completely simulated although there is a slight discrepancy at 25mm from the surface. In terms of the temperature at point II, a rapid temperature rise at around 25 minutes appears in the experiments, but it does not in the simulation. Seeing the vapor pressure of the same depth at point II, the predicted vapor pressure is larger than that of the experiment. It indicates that the vapor in simulation is harder to diffuse than the case of experiment, and temperature can’t rise rapidly because of remaining vapor in the micro-pores. Further detailed validation is required in consideration of the reproducibility of tests as well.

The vapor pressure at the explosive spalling is of predictive difficulty and lots of efforts exist in previous researches (e.g. Kalifa 2000; Gawin et al. 2006; Zhang and Davie 2013; Zhang et al. 2017; Sun et al. 2019). The vapor pressure varies greatly depending on the measurement position, and at the measurement point I of Fig. 14, the vapor pressure is measured as 0.3 MPa at 20 minutes. It is close to the simulation result. The verification of vapor pressure should be conducted by multiple heating experiments.

5.5 Macro-scale validation - heat conduction of RC column with spalling -

The non-uniform profile of temperature at fire is of great importance for macro-scale validation, since the vapor pressure and the microstructure are greatly influenced by location. In the experiment of member level, the large temperature gradient can occur between the heated surface and inside of concrete, and the effects of heat conductivity, heat capacity and cracking conditions are to be considered as well. As shown in Fig. 15, all sides of a RC column member (Umemoto and Kikuta 2006) were heated by the specified ISO834 heating curve. The temperature history of 20 mm, 50 mm, 80 mm and 120 mm from the heated surface is compared with the experimental results. The spalling is thought to occur near the measurement point at 20 mm inside from the heated surface, because the temperature drastically rises. Here, it must be noted that the temperature at 20 mm from the surface exactly matches the fire temperature. Then, it means that the measurement at 20 mm does not indicate the temperature of remaining concrete but just the one of heated air, because of the direct exposure of the thermal-couple due to the complete loss of cover concrete. Accordingly, fire heating may reach the adjacent point of 50 mm but does not affect the deeper places as the simulation without spalling computes. As explained in Chapter 4, when the temperature rises and the concrete is damaged with air spaces, heat is less likely to be transferred. Even if the temperature rises rapidly due to damage near the heating surface, this effect is gradually alleviated, and the temperature rise inside the concrete may be less accelerated.

Here, we have two types of computation. One is such that the impact of spalling-off of cover concrete on the heat conduction is not considered (Simulation-1), and the other takes into account the heat release because of the loss of concrete cover (Simulation-2 as discussed in Section 3.2). If we do not consider the lost heat barrier of cover concrete, there is no simulation of jumping temperature. But, by considering the loss of concrete cover by spalling as formulated in Section 3.2, the sudden rise of temperature can be computed as shown in Fig. 15. After the spalling, temperature of the remaining concrete approaches the one of heated air.

Here, it must be noted that the measurement at 20mm corresponds to the heated air as stated above but the computation at 20 mm is the one of concrete. Therefore, the measured and computed data at the 20 mm depth cannot be compared scientifically, but are helpful for overall validation. The jumping temperature caused by spalling is computationally verified although the computed time of spalling differs from the reality. The accuracy of timing of spalling is the issue of continuous development.

5.6 Macro-scale validation - RC column under compression at fire -

As the third stage of multi-scale validation, the simulation results of deformation of RC column member is compared with the experimental results (Matsudo et al. 2002; Yoshino et al. 2002). The behavioral simulations of RC column include the heat conductivity from the
surface, strength decay due to dehydration of cement hydrates, the damage of cover concrete and the following release of vapor pressure and the reduced member capacity owing to meso and macro-scale cracks.

As shown in Fig. 16, all side faces of the central part of the RC column are heated by the specified ISO834 heating curve. The cross section of the column is 400 × 400 mm and the length is 3600 mm. The longitudinal reinforcement ratio is 2.2%, the hoop reinforcement ratio is 0.8% and the thickness of concrete cover is 40 mm. In this validation, the RC column is made of 35% water to binder ratio subjected to 30% axial compression of its static capacity (Matsudo et al. 2002; Yoshino et al. 2002). The mechanical characteristics of reinforcement are defined in the analysis as the reference does (Matsudo et al. 2002; Yoshino et al. 2002). The RC column and the test specimens were cured for 8 months.

The temperature dependency of reinforcing bars (CEC 1990; Ichise and Kawabe 2003; JSCE 2004; AIJ 2009) is integrated in the proposed model.

The left side of Fig. 16 shows a comparison of the computed and the tested temperature values at each depth (40 mm, 90 mm and 200 mm) from the heating surface. By setting the heat transfer coefficient on the concrete surface to 43.5 W/m²K, it can be seen that the temperature inside the column is properly predicted based on the heat conduction model as discussed in Section 5.5. As the computed temperature approximately matches the experiment, appropriate validation can be performed in terms of the models for the vapor pressure and the progressive spalling.

As the simulation may capture the behavioral trends of the column at fire, the column’s elongation of computation is about 1 mm larger than that of experiment. This
Fig. 16 Comparison of deformation behavior with the experimental results by the RC column.

Fig. 17 Comparison of deformation behavior with the experimental results by the RC slab.

Bond between reinforcements and concrete is lost by fire damage
point of accuracy is to be continuously investigated in future. At this moment, we consider the following points to be discussed on 1) inelastic creep at high temperature, 2) release of vapor pressure through the interface transition zones around aggregates, 3) non-uniform localized paths of vapor.

5.7 Macro-scale validation - RC slab in flexure -
As flat thin slabs under sustained loads have been frequently exposed to fire (Iwama et al. 2019) as a part of tunnels and underground ducts, RC slab at high temperature is focused on (Nishimura and Uehara 2008). In this case, the heat flux primarily flows in the thickness direction of the slab. Actually, these members are hard to be repaired nor replaced after fire.

As shown in Fig. 17, the bottom face (the tension side) of RC slab is heated by the specified ISO834 heating curve. Its span length is 3390 mm and the thickness is 150 mm. The longitudinal reinforcing bars of D13@200mm are arranged and the transverse is D10@200mm. The concrete cover is 20 mm at the bottom surface. The targeted RC slab has 75% water to binder ratio, and the flexural moment is sustained at 0.60 and 0.75 of its bending capacity, and defined properties of reinforcement are those of Nishimura and Uehara’s experiment (2008). The temperature dependency of reinforcing bars is taken into account (Section 5.6).

In order to clarify the damages related to spalling of cover concrete, the computed normal strain tensors in the direction of the member depth are shown together with the transient displacement of the slab at the span center as shown in Fig. 17. We can see the progressive penetration of damages related to spalling from the surface, and the gradual increase in the deflection as well. The general behaviors at fire are properly reproduced by the multi-scale modeling. In more detail, the flexural final failure occurs earlier than the simulation. Unlike the case of column heating, tensile reinforcing bars are exposed closely to fire and the high temperature rapidly reaches the flexural compression side of the member. Thus, we consider that the compression creep at high temperature could be improved to be greater than the current constitutive model. This is to be discussed in future ahead.

5.8 Macro-scale validation - RC beam in flexure -
The validation with regard to RC beams is meaningful in view of the 3D heat flux unlike the case of flat slabs. The stress state becomes more non-uniform and it creates complex damage to concrete. Here, the beam test by Dwaikat and Kodur (2009) is investigated. As the beam flexure is primarily governed by reinforcing bars and bond, the temperature dependence of reinforcing bars (CEC 1990; Ichise and Kawabe 2003; JSCE 2004; AIJ 2009) is taken into account (Section 5.6).

As shown in Fig. 18, the cross section of RC beam is 406 × 254 mm and 3960 mm long. The heated beam length is 2440 mm and the heating path curve follows the specification by ASTM E119. The RC beam was tested under two-point loads, each of which was placed at about 1.4 m from the end supports. Each of the two-point loads was 50 kN, which is equal to 55% capacity of the beam. The beam has three φ19 mm bars as tensile reinforcement and two φ13 mm bars as the compressive one. The shear reinforcement of the beam is φ6 mm stirrups with a spacing of 150 mm (Dwaikat and Kodur 2009). The yield strengths are 420 MPa for main reinforcing bars and 280 MPa for stirrups. The materials used are cement (513 kg/m³), silica fume (43 kg/m³), coarse aggregate (1018 kg/m³), fine aggregate (684 kg/m³), water (130 kg/m³) and water reducing agent (15 kg/m³). The compressive strength of concrete at the testing is 106 MPa.

As shown in the left side of Fig. 18, the calculated temperatures are compared with the experimental results at each depth (54, 91 and 203 mm) from the bottom surface. Having the heat transfer coefficient on the concrete surface of 29.0 W/m²K, temperatures are appropriately simulated up to about 140 minutes. Afterwards, the spalling takes place in simulation and the temperature rise is accelerated owing to the loss of concrete cover, and the beam deflection proceeds rapidly after spalling which causes longitudinal cracking along the main reinforcement and following bond loss between concrete and reinforcement.

The bond interaction is numerically taken into account with regard to the tension stiffening modeling as shown in Fig. 19 (Maekawa et al. 2003). The tension stiffening model built in the multi-scale platform considers the intersecting angle of cracks and reinforcements. When the dispersed crack planes are made parallel to the reinforcement, the strain profile of reinforcing bars is forced to be rather uniform, and the bond mechanism is lost and just the tension softening of plain concrete remains. Then, the mechanistic impact of fire on bond characteristics is automatically taken into the nonlinear analysis. The transient deflection is fairly consistent with the reality.

As mentioned previously, the prediction of spalling is still under investigation (e.g. Kalifa 2000; Gawin et al. 2006; Zhang and Davie 2013; Zhang et al. 2017; Sun et al. 2019), and more detailed investigation is required in this platform as well.

6. Conclusions

It is challenged to extend the applicability of the multi-scale modeling of physical-chemistry and mechanics at high temperature and the following conclusions are obtained.

1. Dehydration model of hardened cement crystals, the progressive spalling of concrete nearby structural surfaces and revival of dehydrated damaged CH are integrated in line with the multi-scale modeling and its functionality is verified qualitatively and partly validated quantitatively.
Fig. 18 Comparison of deformation behavior with the experimental results by the RC beam.

Fig. 19 The tension stiffening/softening model considering the intersecting angle of cracks and reinforcements (Maekawa et al. 2003).
II. The reduced stiffness of both cement hydrates and cracked concrete composite is built in the proposed multi-scale scheme. The space-averaged compressive stress-strain relation of damaged concrete by fire is experimentally validated.

III. The temperature-dependent thermal characteristics of aggregates and cracked concrete are derived from the micro and meso-scale modeling and integrated. The experimental validation is conducted with the rising temperature inside RC column members at rapid heating, and the general trends can be captured.

IV. The coupled thermo-mechanistic analysis can be executed stably under high temperature and the computed deformation of RC columns under compression is compared with the deformation from experiments. The life for collapse of RC columns under combined fire and axial compression is estimated to be a little shorter than the experimental reality. Although the safer estimate is given in practice, further investigation is needed in line with the quantitative assessment.

V. The experimental validation of macro-scale is extended to RC slabs and beams subjected to combined flexure and fire. The simulation can grasp the time-dependent deflection with reasonable accuracy.

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References
Abe, T., Furumura, F., Tomatsuri, K., Kuroha, K. and Kokubo, I. (1999). “Mechanical properties of high strength concrete at high temperatures.” AJJ Journal of Structural and Construction Engineering, 64(515), 163-168. (in Japanese)

AII, (2009). “Guide book for fire-resistive performance of structural materials.” Architectural Institute of Japan, Japan: Maruzen Publishing. (in Japanese)

Alonso, C. and Fernandez, L., (2004). “Dehydration and rehydration processes of cement paste exposed to high temperature environments.” Journal of Materials Science, 39(9), 3015-3024.

Arioz, O., (2007). “Effects of elevated temperatures on properties of concrete.” Fire Safety Journal, 42(8), 516-522.

Asamoto, S., Ishida, T. and Maekawa, K., (2006). “Time-dependent constitutive model of solidifying concrete based on thermodynamic state of moisture in fine pores.” Journal of Advanced Concrete Technology, 4(2), 301-323.

Bazant, Z. P., Sener, S. and Kim, J. K., (1987). “Effect of cracking on drying permeability and diffusivity of concrete.” ACI materials journal, 84(5), 351-357.

Capua, D. and Mari, A. R., (2007). “Nonlinear analysis of reinforced concrete cross-sections exposed to fire.” Fire Safety Journal, 42(2), 139-149.

Castillo, C. and Durrani, A. J., (1990). “Effect of transient high temperature on high-strength concrete.” ACI Materials Journal, 87(1), 47-53.

CEC, (1990). “Eurocode 4, Design of composite structures Part10, Structural fire design.” Europe: Commission of European Communities.

Chan, Y. N., Peng, G. F. and Anson, M., (1999). “Residual strength and pore structure of high-strength concrete and normal strength concrete after exposure to high temperatures.” Cement and Concrete Composites, 21(1), 23-27.

Chen, Y. H., Chang, Y. F., Yao, G. C. and Sheu, M. S., (2009). “Experimental research on post-fire behavior of reinforced concrete columns.” Fire Safety Journal, 44(5), 741-748.

Constantinides, G. and Ulm, F. J., (2004). “The effect of two types of C-S-H on the elasticity of cement-based materials: Results from nanoindentation and micromechanical modeling.” Cement and Concrete Research, 34(1), 67-80.

Dejong, M. J., (2005). “Sources of high temperature degradation of cement-based materials: Nanoindentation and Microporoelastic Analysis.” Thesis (PhD), Massachusetts Institute of Technology.

Dwaikat, M. B. and Kodur, V. K. R., (2009). “Response of restrained concrete beams under design fire exposure.” Journal of Structural Engineering, 135(11), 1408-1417.

Felicetti, R., Monte, F. L. and Pimienta, P., (2017). “A new test method to study the influence of pore pressure on fracture behavior of concrete during heating.” Cement and Concrete Research, 94, 13-23.

Fukuura, N. and Maekawa, K. (2009). “Three-dimensional identification of active crack plane and enhanced space-averaged constitutive modeling.” Journal of JSCE(E), 65(1), 118-137.

Gawin, D., Pesavento, F. and Schrefler, B. A., (2003). “Modelling of hygro-thermal behaviour of concrete at high temperature with thermo-chemical and mechanical material degradation.” Computer Methods in Applied Mechanics and Engineering, 192(13-14), 1731-1771.

Gawin, D., Pesavento, F. and Schrefler, B. A., (2006). “Towards prediction of the thermal spalling risk through a multi-phase porous media model of concrete.” Computer Methods in Applied Mechanics and Engineering, 195(41-43), 5707-5729.

Gawin, D., Pesavento, F. and Castells, A. G., (2019). “On reliable predicting risk and nature of thermal spalling in heated concrete.” Archives of Civil and Mechanical Engineering, 18(4), 1219-1227.

Haddad, R. H., Al-Mekhla, N. and Ashteyat, A. M., (2011). “Repair of heat-damaged reinforced concrete slabs using fibrous composite materials.” Construction and Building Materials, 25(3), 1213-1221.

Hedden, J., Quagliata, M. and Wandzilak, T., (2010). “Emergency renovation, Steel bridge news.” In: Modern Steel Construction. America: American Institute of
Steel Construction, 36-39.
Hertz, K. D., (2003). “Limits of spalling of fire-exposed concrete.” Fire Safety Journal, 38(2), 103-116.
Hoj, N. P. and Tait, C., (1999). “Great belt tunnel repairs and refurbishment.” Tunnel Management International, 16-22.
Ichise, K. and Kawabe, S., (2003). “Analytical study on deformation property of reinforced concrete columns using high-strength concrete during a fire.” AIJ Journal of Structural and Construction Engineering, 68(568), 1-6. (in Japanese)
Ishida, T. and Maekawa, K., (1999). “An integrated computational system of mass/energy generation, transport and mechanics of materials and structures.” Journal of JSCE, 627(44), 13-25. (in Japanese)
Iwama, K., Higuchi, K. and Maekawa, K., (2019). “Multi-scale modelling of deteriorating concrete at elevated temperature and collapse simulation of underground ducts.” In: 10th International Conference on Fracture Mechanics of Concrete and Concrete, Bayonne 23-26 June 2019.
Iwama, K., Ishibashi, N. and Maekawa, K., (2018). “Modeling of decomposition and Self-healing processes of hardened cement paste exposed to high temperature.” In: The 8th International Conference of Asian Concrete Federation, Fuzhou 4-7 November 2018. 227-234.
JCI, (2016). “Guidelines for control of cracking of mass concrete.” Tokyo: Japan Concrete Institute.
JCI, (2017). “Research committee report on evaluation of concrete performance under high temperature environment.” Tokyo: Japan Concrete Institute (in Japanese).
JSCE, (2004). “Report on fire resistance technology for concrete structures.” Tokyo: Japan Society of Civil Engineers. (in Japanese)
Kakae, N., Miyamoto, K., Momma, T., Sawada, S., Kumagai, H., Ohga, Y., Hirai, H. and Aibiru, T., (2017). “Physical and thermal properties of concrete subjected to high temperature.” Journal of Advanced Concrete Technology, 15(6), 190-212.
Kalifa, P., Chéné, G. and Gallé, C., (2001). “High-temperature behavior of HPC with polypropylene fibres: From spalling to microstructure.” Cement and Concrete Research, 31(10), 1487-1499.
Kalifa, P., Menneteau, F. D. and Quenard, D., (2000). “Spalling and pore pressure in HPC at high temperatures.” Cement and Concrete Research, 30(12), 1915-1927.
Kodur, V. K. R., Wang, T. C. and Cheng F. P., (2004). “Predicting the fire resistance behavior of high strength concrete columns.” Cement and Concrete Composites, 26(2), 141-153.
Lee, J., (2016). “Experimental study of high strength concrete on pore pressure and thermal stress in spalling phenomenon during fire.” Thesis (PhD), Kyoto University. (in Japanese)
Li, Y., Zhang, Y., Yang, E. H. and Tan, K. H., (2019). “Effects of geometry and fraction of polypropylene fibers on permeability of ultra-high performance concrete after heat exposure.” Cement and Concrete Research, 116, 168-178.
Lin, W. M., Lin, T. D. and Powers-Couche, L. J., (1996). “Microstructures of fire-damaged concrete.” ACI Material Journal, 93(3), 199-205.
Liu, J. C. and Tan, K. H., (2018). “Mechanism of PVA fibers in mitigating explosive spalling of engineered cementitious composite at elevated temperature.” Cement and Concrete Composites, 93, 235-245.
Liu, J. C., Tan, K. H. and Yao, Y., (2018). A new perspective on nature of fire-induced spalling in concrete.” Construction and Building Materials, 184, 581-590.
Maekawa, K., Ishida, T. and Kishi, T., (2008). “Multi-scale modeling of structural concrete.” Taylor & Francis.
Maekawa, K., Ishida, T. and Kishi, T., (2003). “Multi-scale modeling of concrete performance -Integrated material and structural mechanics (Invited).” Journal of Advanced Concrete Technology, 1(2), 91-126.
Maekawa, K., Pimanmas, A. and Okamura, H., (2003). “Nonlinear mechanics of reinforced concrete.” London and New York: Spon Press.
Matsudo, M., Yoshino, S., Wakamatsu, T., Kondo, S., Sasaki, H., Hirashima, T., Yoshida, M., Uesugi, H. and Saito, H., (2002). “Study on fire resistance of reinforced concrete columns with ultra high strength material (Part1 Outline of fire resistance test under load).” In: AJI Summaries of Technical Papers of Annual Meeting. Ishikawa 1-4 August 2002, 21-22. (in Japanese)
Miyahara, T., Kawakami, T. and Maekawa, K., (1987). “Nonlinear behavior of cracked reinforced concrete plate element under uniaxial compression.” Journal of JSCE, 378(6), 249-258. (in Japanese)
Miyamoto, K. and Abe, T., (2003). “Mechanical properties of high strength concrete at high temperatures.” AJJ Journal of Structural and Construction Engineering, 574, 227-234. (in Japanese)
Monte, F. L. and Felicetti, R., (2017). “Heated slabs under biaxial compressive loading: a test set-up for the assessment of concrete sensitivity to spalling.” Materials and Structures, 50(192), 1-12.
NAOJ, (2018). “Chronological scientific tables.” National Astronomical Observatory of Japan, Japan: Maruzen Publishing. (in Japanese)
Nishimura, T. and Uehara, S., (2008). “Study on fire resistance of reinforced concrete slab under the positive bending moment.” AJJ Journal of Structural and Construction Engineering, 73(626), 677-684. (in Japanese)
Otobe, Y. and Kishi, T., (2005). “Development of hydration and strength model for quality evaluation of concrete.” Industrial Science (University of Tokyo), 57(2), 37-42. (in Japanese)
Ozawa, M., Tanibe, T., Kamata, R., Uchida, Y., Rokugo, K. and Parajuli, S. S., (2018). “Behavior of ring-
restrained high-performance concrete under extreme heating and development of screening test.” *Construction and Building Materials*, 162(20), 215-228.

Park, S. J., Yim, H. J. and Kwak, H. G., (2015). “Effects of post-fire curing conditions on the restoration of material properties of fire-damaged concrete.” *Construction and Building Materials*, 99, 90-98.

Pavani, H. P., Tadepalli, T. and Agarwal, A. K., (2019). “Estimation of porosity and pore distribution in hydrated portland cement at elevated temperatures using synchrotron micro tomography.” *Journal of Advanced Concrete Technology*, 17(1), 34-45.

Phan, L. T., (2008). “Pore pressure and explosive spalling in concrete.” *Materials and Structures*, 41(10), 1623-1632.

Phan, L. T., Lawson, J. R. and Davis, F. L., (2001). “Effects of elevated temperature exposure on heating characteristics, spalling, and residual properties of high performance concrete.” *Materials and Structures*, 34(2), 83-91.

Poon, C. S., Azhar, S., Anson, M. and Wong, Y. L., (2001). “Strength and durability recovery of fire-damaged concrete after post-fire-curing.” *Cement and Concrete Research*, 31(9), 1307-1318.

Schneider, U., (1982). “Behavior of concrete at high temperatures.” Deutscher Ausschuss für Stahlbeton, 337.

Shimooka, K., Utsunomiya, T., Kawasumi, O., Kaizoji, S., Muraoka, S., Tashiro, S. and Araki, K., (1983). “Thermal and mechanical effects of the high level radioactive waste on the rock mass for a repository.” Japan: Japan Atomic Energy Research Institute. (in Japanese)

Sun, Z., Zhang, Y., Yuan, Y. and Mang, H. A., (2019). “Stability analysis of a fire-loaded shallow tunnel by means of a thermo-hydro-chemo-mechanical model and discontinuity layout optimization.” *Numerical and Analytical Methods in Geomechanics*, 43(16), 2551-2564.

Tan, K. H. and Nguyen, T. T., (2013). “Experimental behavior of restrained reinforced concrete columns subjected to equal biaxial bending at elevated temperatures.” *Engineering Structures*, 56, 823-836.

Umemoto, M. and Kikuta, S., (2006). “Study on fire resistance of reinforced concrete columns with ultra high strength material.” *Toda technical research report*, 32, 1-13. (in Japanese)

Vance, K., Falzone, G., Pignatelli, I., Bauchy, M., Balonis, M. and Sant, G., (2015). “Direct carbonation of Ca(OH)2 using liquid and supercritical CO2: implications for carbon-neutral cementation.” *Industrial & Engineering Chemistry Research*, 54(36), 8908-8918.

Vecchio, F. J., Collins, M. P., (1986). “The modified compression-field theory for reinforced concrete elements subjected to shear.” *ACI Journal*, 83(2), 219-231.

Velez, K., Maximilien, S., Damidot, D., Fantozzi, G. and Sorrentino, F., (2001). “Determination by nanoindentation of elastic modulus and hardness of pure constituents of Portland cement clinker.” *Cement and Concrete Research*, 31(4), 555-561.

Zhang, H. L. and Davie, C.T., (2013). “A numerical investigation of the influence of pore pressures and thermally induced stresses for spalling of concrete exposed to elevated temperatures.” *Fire Safety Journal*, 59, 102-110.

Zhang, Y., Zeiml, M., Maier, M., Yuan, Y. and Lackner, R., (2017). “Fast assessing spalling risk of tunnel linings under RABT fire: From a coupled thermo-hydro-chemo-mechanical model towards an estimation method.” *Engineering Structures*, 142, 1-19.