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**Numerical analysis of heating rate effect on spalling of high- performance concrete
under high temperature conditions**

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ABSTRACT

High-performance concrete (HPC) is vulnerable to spalling under high temperature conditions and it has been found that the heating rate can exert a tremendous effect on spalling of HPC. To prevent HPC from spalling, the heating rate effect should be understood. However, quantitative analyses are still lacking and the heating rate effect has not been well interpreted so far. In this paper, a numerical analysis of the heating rate effect on spalling of HPC is presented. Based on the experimental results reported in the literature, the spalling behavior of cubic HPC specimens under fire heating and slow heating with a heating rate of 5 °C/min is modeled. With a meso-level thermo-chemo-hydro-mechanical analysis, the temperature gradient induced thermal stress and the mechanical effect of build-up vapor pressure are investigated. The results show that, at different heating rates, the spalling mechanisms are different. Finally, possible manners and mechanisms of spalling are discussed.

26 **Keywords:** High-performance concrete; High temperature; Heating rate; Spalling

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1. Introduction

Nowadays, high-performance concrete (HPC) has been widely used in various structures due to its high strength and excellent durability. However, under high temperature conditions, such as fire, HPC is vulnerable to spalling, which greatly endangers the safety of HPC structures. How to prevent HPC from spalling has become a great concern in the fire safety design of HPC structures. To investigate spalling of HPC, many experimental investigations have been conducted and it has been found that the heating rate can exert a tremendous effect on spalling of HPC.

Hertz [1] and Anderberg [2] concluded that the risk of explosive spalling of dense concrete increased with the increase in the heating rate. Phan and Carino [3] observed that, under slow heating with a heating rate of 5 °C/min, cylinder specimens of high strength concrete spalled when the surface temperature was in the range of 280 °C to 320 °C after heating for about two hours. Peng [4] found that spalling of HPC occurred at the heating time of about 170 second under the ISO 834 standard fire, while Yan et al. [5] found that spalling occurred much early at the heating time range of 30 to 120 seconds under hydrocarbon fire. Peng [4] also found that HPC did not spall under slow heating conditions. Yan et al. [6] reported that the spalling mode of 150 mm cubic high strength concrete specimens was heating rate dependent, i.e. under slow heating with a heating rate of 2 °C/min, specimens spalled into small pieces, while under the BS 476 standard fire condition, only the corners of specimens spalled. Kanéma et al. [7] applied two heating rates to concrete specimens and found that $\Phi 0.16 \times 0.32$ m cylindrical high strength concrete specimens spalled when the heating rate was 1.0 °C/min, but did not spall when the heating rate was 0.1 °C/min. Klingsch et al. [8] experimentally investigated the effect of the heating rate in the range of 0.25 to 8.0 K/min on spalling of HPC cylinders ($\Phi 0.15 \times 0.30$ m). Two different types of spalling were observed, that is, spalling started from the surface layer at high heating rates and initiated from

the core at low heating rates. It was also found that spalling can be avoided by decreasing the heating rate or the strength of concrete.

From the above experimental investigations it can be seen that the heating rate can exert effects not only on the spalling occurrence but also on the spalling manner of HPC. In addition to the experimental investigations, a number of numerical modeling contributions have been made by researchers to explain and to assess the spalling risk of concrete. Ulm et al. [9,10] developed a chemo-plastic model to analyze the fire-induced spalling of concrete rings of the Channel Tunnel. Ichikawa and England [11], Dwaikat and Kodur [12], and Beneš and Štefan [13] proposed one-dimensional models to simulate the spalling of concrete elements. Tenchev and Purnell [14] studied the fire spalling of a concrete wall on an arithmetic parallel averaged meso-level. Gawin et al. [15] used a fully coupled model and employed four spalling indices of different failure modes for the concrete spalling analysis. De Moraes et al. [16] numerically analyzed spalling of a cylindrical specimen subject to slow heating with a heating rate of 1 °C/min at a macro level. Fu and Li [17] simulated the progressive spalling of concrete subjected to a constant temperature of 1200 °C by analyzing the thermal stress-induced damage. Zhang and Davie [18] analyzed fire spalling of a concrete wall and a concrete column. By developing Gawin's model, Zhang et al. [19] estimated the fire spalling risk of concrete by comparing the strength profile with the stress profile in concrete. Xotta et al. [20] investigated the effects of the porosities of aggregate and cement paste on the internal stresses of heated concrete under slow and fast heating conditions at a meso-level. Based on the experiments and by analyzing the thermal stress development, Ju et al. [21] modeled the spalling process of reactive powder concrete specimens exposed to slow heating with a heating rate of 4.8 °C/min.

From the above existing modeling work of spalling it can be seen that the investigation of the heating rate effect on spalling is still insufficient. To prevent HPC from spalling, the

heating rate effect on spalling should be well understood. Although, two hypotheses have been proposed to explain spalling: the vapor pressure mechanism [3,4,22,23] and the temperature gradient-induced thermal stress mechanism [9,10,24,25], the heating rate effect on the spalling mechanism of HPC still needs to be clarified and the quantitative analyses of the heating rate effect are still lacking. Thus, the purpose of this paper is to investigate the heating rate effect on spalling of HPC. To this end, HPC cubes with a side length of 100 mm under two heating conditions, i.e. the ISO 834 standard fire and slow heating with a heating rate of 5 °C/min, reported in Peng's experiments [4] are numerically modeled at a meso-level. With a thermo-chemo-hydro-mechanical analysis, the temperature field, the moisture transport, the vapor pressure build-up, and the internal stress induced by the temperature gradient and vapor pressure are modeled. The effects of the temperature gradient and vapor pressure on spalling of the specimens under the two heating conditions are analyzed. The heating rate effect on spalling of HPC is then quantitatively interpreted.

2. Model description

To model the heating rate effect on spalling of HPC, the complex chemical and physical reactions of concrete to high temperatures are modeled at a meso-level and briefly presented as follows.

2.1 Thermal decomposition based material properties of cement paste

When exposed to elevated temperatures, cement paste will undergo decomposition, resulting in the variation of various constituents and hence the variation of material properties. Zhao et al. [26] proposed a thermal decomposition prediction model. In the model, by considering the kinetics of thermal decomposition, the conversion degree of each hydration product in cement paste is determined as a function of heating history. Thus, with the initial volume fractions of various constituents f_i^0 and the conversion degrees a_i known, the

volume fractions of decomposed constituents f_i^d , residual constituents f_i^r , and decomposed water f_i^w can be respectively obtained as follows:

$$f_i^d = f_i^0 a_i \quad (1)$$

$$f_i^r = f_i^0 (1 - a_i) \quad (2)$$

$$f_i^w = f_i^d n_i^w \frac{\rho_i / M_i}{\rho_w / M_w} \quad (3)$$

where the subscript i represents different hydration products, w represents water, n_i^w is the amount of water in mole decomposed per mole of reactant i , and ρ and M with subscripts are the mass density and molar mass, respectively [26]. By considering decomposed water as additional pores, the variation of the volume fraction of capillary pores can also be estimated with the heating process.

Based on the thermal decomposition analysis, the Young's modulus and intrinsic permeability of heated cement paste can be estimated using the models proposed by Zhao et al. [27,28]. In the prediction of Young's modulus [27], with the residual undecomposed phase and the decomposition products treated as matrix and inclusion, respectively, a two-phase composite sphere model is developed. By analyzing the porosities of decomposition products, the Young's modulus of the inclusion can be estimated according to the granular mechanics. A two-step approach is then adopted to evaluate the Young's modulus of cement paste as a function of heating history.

For the prediction of the intrinsic permeability [28], cement paste is represented by three two-phase composite constituents since pores of different scales coexist in cement paste. By applying the effective medium theory, the intrinsic permeability of heated cement paste can be formulated in terms of the volume fractions and permeabilities of various constituents in cement paste. To consider the effect of slip-flow on the intrinsic permeability to gas, the

relation proposed by Klinkenberg [29] is adopted. By adopting the expression of Klinkenberg constant proposed by Chung and Consolazio [30] and accounting for the blocking effect of liquid water [30], the effective intrinsic permeability to gas can be obtained [31].

2.2. Temperature field

According to the principle of energy conservation and Fourier's law, the transient temperature field is governed by

$$\rho c \dot{T} = \frac{\partial}{\partial x_i} \left(\lambda_{ci} \frac{\partial T}{\partial x_i} \right) + \dot{\phi} \quad (4)$$

where ρ , c , λ_c , T , and $\dot{\phi}$ are the mass density, the specific heat, the thermal conductivity, the temperature, and the internal heat source, respectively. With the parameters known, the temperature field in the solid body under specified boundary conditions can be determined by solving the governing equation with the finite element method.

2.3. Vapor pressure and moisture transport

Under high temperature conditions, vapor pressure will build up in concrete and contribute to the thermo-mechanical damage to concrete. According to thermodynamics, the vapor phase in concrete can be either saturated vapor or superheated steam. By taking the volume fraction of dry air and its effect on vapor pressure as negligibly small, for a given temperature and specific volume of moisture, the vapor pressure can be determined from steam tables. The specific volume of moisture in capillary pores is given by

$$v = \frac{V_m}{m_m} = \frac{f_{cap} \cdot V_0}{f_{cap} \cdot V_0 \rho_w S_d} = \frac{1}{\rho_w S_d} \quad (5)$$

where V_m and m_m are the volume and mass of the moisture, respectively, f_{cap} is the capillary porosity, V_0 is the bulk volume of cement paste, and S_d is the moisture content defined as

$$S_d = \frac{V_l + V_v \cdot \rho_v / \rho_w}{f_{cap} \cdot V_0} \quad (6)$$

with V_l and V_v being the volumes of the liquid phase and vapor phase of moisture in the capillary pores, respectively, and ρ_v being the mass density of vapor. The degree of water saturation of capillary pores, which is used in the moisture transport analysis, can also be obtained as

$$S_w = \frac{V_l}{f_{cap} \cdot V_0} \quad (7)$$

In the determination of vapor pressure, since it is mainly induced by free water in capillary pores [32], only free water in capillary pores is considered and the thermal decomposition effects on the moisture content and the capillary porosity are accounted for. Moreover, as the surface tension of water decreases with the increase of temperature and reaches zero value at the critical point of 374.15 °C, the meniscus effect of the interface between liquid water and water vapor on the vapor pressure, which is governed by the Kelvin equation, is ignored.

When concrete is exposed to elevated temperatures, a moisture transport driven by the gradient of build-up vapor pressure occurs. In view of the low permeability of concrete, which results in a low velocity of moisture flow, Darcy's law is used for the description,

$$q = -k \nabla p \quad (8)$$

where q is the moisture flux, k is the permeability, and p is the pressure. In modeling the mass transport, only the transport in vapor phase is considered since the transport in liquid phase is negligibly small compared with that in vapor phase [30,33]. Based on the mass conservation principle, the governing equation of the moisture transport can be derived as

$$\frac{\partial}{\partial x_i} \left(k \frac{\partial p}{\partial x_i} \right) - \frac{\partial \rho_v}{\partial t} + \dot{m}_{dh} = 0 \quad (9)$$

where t is time and $\dot{m}_{dh}$ is the moisture source from thermal decomposition. The

permeability k is given by

$$k = \rho_v \frac{k'_s}{\eta} \quad (10)$$

with η being the dynamic viscosity of vapor and k'_s being the effective intrinsic permeability to gas. By applying the Galerkin weighted-residual scheme, the moisture transport is analyzed with the finite element method.

2.4. Poro-mechanical analysis

To account for the effect of vapor pressure on the stress and strain fields in concrete, the poro-elastic theory [34] is applied since concrete can be considered as a porous medium due to the presence of pores in cement paste. Thus, the total strain tensor ε_{ij} is related to the stress tensor σ_{ij} and the vapor pressure p by [35,36]

$$\varepsilon_{ij} = \frac{1}{2G} \left[\sigma_{ij} - \frac{\nu}{1+\nu} \sigma_{kk} \delta_{ij} \right] + \frac{1}{3H} p \delta_{ij} + \varepsilon_{th}^e \delta_{ij} \quad (11)$$

where G is the drained shear modulus, ν is the drained Poisson's ratio, δ_{ij} is the Kronecker delta, $1/H$ is the Biot modulus, ε_{th}^e is the effective thermal strain. In the derivation of Eq. (11) [36], the transient creep strain [37,38] is decomposed into a material degradation-induced strain and a microcracking-induced thermal strain. The former is reflected in the variation of Young's modulus and the latter is accounted for by deducting it from the free thermal strain and the effective thermal strain ε_{th}^e is then obtained and equal to

$$\varepsilon_{th}^e = \alpha_t^e \cdot \Delta T \quad (12)$$

with α_t^e and ΔT being the effective thermal expansion coefficient and the temperature change, respectively. According to poro-mechanics [35], the effective stress, which governs the elastic volume change and failure behavior of concrete, is as follows

$$\sigma_{ij}^e = \sigma_{ij} + \alpha_b \cdot p \delta_{ij} \quad (13)$$

where α_b is the Biot-Willis coefficient, which is taken to be the capillary porosity [31], and $\alpha_b \cdot p$ is defined as the effective vapor pressure.

2.5. Non-linear mechanical analysis

For the cracking and spalling modeling, the theory of fixed anisotropic smeared crack is adopted. Prior to cracking, both the aggregate and the cement paste are modeled as linear-elastic isotropic materials. Once the combination of effective principal stresses reaches the tension cut-off criterion, a crack perpendicular to the direction of the principal stress is initiated and its orientation is fixed thereafter. At this stage, the initial isotropic constitutive relation is replaced by the orthotropic one with fixed axes of orthotropy. The evolution of cracking damage is considered by degrading the Young's modulus in the cracking direction as

$$E_i = \alpha_i E_c \quad (14)$$

where E_c is the Young's modulus of undamaged concrete and α_i ($0 \leq \alpha_i \leq 1$) are the damage variables, which reflect the degrading degrees of E_i . To describe the cracking damage evolution in the local n -s coordinate system, the loading function is as follows

$$f(\varepsilon'_{nn}, \kappa) = \varepsilon'_{nn} - \kappa \quad (15)$$

where κ is a history-dependent damage parameter used for memorizing the highest value of ε'_{nn} , which is defined as

$$\varepsilon'_{nn} = \varepsilon_{nn} - \varepsilon_{th}^e \quad (16)$$

The loading function of Eq. (15) is subjected to the standard Kuhn-Tucker loading-unloading conditions [39]

$$f \leq 0, \quad \dot{\kappa} \geq 0, \quad f \cdot \dot{\kappa} = 0 \quad (17)$$

where $\dot{\kappa}$ is the rate of κ . During the whole loading process, the value of κ increases monotonically. The evolution of damage variable α in Eq. (14) is inferred from the tensile stress-strain relation shown in Fig. 1 and expressed as a function of κ as

$$\alpha = \alpha(\kappa) = \begin{cases} 1, & \text{if } \kappa \leq \varepsilon_e \\ (\varepsilon_e / \kappa) \exp[-\mu(\kappa - \varepsilon_e)], & \text{if } \kappa > \varepsilon_e \end{cases} \quad (18)$$

where ε_e is the strain at the peak stress under uniaxial tension, and μ is a parameter that controls the slope of the exponential strain softening curve and can be determined from the fracture energy. Since the fixed anisotropic smeared cracking model is adopted, to reflect the capacity of a crack to transfer shear stress in mode-II fracture, a shear retention factor is used and taken as inversely proportional to the crack strain ε_{cr} [39], which is given by [36]

$$\varepsilon_{cr} = (1 - \alpha) \varepsilon'_{m} \quad (19)$$

Since the magnitudes and directions of the stress and strain in heated concrete may change with temperature field evolution, a stiffness recovery caused by crack closure is also considered in the analysis.

For the non-linear mechanical analysis, the Newton-Raphson iteration method is used in conjunction with the finite element method based on the principle of minimum potential energy. Since HPC is rather brittle and spalling usually occurs without warning, it is reasonable to ignore the geometrical non-linear effect in the spalling modeling. Thus, when the non-linear iteration fails to converge, which means that concrete can no longer sustain the thermo-mechanical loading, spalling occurs. From the cracking pattern and the stress distribution before failure, the manner of spalling can be deduced. To evaluate the energy stored in heated concrete, the elastic strain energy for two-dimensional analysis can be calculated as follows

$$I_c = \sum_{k=1}^{ne} \frac{1}{2} \sigma_{ij}^e \varepsilon'_{ij} A_e \quad (20)$$

where σ_{ij}^e is the effective stress, ε'_{ij} is the elastic strain, A_e is the surface area of each element, and ne is the number of elements.

3. Heating rate effect on spalling

To analyze the heating rate effect on spalling of HPC, the thermo-mechanical behavior of 100 mm cubic HPC specimens with an initial moisture content of 90% exposed to the ISO 834 standard fire (Fig. 2) and a slow heating with a heating rate of 5 °C/min reported in Peng's test [4] is numerically modeled at a meso-level. In Peng's test [4], ordinary Portland cement (OPC 52.5) with a chemical composition of C₃S-55.8%, C₂S-15.8%, C₃A-9.2%, and C₄AF-9.1% by mass was used. Ten percent cement by mass was replaced by silica fume. Crushed granite and river sand with a density of 2.62 g/cm³ were used as coarse and fine aggregates, respectively. The volume content of aggregate was 64.8%. The water to binder ratio was 0.26. The spalling test was conducted at a curing age of 90 days. The measured compressive strength, tensile strength, and Young's modulus of concrete at room temperature were 115 MPa, 7.2 MPa, and 42 GPa, respectively. During the test, the temperature evolution in the specimens was recorded. It has been found that, under fire exposure, explosive spalling occurred when the surface temperatures of the specimens were in the range of 480 to 510 °C. However, under slow heating, the specimens did not spall. Since the probability of explosive spalling was not 100%, the un-spalled specimens exposed to fire and the specimens exposed to slow heating were sawn in half for the observation of internal cracks as shown in Fig. 3.

In the numerical modeling, a two-dimensional analysis is conducted at a meso-level as shown in Fig. 4. The concrete cube is modeled as a two-phase composite consisting of aggregates and cement paste in view of the fact that the interfacial transition zone (ITZ) effect is negligibly small for HPC [4]. The aggregates are treated as spheres and randomly distributed according to the aggregate gradation reported in the experiments [4,40] as shown in Fig. 4b. Three-node triangle elements are used for the discretization.

The thermal material properties used in the temperature analysis are listed in Table 1. The mass densities are obtained from the experiment [4] and the other values in Table 1 are

obtained from the inverse analysis according to the measured temperature evolutions at the four measuring points shown in Figs. 4 and 5. For the thermal decomposition analysis, the hydration degree of cement and silica fume are estimated to be 55% and 50%, respectively, according to the prediction model proposed by Parrot and Killoh [41] and the experimental investigation of Lu et al. [42]. Thus, from the chemical composition of the used cement [4], the original volume fractions of various constituents in cement paste are obtained as shown in Table 2 with the method proposed by Zhao et al. [26]. Based on the thermal decomposition analysis, the Young's modulus and intrinsic permeability of cement paste can then be predicted with the proposed models [27, 28] according to the temperature distribution evolution. The Young's modulus of granite aggregate at room temperature is taken as 45 GPa [43] and, at high temperatures, its relative value first gradually decreases from 1 at 20 °C to 0.967 at 200 °C, then continues to decrease up to 0.77 at 400 °C, and afterwards keeps constant [44]. For the permeability of aggregate, it has been reported that the permeability of granite is very low, that is, at room temperature, the permeability is in the range of 5×10^{-20} to $1 \times 10^{-19} \text{ m}^2$ [45-47] and, at high temperatures, the permeability decreases with the increase in temperature [45, 46]. Thus, the aggregate is considered impermeable in the analysis. The effective expansion coefficient is taken as $1.5 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$ for both cement paste and aggregate [36]. Although it will be more precise if the strength and constitutive law of individual component are considered in the meso-level analysis, owing to the lack of experimental data, the strengths and constitutive laws of cement paste and aggregate at room temperature are approximately taken to be those of concrete. At high temperatures, the decrease in the strength of materials is correlated with the degradation in the Young's modulus according to the descending branch of the constitutive relation shown in Fig. 1. From the measured fracture energy of 165 N/m, the strain softening parameter is estimated to be 2686 with the crack band model proposed by Bažant [48].

With these inputs and time intervals of 5 seconds and 2 minutes for fire heating and slow heating, respectively, the thermo-chemo-hydro-mechanical analyses are conducted by applying the same boundary conditions as in the experiment. The temperature evolutions and temperature distributions at 300 °C surface temperature of the specimens under fire heating and slow heating are shown in Figs. 6 and 7, respectively. It can be seen from these figures that the temperature gradient under fire heating is much greater than that under slow heating. The predicted distributions of effective vapor pressure in the specimens at 400 °C and 500 °C surface temperatures under the two heating conditions are shown in Figs. 8 and 9, respectively. It can be seen from these figures that the vapor pressure distributions under the two heating conditions are quite different. Under fire heating, the vapor pressure resides in the outer layer of the specimen and the peak moves inwardly with the evolution of temperature, while, under slow heating, high vapor pressure evenly distributes in the central region owing to the low temperature gradient.

To investigate the effects of the temperature gradient and vapor pressure on the mechanical behavior of specimens under the two heating conditions, the evolutions of the stress distributions induced only by vapor pressure and only by temperature gradient are shown in Figs. 10 to 13, respectively. Since the temperature gradient in the specimen under slow heating does not change much (Fig. 6b), the stress distribution shown in Fig. 13 keeps nearly stable for the whole heating process. It can be seen from Fig. 12 that the tensile thermal stress induced by the temperature gradient under fire heating evolves from the corners to the central region of the specimen and its magnitude is much higher than that under slow heating as shown in Fig. 13. By comparing Figs. 10 and 11 with Figs. 8 and 9, it can be seen that the vapor pressure induced stress associates with the vapor pressure distribution, i.e. the stress exists where the vapor pressure exists. Thus, vapor pressure has a local effect on the induced stress.

When the effects of the temperature gradient and vapor pressure are both taken into account, for fire heating, the non-linear mechanical analysis fails to converge when the surface temperature of the specimen reaches 476.1 °C, which means spalling occurs. For slow heating, however, despite some damaged elements in the matrix, no divergence occurs for the whole heating process, which implies no spalling occurs. It is in agreement with the experimental results. The damage patterns and effective first principal stresses of the specimens under fire heating just before spalling and under slow heating at 600 °C are shown in Figs. 14 and 15, respectively. The evolutions of the elastic strain energy under the two heating conditions are shown in Fig. 16, where the total strain energy is subdivided into the strain energy induced by the temperature gradient and the strain energy increment induced by vapor pressure.

For fire heating, it can be inferred from Fig. 14 that the spalling mode of HPC is explosive since the effective first principal stress in the central region is the highest and some cracks exist in the central region already. Comparing Fig. 14a with Fig. 3a, it can be seen that the predicted cracking pattern is similar to the experimentally observed one. Therefore, the numerical result of fire spalling correlates well with the experimental results in terms of both the spalling time and the damage pattern. By comparing Fig. 14b with Figs. 10 and 12, it can be concluded that fire spalling is mainly caused by the temperature gradient induced thermal stress since the thermal stress induced by temperature gradient in the central region is much higher than that induced by vapor pressure. The conclusion can also be confirmed by the energy analysis. It can be seen from Fig. 16a that, at the time of spalling, the energy induced by the temperature gradient reaches the highest value and the energy increment induced by vapor pressure counts only 11.2% the total strain energy. For slow heating, however, it can be concluded that the damage shown in Fig. 15a is mainly caused by the build-up vapor pressure since the temperature gradient induced stress and strain energy are much lower than those

induced by vapor pressure as shown in Figs. 11, 13 and 16b. Thus, it can be inferred from the analysis that at different heating rates, the spalling mechanisms can be different.

4. Discussions

Although the material properties, size, and shape of concrete specimens can also exert tremendous effects on the occurrence of spalling, which is out of the scope of this paper, some interpretations of spalling can still be drawn from the analysis as follows:

First, under fast heating conditions, in addition to the explosive spalling as in this study, the probable spalling manner of cubic specimens can also be corner spalling as encountered in the experiment of Yan et al [6]. It can be seen from Fig. 12 that the temperature gradient induced tensile thermal stress evolves from the corners of the specimen and together with the vapor pressure induced stress as shown in Fig. 10, corner spalling can be induced.

Second, under fast heating conditions, surface spalling of concrete can occur as reported in the experiments of Yan et al. [5], Yan et al [6], and Klingsch et al. [8]. From the vapor pressure induced stress distribution shown in Fig. 10 it can be seen that surface spalling is possible since vapor pressure evolves from the surface layer of concrete and together with the compressive stress induced by the temperature gradient, surface spalling can occur.

Third, under slow heating conditions, concrete specimens can spall into small pieces as shown in the experiments of Yan et al [6] and Debicki et al. [49]. This is because the vapor pressure distributes much evenly and hence induces evenly distributed tensile stress and damage in the matrix as shown in Figs. 11 and 15. Thus, it is possible that concrete spalls into small pieces.

Forth, under fire exposure, the spalling mechanism can evolve from temperature gradient governed spalling to vapor pressure governed spalling. Due to the fast decrease in the heating rate as shown in Fig. 2b, the temperature gradient in concrete decreases with the heating

process and hence the induced thermal stress effect on spalling decreases. The trend can also be seen from the energy development in the case of this study as shown Fig. 16a, where the temperature gradient induced strain energy decreases after reaching the peak at around 470 °C. On the other hand, with the decrease in the temperature gradient, the vapor pressure effect penetrates from the surface to the interior of concrete and becomes more evenly distributed as shown in Figs. 8 and 10. Thus, if concrete can sustain the temperature gradient induced thermal stress in the early stage of fire heating, the vapor pressure effect will take the lead in spalling.

5. Conclusions

The heating rate effect on spalling of 100 mm cubic HPC specimens has been numerically investigated based on the experiments reported in the literature. In the analysis, the effects of two heating conditions, i.e. ISO 834 standard fire and slow heating with a heating rate of 5 °C/min, on the thermal mechanical behavior of HPC cubes have been compared and studied at a meso-level. By conducting the thermo-chemo-hydro-mechanical analysis, the effects of the temperature-gradient and vapor pressure on the stress distribution and damage pattern have been numerically quantified. It can be concluded that **the spalling mechanisms of HPC are different under different heating conditions:** for fire heating, the temperature-gradient induced thermal stress plays a dominant role in spalling of the cube and, for slow heating, the vapor pressure governs the mechanical behavior of the specimen. **It can also be inferred from the investigation that, if concrete can sustain the thermal stress at the early stage of fire heating, vapor pressure will become the driving force of spalling at the later stage of fire because of the decrease in the heating rate. Other spalling manners, such as corner spalling, surface spalling, and small pieces spalling, are also discussed and explained based on the analysis.**

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538 Table 1. Thermal material properties of aggregate and cement paste.

539 Table 2. Predicted initial volume fractions of various constituents in cement paste.

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541

Table 1. Thermal material properties of aggregate and cement paste.

Material	Thermal conductivity (W/m·°C)	Specific heat (J/kg·°C)	Mass density (kg/m ³)
Aggregate	5.0	710.0	2620.0
Cement paste	4.0	1175.0	2078.0

Table 2. Predicted initial volume fractions of various constituents in cement paste.

Constituent	Hydrated aluminates	CH	C-S-H	Pozzolanic C-S-H	Unhydrated silica fume	Unhydrated cement	Capillary pore
Volume fraction (%)	8.50	5.37	37.66	14.43	3.82	21.83	8.34

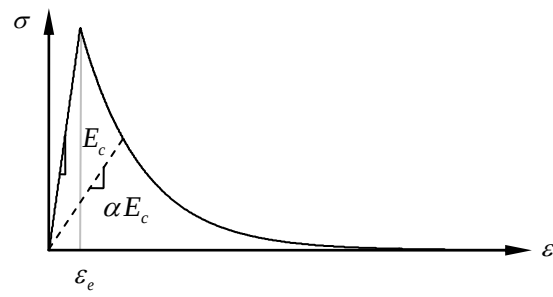
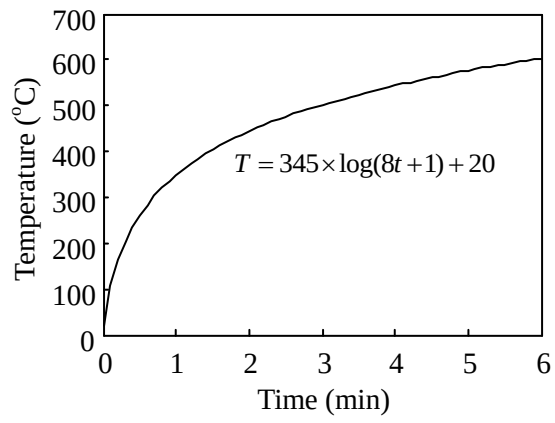
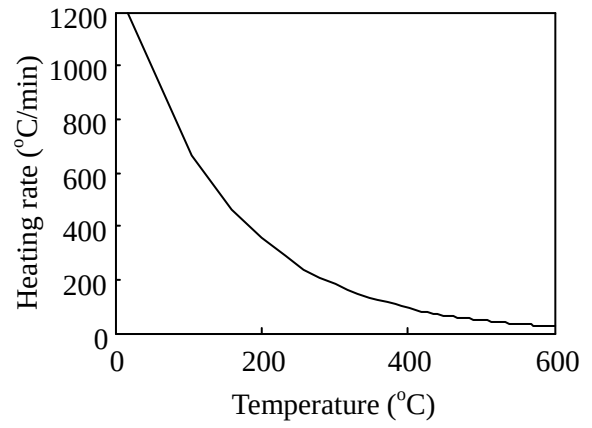


Fig. 1. Damage variable and exponential stress-strain relation.

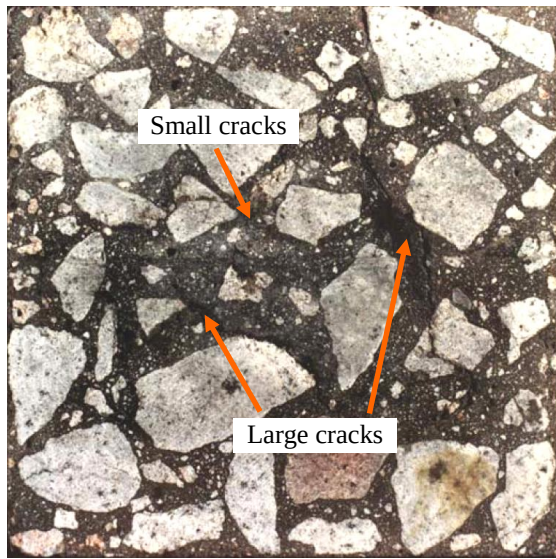


(a)

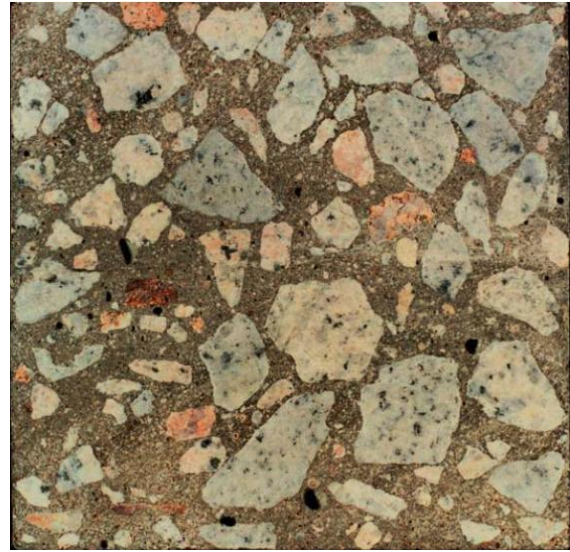


(b)

Fig. 2. (a) Heating curve and (b) heating rate of ISO 834 standard fire.

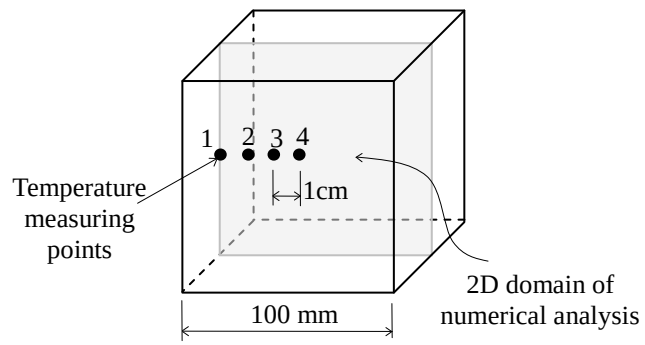


(a)

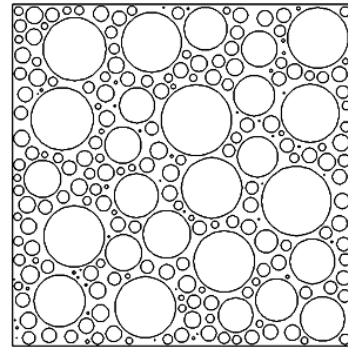


(b)

Fig. 3. Internal cracking observation of un-spalled specimen exposed to fire heating and specimen exposed to slow heating [4].



(a) Concrete cube



(b) Particle distribution of 2D domain

Fig. 4. 2D domain of numerical analysis and temperature measuring points.

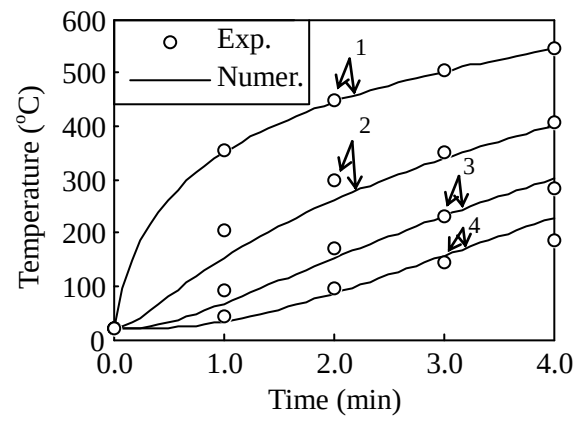
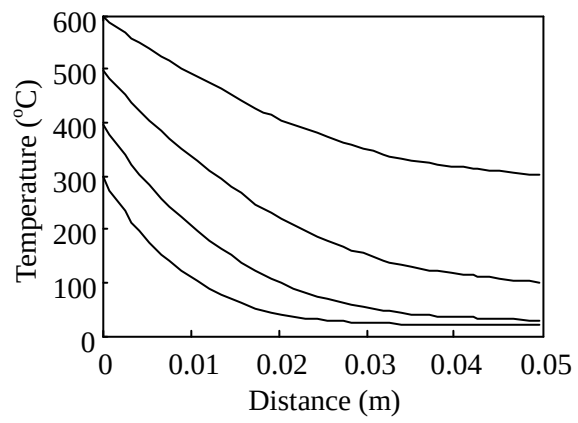
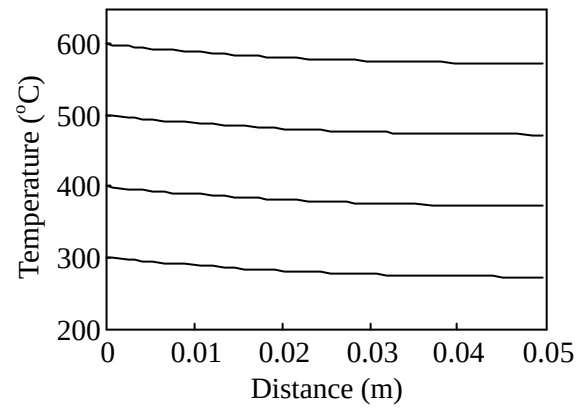


Fig. 5. Comparison of temperature evolution at four measuring points.

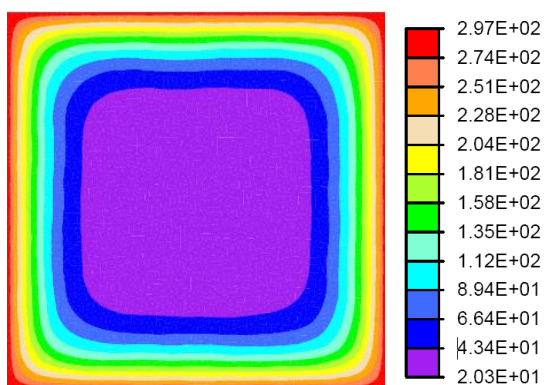


(a) Fire heating

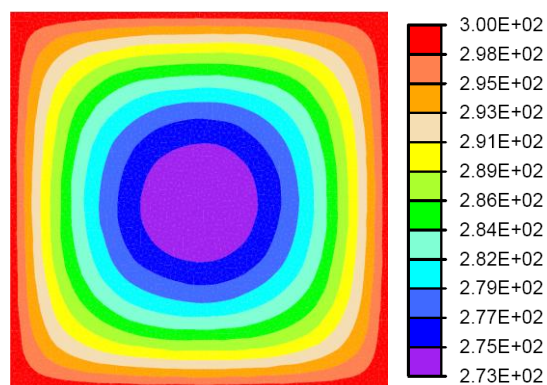


(b) Slow heating

Fig. 6. Predicted evolution of temperature profile in middle of specimen.



(a) Fire heating



(b) Slow heating

Fig. 7. Temperature field at 300 °C surface temperature.

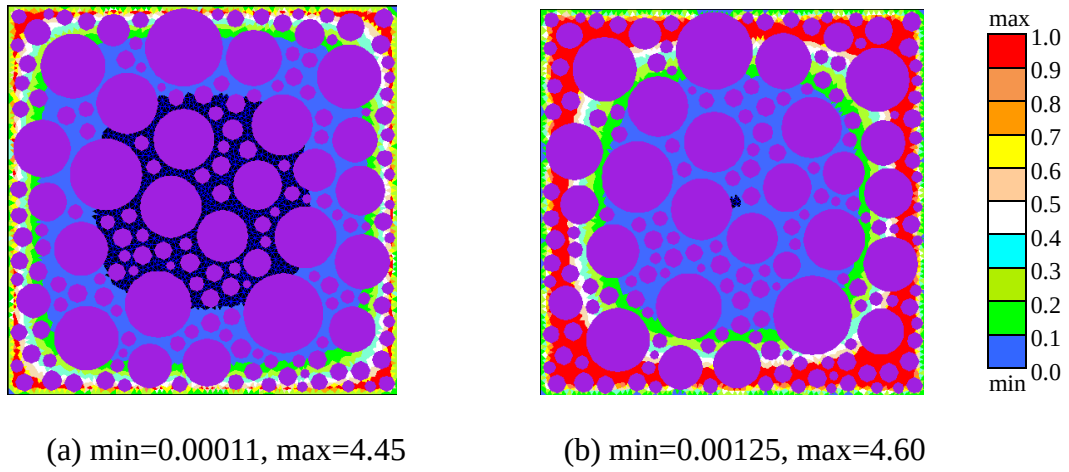
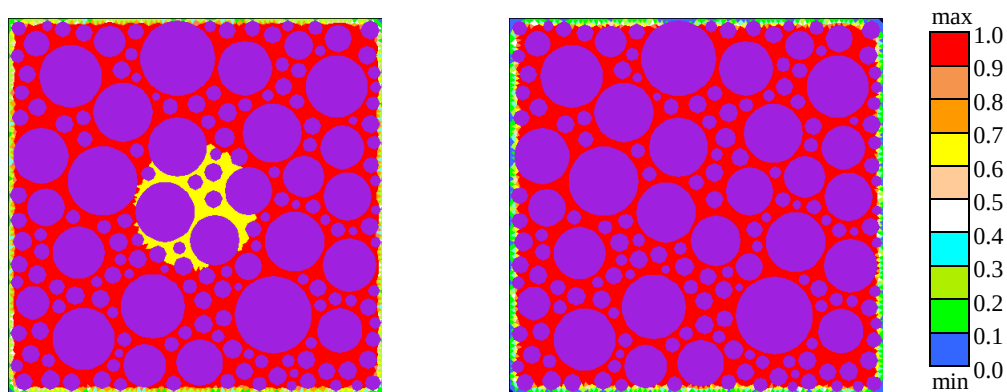


Fig. 8. Distribution of effective vapor pressure (MPa) in specimen at (a) 400 °C and (b) 500 °C under fire heating.



(a) min=0.00010, max=4.45

(b) min=0.00016, max=5.46

Fig. 9. Distribution of effective vapor pressure (MPa) in specimen at (a) 400 °C and (b) 500 °C under slow heating.

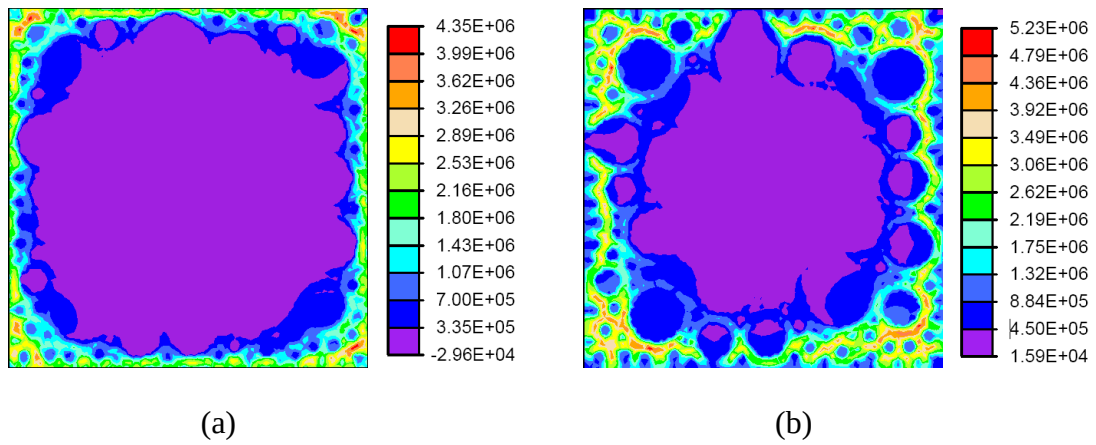


Fig. 10. Effective first principal stress (Pa) induced by vapor pressure at (a) 400 °C and (b) 500 °C under fire heating.

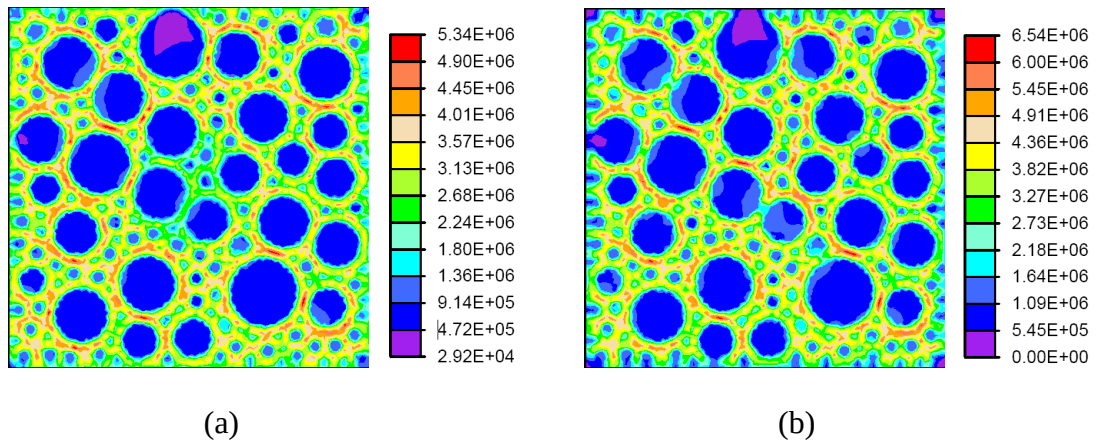


Fig. 11. Effective first principal stress (Pa) induced by vapor pressure at (a) 400 °C and (b) 500 °C under slow heating.

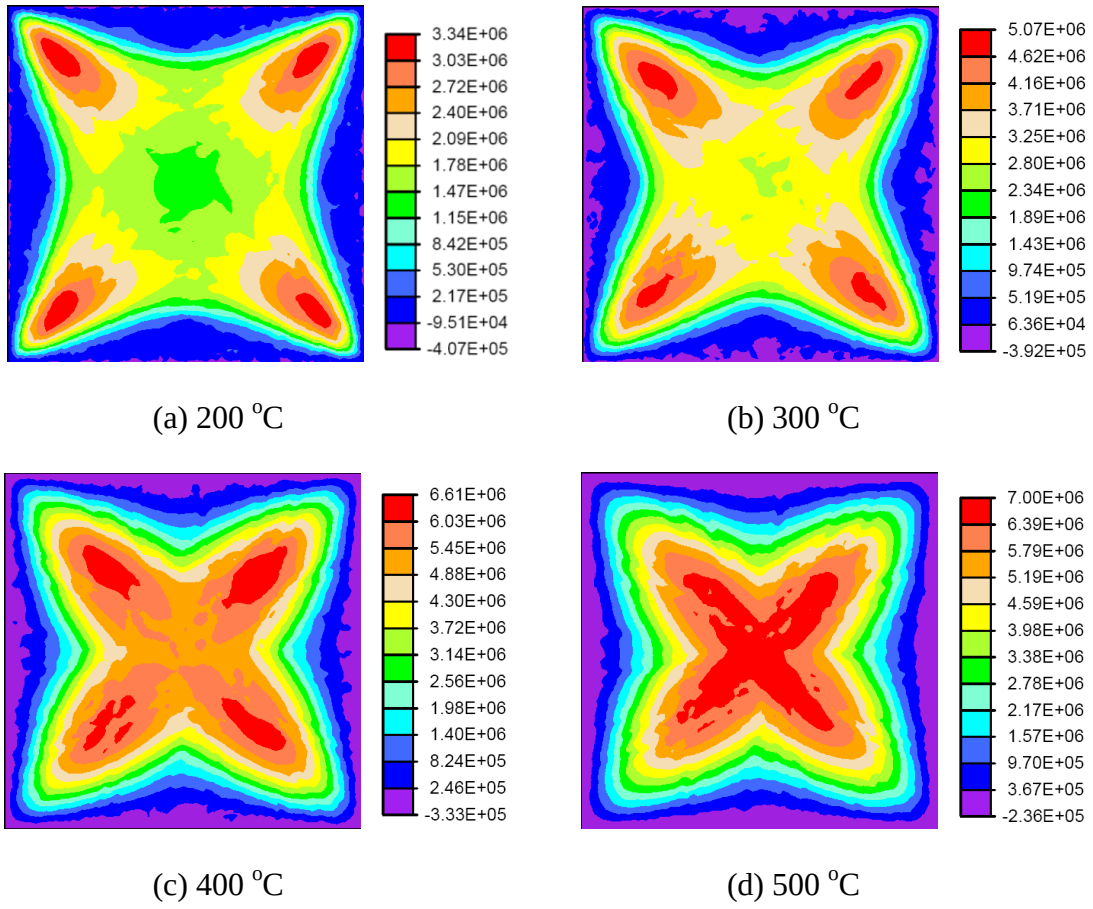


Fig. 12. Evolution of first principal stress (Pa) induced by temperature gradient under fire heating.

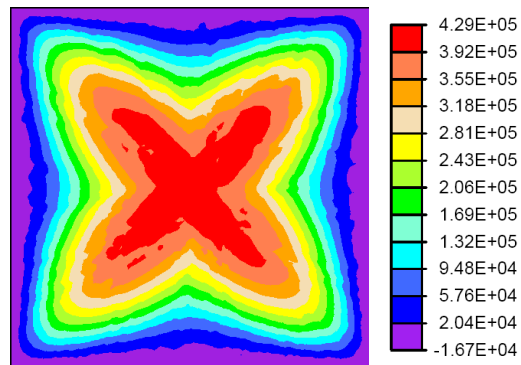


Fig. 13. First principal stress (Pa) induced by temperature gradient under slow heating.

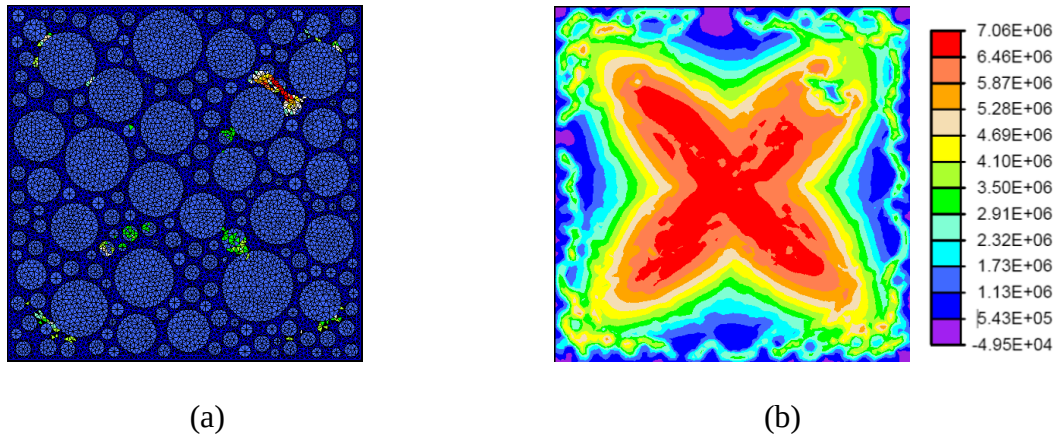


Fig. 14. (a) Damage pattern and (b) effective first principal stress (Pa) just before spalling under fire heating.

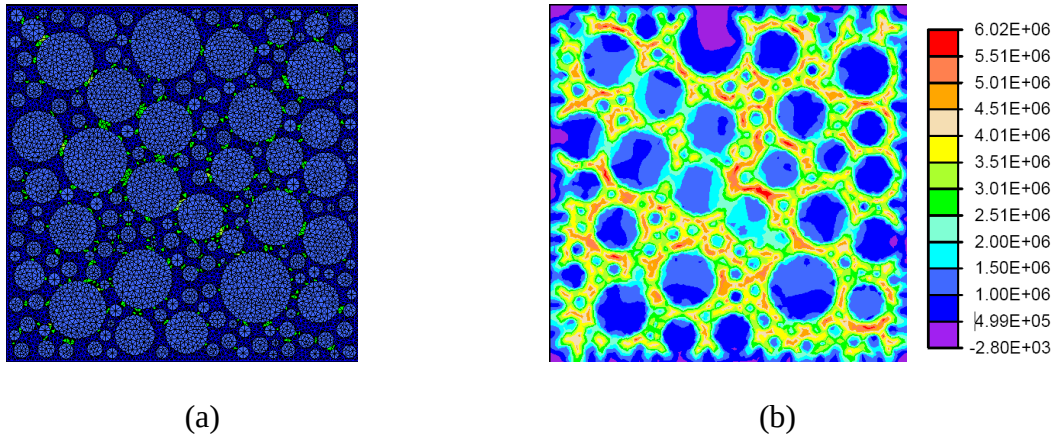
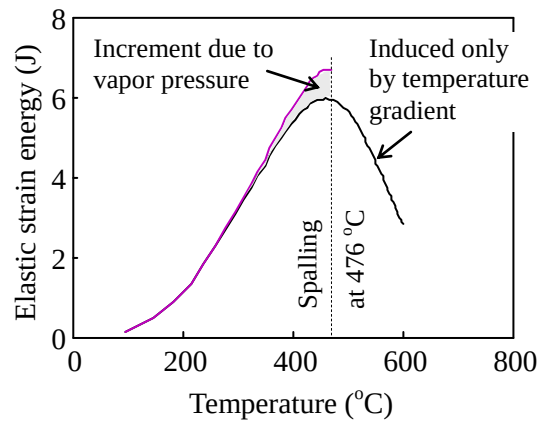
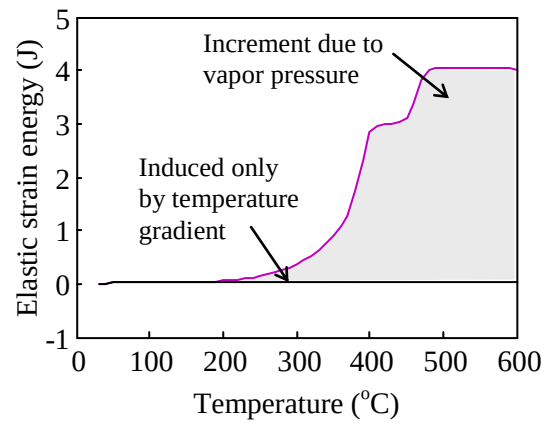


Fig. 15. (a) Damage pattern and (b) effective first principal stress (Pa) at 600 °C under slow heating.



(a)



(b)

Fig. 16. Evolution of elastic strain energy in specimens under (a) fire heating and (b) slow heating.