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Mesoscale Damage Assessment of Cementitious Material Exposed to High Temperature

高温を受けたセメント系材料の準微視的損傷評価

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September 2016

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A DISSERTATION

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the requirement for the degree of

DOCTOR OF ENGINEERING

by

RONGVIRIYAPANICH ONNICHIA

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September 2016

DEDICATION

To

My Father

*A strong and gentle soul who taught me to trust in a meaning of Life,
believe in great effort and impossible dream*

My Mother

*For supporting and encouraging me to believe in myself and for your
unconditional Love*

My Brother

*For your sacrifice since our childhood that taught me to trust in a
destiny of Life*

Rongviriyapanich's the Family

For being beside me during my educational career

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ABSTRACT

Cementitious materials, such as cement paste, mortar or concrete, are among the most widely used typical construction material because of their own benefits in use. The performance, such as workability, strength and durability, varies with mix proportions including the cement content, type of aggregate, additives and water consistency, as well as the service conditions that the structural concrete is subjected to. The structural concrete can be deteriorated owing to various factors, such as decrease in overall performance with service time and deterioration of cementitious material. Fire exposure is one of the most serious accidents to which structural concrete can be exposed, and can introduce the severe and devastating deterioration to cementitious material. In one-directional fire problem, the multi-scale material properties, including chemical structure, physical appearance and mechanical behavior, deteriorate with the different degree of deterioration dependent upon the distance from the fire origin. The conventional methods which are able to only report an average response of Ø100×200 mm cylindrical specimen may not be adequate to investigate the characteristics of fire damaged cementitious material. Furthermore, it is obvious that much less attention has been paid to numerical studies of structural response of concrete after exposure to fire in comparison to the experimentations. Therefore, the analytical methods using the viewpoint of small scale assessments that can simulate the behavior of mortar react against fire exposure are strongly needed. In this research, both of experimental and analytical studies are conducted in order to develop the methodology to investigate the mechanical behavior of one-directional fire-damaged mortar.

The series of experiments have been designed in order to investigate the influence of external thermal loadings and types of raw materials made mortar specimens, how damage progresses after one-directionally expose to fire, and to develop the meso scale constitutive model. The 100×100×400 mm mortar prisms were made from carbonate and siliceous fine aggregates and two lots of ordinary Portland cement that are typical raw materials made mortar in Japan and Thailand. The mass ratio among water, cement and sand is 0.55 : 1.00 : 2.00 for all mortar series. Thermocouples were embedded at various depths from the surface during fabrication. At the age of 28-day old, all mortars were dried at 105 °C in the oven, and keep constant moisture content until fire test, to control only the fire damage induced by a deterioration of material. The uni-directional fire exposure, conforming to standard fire curves of ISO 834 and ASTM E119, was simulated by applying the thermal loading to one face of mortar (100×400 mm), developed temperatures were gathered during entire period of fire tests. After being fully cooled-down to ambient temperature, the multi-scale experimentations begin with assessments of surface damage, test of meso scale mechanical characteristics (3-point flexural test), porosity by water absorption and chemical properties (calcium hydroxide, CH, and calcium silicate hydrate, CSH), respectively. Experimental results clearly indicate that mortar was obviously deteriorated by fire exposure. The degree of deterioration increases with an increment of temperature, with high variation in post-fire

strength because of the non-uniform distribution of crack induced by fire. In addition, the crack induced by fire has a strong effect to the mechanical properties of damaged mortar, i.e., reduced in strength, and failure location after bending test; therefore, it must be taken into account in order to achieve the fire-damaged material properties more precisely. As for mechanical properties, the cement hydration products were also fully decomposed after fire exposure, while the porosity does not change. However, the relationships between physico-chemical and material strength show that there are some complexities for describing the reduction of strength and stiffness of fire-damaged mortar. The temperature is the most appropriate index to describe how the damage of cementitious material in fire problem progresses and to understand the post-fire mechanical properties, and it could be involved in all aspects of damage. Also, the different in raw material used in mix proportions could introduce the different damage characteristics of material exposed to fire.

The analytical study aims at to simulate an internal temperature distribution along the cross section, a propagation of cracks of mortar under one-directional fire exposure, and to evaluate the post-fire strength in semi-macro scale. The present analytical investigation was conducted with a two dimensional couple analysis of heat transfer using Finite Volume Method (FVM) and structural analysis using Rigid Body Spring Method (RBSM). By means of heat transfer using FVM, a temperature as time dependence at any points was calculated based on the energy conservation equation. This developed temperature introduces an expansion strain which can be treated as an initial strain in the structural analysis together the deterioration of mechanical properties after exposed to high temperature. Prediction equations with the function of temperature for meso-scale tensile strength and Young's modulus which is developed based on the experiment, is introduced in the RBSM analysis. In RBSM, since cracks initiate and propagate along boundaries between elements, mesh arrangements affects the crack pattern. To avoid a formulation of cracks in certain direction, a Voronoi diagram was used to create a fine and random geometry. This method of analysis was able to simulate the temperature distribution along the cross section and the crack mapping of mortar beam subjected to fire exposure applied at one surface, while other surfaces are free of loadings. The analytical result shows that an increase in temperature depends on elapsed exposure duration and distance from fire boundary. In addition, the analytical result also illustrates a propagation of crack induced by fire exposure. Finally, the outputs of analytical study were validated with the relevant experimental results in order to verify the reliable of developed numerical code.

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CHAPTER 1

INTRODUCTION

- **General Background**
- **Literature Review**
- **Research Objective**
- **Scope of Research**
- **Thesis Outlines**

CHAPTER 1

INTRODUCTION

1.1 GENERAL BACKGROUND

Nowadays, there are several materials which are widely used in construction. Among these construction materials, cementitious material, such as cement paste, mortar or concrete, are quite popular because of its advantage. A component of concrete structure with various configurations can be fabricated with the high benefit-cost ratio comparing with other materials and is non-combustible [1]. Generally, the performance, such as workability, strength and durability, varies with mix proportions including the cement content, type of aggregate, additives and water consistency, as well as the service conditions that structure concrete is subjected to. During the life span, the structure integrity may be reduced by various factors, such as the exceed live load, service conditions or accidents. The decrease in structural performance can be categorized into two main parts, i.e., decrease in overall performance with service time and deterioration of material. In the case that structural performance decreases with service time, the strengthening can be applied for making the recovery of performance. Meanwhile, the various extreme service conditions, such as chemical attack and high/low temperature effect, that concrete structures were exposed to cause the deterioration in cementitious materials [2-5]. In addition, the different service conditions cause a difference in deterioration mechanism of material. The degree of material deteriorations depends on how external conditions introduce the damage. For example, the fire accident can rapidly induce the damage to the damage to building rather than the structure which is subjected to other extreme service conditions. Some of the existing researches discovered that fire exposure is one of the most extreme condition to which structural concrete can be exposed, and can induce severe and devastating deterioration [6-7].

For RC structure in practice, it is designed and built without fireproofing systems. Because of its thermal properties, concrete is considered as a material that can protect the steel reinforcements against fire, while mortar is usually used as a finishing material. Therefore, cementitious materials are the first material to be exposed to fire accident. When the concrete structure is subjected to fire, material properties, including chemical structure, physical appearance and mechanical strength, deteriorate [8-15]. As a result, the overall performance of a fire-damaged concrete structure is thought to be diminished. To ascertain whether a fire-damaged concrete structure should be repaired, strengthened or demolished, its residual integrity must be well examined. According to the characteristics of fire loading, the concrete building might have different damage characteristics compared with the fire accident in tunnel. The degree of deterioration of tunnel under fire, or one-directional heat treatment, is supposed to be same at any points where the distance from fire origin is same. Meanwhile the fire in buildings can introduce the different degree of deterioration everywhere.

Although it is widely known that cementitious material is substantially diminished by fire exposure, much of existing researches have focused on only the typical scale of experiments. Also, the performance of structural concrete is usually evaluated by the average response. However, based on the expecting of non-uniform damage distribution, the conventional method of material strength evaluation may not be able to measure the actual damage to cementitious material after a fire exposure precisely, especially for uni-directional fire exposure. Therefore, the meso scale of experimentations could show the response of cementitious material deteriorated by fire exposure more precisely.

In principle, fire causes damage through three main mechanisms: different in thermal characteristics between mortar and coarse aggregate, the effect of pore pressure buildup, and decomposition of cement hydration products [16]. Heating above 300 °C causes micro cracking to occur and propagate continuously; cracking becomes visible at approximately 400 °C, and then spalling occurs when the temperature is greater than 1200 °C [14, 17]. When temperature is sufficiently high, the physical damage coincides with the decomposition of cement hydration products, leading to a decrease in material strength [9-11, 18]. Consequently, the damage characteristics of cementitious material in fire problem should be more precisely understood in small scale.

Since the initial properties of cementitious materials vary with mix proportions including the cement content, type of aggregate, additives and water consistency, the post-fire material properties should also vary with these factors. Several factors, including external thermal loading and mineral structure of raw materials could affect the fire damage characteristics. For example, concrete is made by adding the coarse aggregate to mortar; therefore, the different in thermal characteristics between mortar and coarse aggregate may introduce the different response of concrete and mortar. Carbonate and siliceous concrete could show different degrees of deterioration in response to fire [19-22].

In recent decades, much of existing research focused on experimental works, while less attention has paid to numerical studies of structural response of concrete after exposure to fire in comparison to the experimentations. Therefore, the analytical methods that can simulate the behavior of mortar react against fire exposure are strongly needed. Moreover, the coupled analysis system between heat transfer considering deteriorated material properties and structural response has not been yet proposed.

1.2 LITERATURE REVIEW

The literature review covers the relevant background information to this dissertation. The detail of experimental program is designed based on the knowledge of fire exposure and its severity on cementitious material. Following that, the relevant research and information regarding the raw material used in mix proportion is discussed. Finally, the numerical approaches for coupled analysis system to simulate the behavior of mortar after fire exposure are reviewed with focus on Finite Volume Method (FVM) and Rigid Body Spring Method (RBSM).

1.2.1 Fire severity

The characteristics of applied thermal loading might relate to the initiation and progress of damage to cementitious materials. It has been found that the different condition of fire exposure affects the internal temperature concentration of concrete beam [23]. They have conducted the full-scale beam under two different conditions of fire exposure: standard fire curve of ASTM E119 and short-duration high-intensity (SDHI) exposure. The SDHI fire curve increased rapidly with 22.5 °C/min during the first 45 minutes of exposure, and then cooled rapidly to 316 °C at 100 minutes of exposure. The contours of developed temperature of these two fire exposures are totally different when comparing with the same exposure duration. The beam specimen that was exposed to ASTM E119 had a greater temperature background than SDHI at any points of cross-sectional area. The interior temperature of beam subjected to the SDHI cannot be dissipated quickly due to the low thermal conductivity of concrete.

The fire damage to concrete after high temperature treatment can be roughly observed by the surface damage. The visible damage on the surface of the concrete occurred when the temperature increased to 600 °C. At the temperature above 1200 °C, the spalling due to an excessive cracking was observed [14]. Figure 1-1 shows the initiation and progress of surface damage induced series of maximum temperature. Generally, there are two major causes of spalling in fire damaged cementitious material: pore pressure buildup and thermal expansion [17, 24]. During fire, moisture was transported in two directions: (i) outward or escaping; (ii) inward or saturating concrete. However, the moisture content less than 3%W/W would not susceptible to spalling in non-dense concrete. Furthermore, the explosive spalling might reduce the load bearing capacity of structural concrete more significantly.

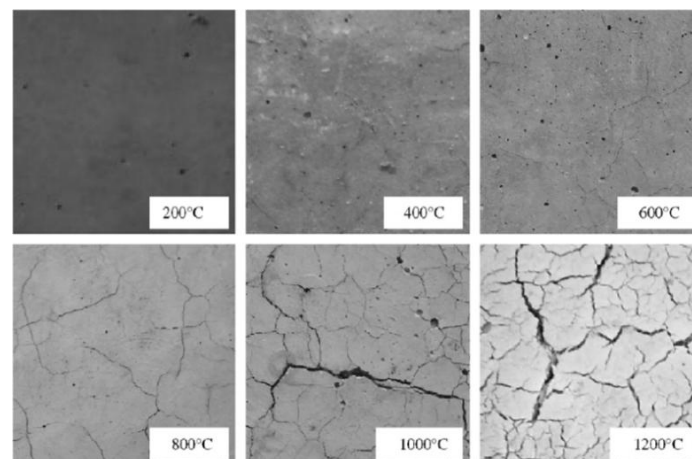


Fig. 1-1 Initiation and progress of surface damage [14]

Much of existing researches have focused mainly on the decrease in mechanical strength using the classical methods of evaluation. It is stated that high temperature treatment can significantly introduce a severe damage to cementitious material. The residual compressive strength of concrete after exposure to high temperature up to 800 °C was less than half of the initial compressive strength of non-damaged concrete [14, 25-27]. Besides the decrease in

mechanical strength, the pore structure of fire damaged cementitious materials and porosity were also changed. The pore structure coarsening was intensified, while the rounded peak of Mercury Intrusion Porosimetric analysis (MIP) could indicate a different intrusion mechanism of fire damaged cementitious material [28-30].

In 1957, Ingberg proposed the fire-load concept based on two assumptions: fire severity is examined by area under temperature-time relation, and fire severity relies on only an intensity of fire [31]. This fire-load concept does not consider the effect of fuel type, rate of ignition, and thermal conductivity of material. By means of this knowledge, cementitious materials with same initial material properties which were exposed to longer duration are supposed to have the higher degree of deteriorations.

1.2.2 Material properties of fire damaged cementitious material

There are several existing researches focusing on the deterioration of cementitious material subjected to fire in various directions, including the decomposition of cement hydration products, and change in mechanical properties at elevated temperature. By being subjected to high temperature treatment, the driving out of free water started at approximately 100 °C [32]; then, the fraction water would be released by dehydration of cement hydrates if temperature was increased continuously. By increasing temperature, the material strength was supposed to decrease leading to the reduction in resistance of crack initiation [33].

Where the temperature ranges between 100°C and 300 °C, the additional hydration products may be generated from the anhydrate cement particle, as well as a partial decomposition of some kinds of cement hydrates. The ignition loss increases with the high temperature treatment. This is due to the released dehydration water from chemical components in material. Basically, the rate of ignition loss was less than 10% at the temperature below 600 °C. After that, there was a sharp increasing gradient in weight loss beyond 800 °C. It was approximately 45% after exposed to 1200 °C [14, 29]. This ignition loss also related with the initiation and progress of surface damage after fire exposure. The temperature that could introduce the decomposition of calcium hydroxide (CH), as shown in Eq. (1-1), and calcium silicate hydrate (CSH) was approximately above 500 °C. Lime or calcium oxide (CaO) was newly formed in the decomposition of CH. This process causes expansion due to lime formation and shrinkage due to water evaporation at the same time [34]. The expansion and shrinkage might introduce the crack induced by fire. The non-linear prediction models for residual CSH content at various maximum temperatures have been proposed in reference [30], as shown in Fig. 1-2. The decomposition of CSH was initiated whose rate of concrete that was exposed to maximum temperature of 700 °C was higher than 600 °C. It could confirm the influence of high temperature to deterioration of cementitious material. This information also agrees with the Ingberg's fire-load concept. Also, the temperature above 600 °C is sufficiently high for initiating the decomposition of CSH.



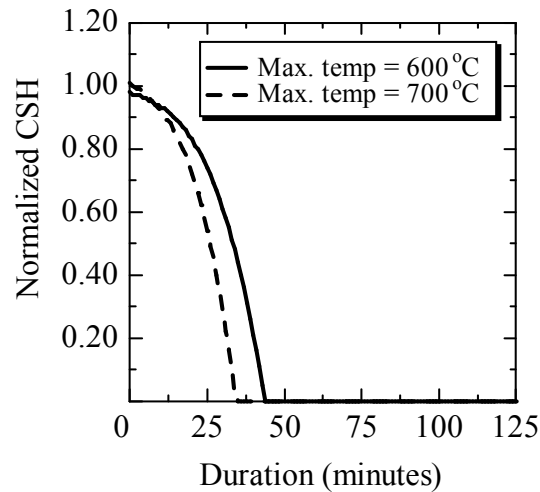


Fig. 1-2 Residual CSH in sample [30]

As widely known that the cement hydration products would fill in pore after hydration process; therefore, the decomposition of these compounds might affect the pore structure. The pore structure coarsening of fire-damaged cementitious material could be confirmed by the results of Mercury Intrusion Porosimetry (MIP) and Scanning Electron Microscope (SEM) [28-30, 35-36]. This was mainly caused by the decomposition of chemical compounds in fire problem. In addition, the total pore volume by MIP was also observed the increasing tendency with the growth of rounded peak. This growth of rounded peak could show the different mechanism of intrusion process, i.e., breaking through isolated pore. However, the technique of MIP cannot precisely describe the pore size distribution. Because the mechanical strength had a relationship with porosity [37], it might be diminished after damaged by fire exposure.

It has been reported that the temperature above 300 °C cause a significant decreasing of material strength [38]. The existing numerical equations to determine the mechanical characteristics of fire-damaged concrete have been proposed in reference [39], as shown in Fig. 1-3 for compressive strength, tensile strength and modulus of elasticity. It has also been found that the reduction in mechanical strength could be related to the loss in weight of concrete or the ignition loss after exposed to high temperature [14]. In addition, it was indicated in Eurocode [40] that the reduction of compressive strength of fire-damaged concrete is dependent upon the type of aggregate used in mix proportion, as shown in Fig. 1-4, as well as some existing researches also show the good agreement with this information [19, 21, 41].

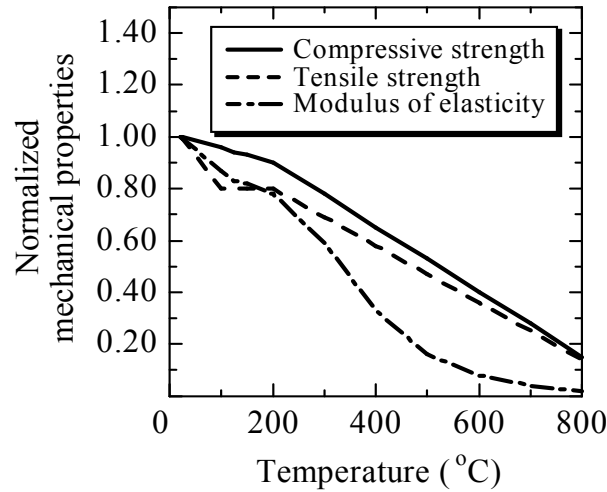


Fig. 1-3 Mechanical characteristics of fire damaged concrete [39]

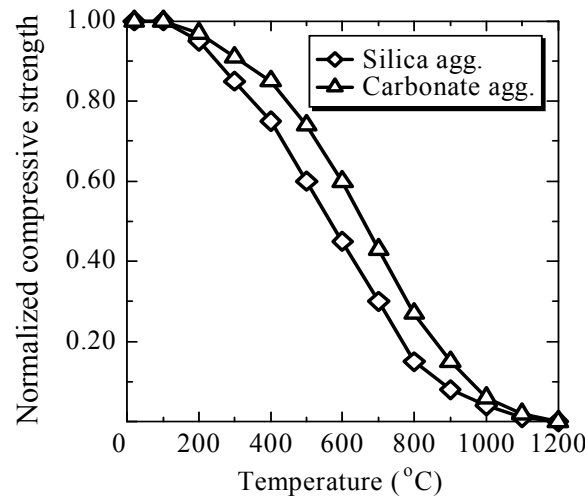


Fig. 1-4 Decreased compressive strength [40]

1.2.3 Influence of raw material used in mix proportion

Aggregate's effect on concrete at high temperatures is related to their mineral structure. In siliceous aggregate, quartz changes polymorphically at approximately 570 °C leading to volume increase [42]. However, calcium carbonate (CaCO_3) turns into calcium oxide (CaO) at approximately 800-900 °C, in limestone aggregate. CaO expands with temperature, while released CO_2 cause shrinkage [43]. Therefore, aggregate's mineral structure is an important factor in degree of deterioration in cementitious material subjected to fire exposure.

On heating above 300 °C, the color of siliceous aggregate concrete was changed from normal to pink or red (300-600 °C), whitish gray (600-900 °C) and light yellow (900-1000 °C) [19]. This color change is useful since it coincides with the loss of concrete strength after high temperature treatment. However, it was less prominent with carbonate and igneous aggregate concrete. Some of existing researches have investigated about the influence of type of aggregate made concrete on the post-fire concrete strength [14, 44]. It has been found that the concrete made from different aggregate had a different response to fire exposure.

In response to fire exposure, the siliceous aggregate expand and give more severe damage rather than carbonate aggregate due to their thermal expansion, as shown in Fig. 1-5. The thermal strain was rapidly increased at the temperature below 700 °C and 805 °C for siliceous and carbonate aggregate, respectively. After those certain temperatures, the thermal strain became constant value for both aggregate types. The thermal strain in carbonate aggregate was approximately 70% of siliceous aggregate. As a result, the concrete made from siliceous aggregate was supposed to have a higher degree of fire deterioration due to the thermal expansion, as well as the decrease in material strength.

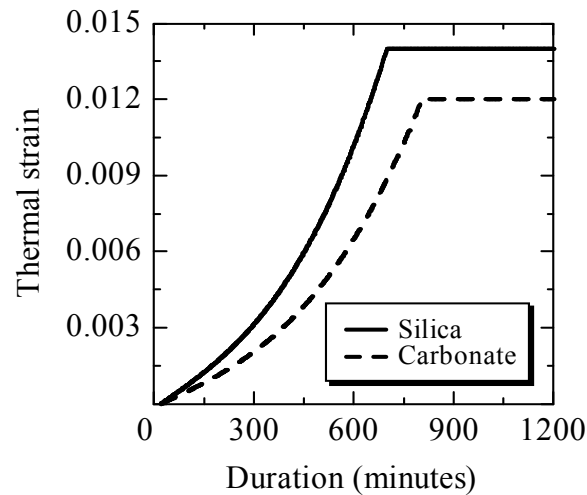


Fig. 1-5 Thermal strain of different type of aggregate [40]

1.2.4 Introduction to analytical approach

Since the existing researches relating to fire damage characteristics of cementitious materials have focused on only the quantitative experimentations, both experimental and numerical investigation of cementitious materials in fire problem should be incorporated into the development of the reliable simulation. In addition, a numerical method for simulating the temperature distribution and surface cracking induce by fire exposure is becoming more effective for safety and economical reasons.

To investigate the crack formation and propagation in cementitious material, smeared cracking model has been typically used for representing of cracking phenomenon and reducing a performance of material. However, it is difficult to obtain the realistic cracking patterns, especially for cementitious material under fire exposure, because of the fire damage characteristics. Therefore, the method of discontinuity of the continuum elements is probably more appropriate numerical approach for simulating the temperature distribution and cracking pattern of mortar exposed to one-directional fire exposure.

For cementitious material in fire problem, two types of analysis are needed: heat transfer and structural analysis. Therefore, two approaches of this coupled analysis system are briefly reviewed; Finite Volume Method (FVM) and Rigid Body Spring Method (RBSM).

1) Finite volume method (FVM)

Finite volume method (FVM), firstly introduced by McDonald, MacCormack and Paullay in 1970, is a discretization technique for partial differential equations (PDEs), especially for those that arise from physical conservation laws. It was sometimes also called box methods. FVM uses a volume integral formulation of the problem with an infinitesimal volume to discretize the equations. It is commonly used for discretizing computational fluid dynamics equations; however, it is not limited to only flow problem. An important property of FVM is the balance principles, which are the basis for the mathematical modeling of continuum mechanical problems.

For the heat transfer, it was governed by the heat conduction which is also a basic form of PDEs. Therefore, the mesh and dual mesh of cell-centered FVM is applicable to heat transfer analysis in this study.

2) Rigid body spring method (RBSM)

Rigid body spring model (RBSM), firstly developed in 1977 by Kawai, is one of the discrete approaches. Concrete is modeled as an assemblage of rigid elements consisting of mortar, and aggregate. The interfaces between these rigid elements are zero-size spring, i.e., normal and shear spring. The fracture propagation can be modeled by introducing the fracture criterion of material to spring properties.

In this study, two-dimensional RSBM was used as a numerical approach for structural analysis because of its simplicity in modeling the different materials, and ability to provide reasonable prediction for loading capacity, crack initiation and propagation, as well as overall performance. In addition, it is also able to analyze the initial strain problem, such as thermal expansion of mortar in fire problem.

Since the continuum material is modeled by rigid element, there is no deformation of element due to its rigid movement. Fracture process can be simulated by the failure of springs located at the boundary of element. Also, it is modeled by using Voronoi element whose geometry is randomly generated. Therefore, a mesh bias on the fracture conditions can be negligible.

1.3 RESEARCH OBJECTIVES

The key objective of this research is to understand how damage to mortar progresses after one-directional exposure to fire. In order to prevent the unexpected damage owing to pore pressure buildup and thermal mismatch of mortar and coarse aggregate, the meso scale material properties of oven-dried mortar after fire exposure would be experimentally examined. Three objectives of the current research are addressed as follows:

- 1.3.1 To investigate the influence and damage progress of one-directional fire exposure on cementitious material, and the relationship between fire-damaged material properties.

- 1.3.2 To investigate the influence of different thermal loadings and type of raw materials used in mix proportion in response to fire exposure.
- 1.3.3 To simulate an internal temperature distribution and crack propagation of mortar exposed to one-directional fire exposure using a coupled analysis of Finite Volume Method and Rigid Body Spring Method.

The outcome of the current research is expected to facilitate engineers in understanding the damage characteristics of mortar exposed to fire exposure.

1.4 SCOPE OF RESEARCH

For the current study, the experimentations and numerical simulation have been designed in order to achieve the objectives of study.

In order to prevent the unexpected damages that were induced by the different in thermal properties of each phase and explosive spalling during fire tests, the series of fire simulation was conducted on the oven-dried mortar. Since the characteristics of thermal loading affect the characteristics of material deterioration, one-directional fire exposure was used in this study. Three exposure durations, e.g., 30, 60 and 90 minutes can describe the progress of fire damage to cementitious material in short, semi-long, and long duration of fire exposure.

The mortar specimens for whole experimental program represent the fully non-damaged material before fire test with exactly same mix proportions, maximum aggregate size, curing time, and oven-dried conditions. Therefore, the parametric analysis in this study involves only different raw materials and different thermal loadings for mortar in response to one-directional fire exposure.

Since the carbonate aggregate and siliceous aggregate are locally available and widely used in Japan and Thailand, respectively, both of aggregate types were chosen to understand the effect of different raw material in response to fire exposure of oven-dried mortar. Also, the different cement was also used in this study.

1.5 THESIS OUTLINES

Chapter 1 This chapter provides general background and literature review of the topics related to this research. A fire severity and change in material properties of cementitious materials after fire exposure will be given, followed by briefly information of coupled analytical system of heat transfer and structure analysis. Finally, the research objectives and scope, and outline of this study will be emphasized.

Chapter 2 This chapter focuses on the experimental program that was designed to achieve the research objectives. The experimental results indicated in this chapter can describe the progress of fire deterioration to material strength and their comparisons.

Chapter 3 This chapter presents the meso scale damage assessment, including modulus of elasticity, porosity, hydration products. Also, the tensile strength and fracture energy was calculated by using the multi-linear approximation method.

Chapter 4 The results of analytical simulation will be given in this chapter, together with a comparison with the experimental results. The sensitivity analysis will also be discussed.

Chapter 5 This chapter will summarize the major conclusion and recommendations for future works.

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CHAPTER 2

EXPERIMENTAL OUTLINES

- **Experimental Procedures**
- **Experimental Results of Carbonate Mortar**
- **Experimental Results of Siliceous Mortar**
- **Relationship of Fire Damaged Cementitious Material**

CHAPTER 2

EXPERIMENTAL OUTLINES

2.1 INTRODUCTION

As previously discussed, the fire damaged buildings is usually evaluated the residual performance by the classical method, which shows only the average response. However, the damage mechanisms of fire damaged cementitious material are in various scales. In addition, the non-uniform degree of deterioration along the cross section, especially for one-directional firing, is expected. Therefore, the experimentations for understanding the progress of fire damage characteristics to mortar are designed based on the following key points:

- The increase of degree of deterioration depends on the fire exposure duration.
- The degree of deterioration at each depth from fire origin should be understood and the gradient of material properties should be drawn along the specimen depth.
- The influence of thermal loadings and raw materials must be verified.

Therefore, four mortar series whose raw materials were different has been exposed to two of standard fire curves: ISO 834 and ASTM E119, for three durations, i.e., 30, 60 and 90 minutes.

2.2 EXPERIMENTAL PROCEDURES

2.2.1 Materials and specimen fabrication

The raw materials used in this study are locally available in Japan and Thailand. The ordinary Portland cement (OPC) conforms to the Japan Industrial Standard (JIS) and the Thailand Industrial Standard (TIS). The fine aggregates, i.e., crushed limestone and natural river sand, are locally and widely used in Japan and Thailand, respectively. The aggregate is fine, uniformly graded sand that has passed through a 1.70 mm mesh sieve.

In this study, the mortar is non-air-entraining type and was designed based on the absolute volume of the material constituents in a saturated surface dry condition that has a water-to-cement ratio of 0.55 and a cement-to-sand ratio of 0.50. The designated mix proportions in this study, as shown in Table 2-1, are exactly the same for all mortar series made from raw materials locally available in both Japan and Thailand.

Table 2-1 Mix proportions per cubic meter

Ingredient	Specific gravity	Amount (kg)
Cement	3.16	624
Fine aggregate	2.71	1248
Water	1.00	343

The 100×100×400 mm prismatic specimens were cast for the one-directional fire test. First, cement and fine aggregate were dry mixed to ensure a uniform distribution before being hydrated by water in the mix proportion. After being mixed well, the fresh mortar was poured and compacted in a 100×100×400 mm prismatic mold. It was then kept in the mold for 24 hours. As shown in Fig. 2-1, thermocouples were embedded during casting at various depths, e.g., 25 mm, 50 mm and 75 mm from the bottom surface. This installation would not introduce any unexpected damage by drilling a hardened specimen. Therefore, the mortar specimens were completely non-damaged condition before fire test. Two types of surfaces for the specimen, called the heated face and the side face, are considered. The heated face is the bottom face of the specimen, where the fire is loaded, while the side face is perpendicular to the heated face. Because the surface roughness of heated face might affect the mechanism of heat transportation during fire tests, the bottom face was chosen to be the heated face due to its flatness. Therefore, the applied thermal loading at any points on heated face was supposed to be uniform.

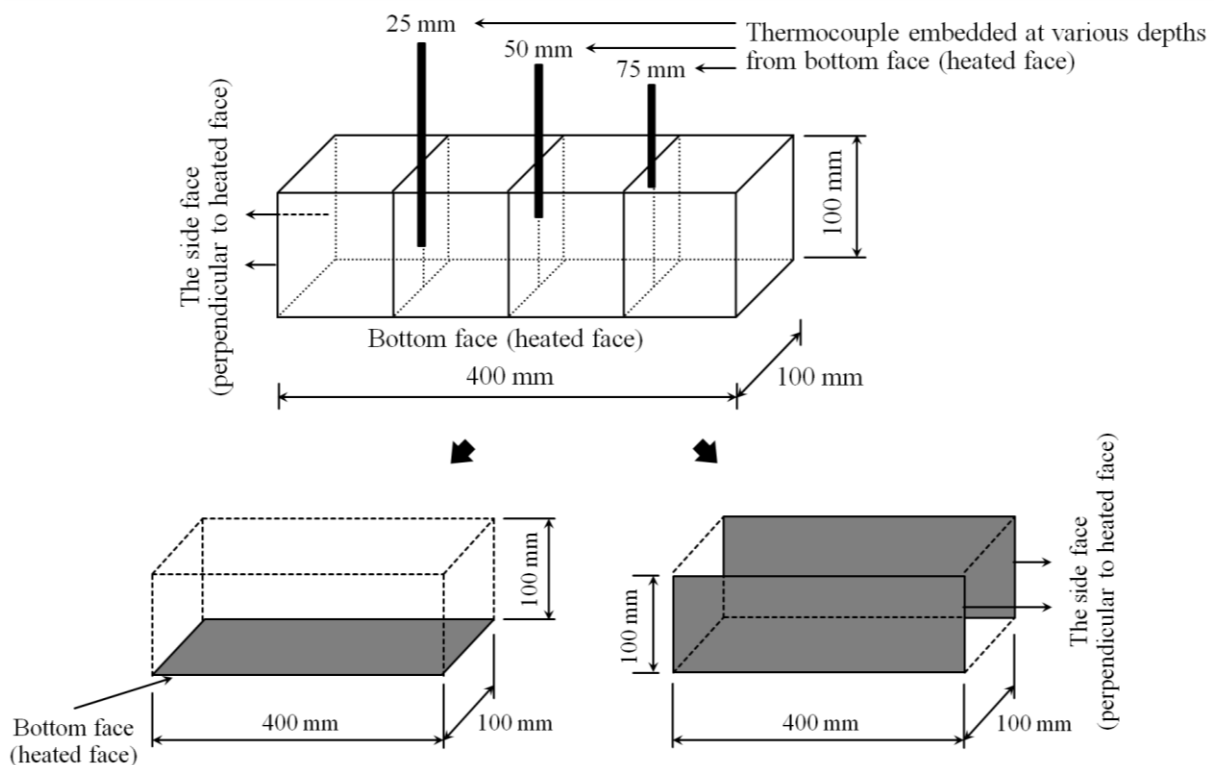


Fig. 2-1 Details of specimens and surface types

After demolding at 24 hours, the specimens were cured in lime-saturated water for 27 days. Next, they were oven dried at 105 °C for 24 hours to release residual free water in the

capillary pores, which causes pore pressure buildup during the fire test [1-3], and to keep the moisture content constant until the fire test date. The influence of curing time and oven-dried condition is negligible because they were controlled the same conditions for all mortar series. These regimes provided well-cured specimens and minimized any effects of accelerated hydration and unexpected damage characteristics when heated. Table 2-2 shows the unit weight of the saturated surface dry and oven-dried specimens. At 105 °C of oven's temperature, the decrease in unit weight is only due to the vaporization of exceed free water in mix proportion at 28-day old [4]. The initial amount of cement hydration products would not be affected at this temperature. As seen from table, the unit weight of oven-dried mortar is approximately 200 kg/m³ lower than air-dried condition. On the date of fire test, two thermocouples were directly installed to the heated and unheated surfaces. By using the embedded and newly installed thermocouples, developing temperature gradient during the entire period of burning could be measured.

Table 2-2 Unit weight of specimens

Series name	Unit weight (kg/m ³)		Loss of free water (kg/m ³)
	Saturated surface dry	Oven dry	
JP ISO	2290	2092	198
JP ASTM	2255	2136	119
TH ISO	2463	2316	147
TH ASTM	2154	1968	186

2.2.2 Heating and cooling regimes

The mortar specimens were one-directionally heated using a furnace programmed with the standard fire curves of ISO 834 and ASTM E119, as shown in Eqs. (2-1) and (2-2), respectively, and then cooled to ambient temperature. Fire tests were simulated for three durations (30, 60 and 90 minutes) in order to understand the progress of fire damage behavior of mortar. When the targeted duration was reached, the furnace was automatically switched off, the doors opened immediately, and the specimens were left to cool in the air over many hours to room temperature, as shown in Fig. 2-2. After that, the fire damaged specimens were fully wrapped and kept in a sealed box for post-cooling experimentations in order to prevent the additional damage for external condition, such as air humidity.

$$T = 345 \log(8t + 1) + T_0 \quad (2-1)$$

$$T = 750[1 - e^{-3.79553\sqrt{t}}] + 170.41\sqrt{t} + T_0 \quad (2-2)$$

where T and t represent temperature (°C) and elapsed time (minutes for ISO and hours for ASTM curves), respectively. The ambient temperature is indicated by T_0 .

However, the experimental conditions of fire tests under ISO 834 and ASTM E119 were slightly different owing to the configurations of the furnace. In the case of specimens which were burnt with fire curve of ISO 834, they were placed in a wooden frame as the lid of the furnace. The 800×800 mm wooden frame that has a 600×600 mm of fire area was an assemblage of wood and fireproof material at the back side. The thermocouples for measuring temperature at heated face were between wood and fireproof layer of wooden frame. Three openings whose size was slightly bigger than 100×400 mm were prepared for putting mortar specimens. The small gap was left between specimen and wooden frame to prevent the movement constraint, as shown in Fig. 2-3. Then, this gap was filled by soft clay at both heated and unheated faces of specimen as flame retardant. Meanwhile, fireproof material was used to protect all faces of the specimens except the heated face before being left inside the furnace programmed with ASTM E119. The fireproof material was very soft; therefore, the specimens could be freely deformed during fire test. The details of raw materials made of mortar, as well as the standard fire curves and experimental conditions, are summarized in Fig. 2-4 and Table 2-3.

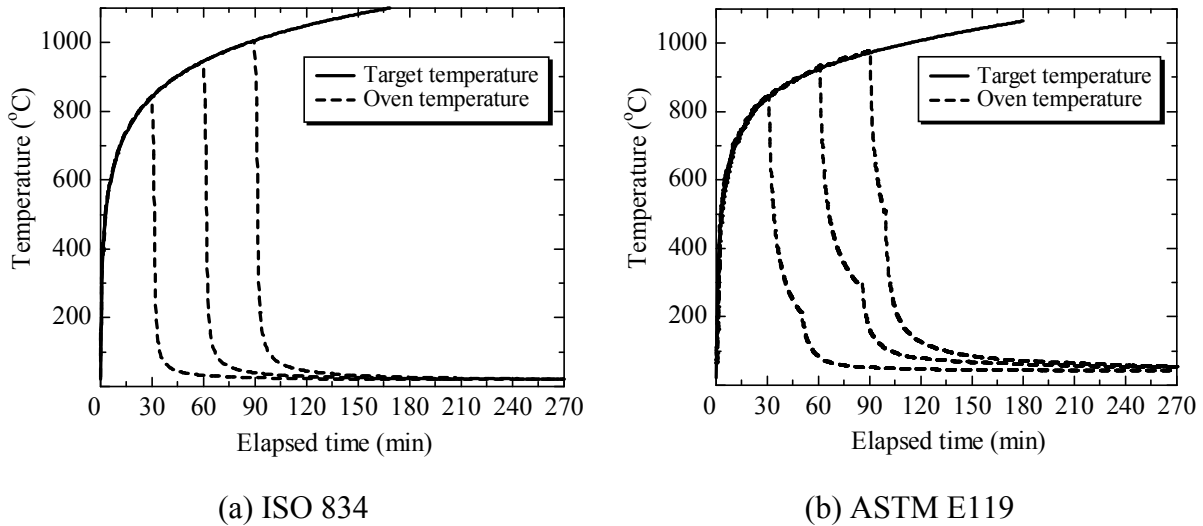


Fig. 2-2 Target and oven temperature

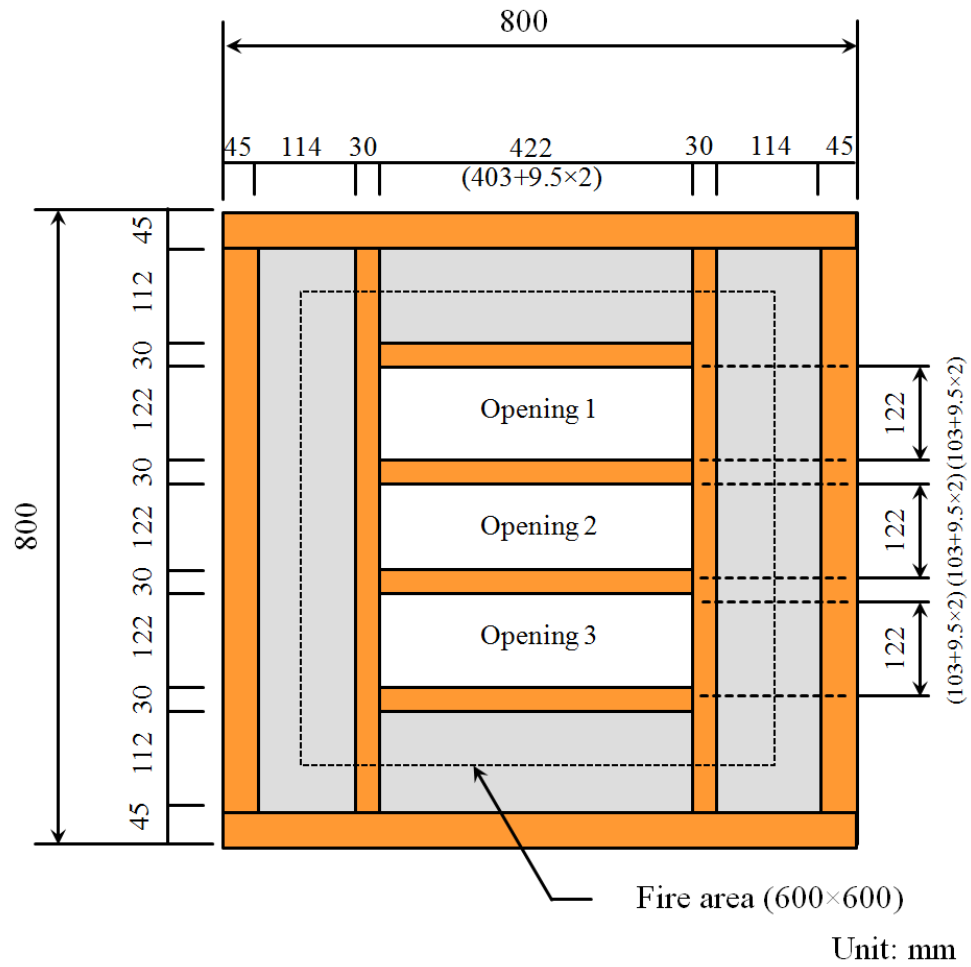


Fig. 2-3 Details of wooden frame for ISO 834 furnace



(a) ISO 834



(b) ASTM E119

Fig. 2-4 Experimental conditions of fire test

Table 2-3 Specimen details

Series name	Cement	Sand	Firing	Experimental condition
JP ISO	C1	Carbonate	ISO 834	1D without fireproof
JP ASTM	C1	Carbonate	ASTM E119	1D with fireproof
TH ISO	C2	Carbonate	ISO 834	1D without fireproof
TH ASTM	C2	Silica	ASTM E119	1D with fireproof

Note: 1. C1 and C2 are the cement that locally available in Japan and Thailand.

2. The experimental condition of *1D without fireproof* means mortars were placed at the lid of the furnace of ISO 834. Meanwhile, *1D with fireproof* means the fireproof material was used to protect all specimens' faces except heated face before being left in the furnace of ASTM E119.

3. All series, except TH ISO, were subjected to fire for 30, 60 and 90 minutes. Meanwhile, TH ISO was subjected to fire for only 90 minutes.

2.2.3 Quantitative experimentations

The quantitative experimentations aim at to understand the progress of fire damage to oven-dried mortar and the influence of different raw material in mix proportions in response to fire. The experimental works usually started from the visual observation to understand the general condition of all fire-damaged mortar series, as well as the developed temperature gradients. However, the series of JP ISO and TH ISO was conducted a meso scale 3-point flexural test to obtain the influence of Ordinary Portland cement used in mix proportions. Table 2-4 shows the details of chemical composition of C1 and C2.

Table 2-4 Chemical composition of C1 and C2

Type	Oxide (%W/W)								LOI
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	SO ₃	
C1	22.3	5.5	3.0	64.5	2.5	-	-	2.2	-
C2	20.2	4.8	3.4	64.6	1.4	0.2	0.5	2.4	1.6

Note: 1. C1 and C2 are the cement that locally available in Japan and Thailand.

2. LOI means the percentage of loss of ignition.

The fire-damaged 100×100×400 mm specimens were firstly investigated the surface damages. These preliminary observations allowed us to understand the general damage conditions to the materials after exposure to fire, and they are also useful for further experimental work, such as eliminating a major crack in the specimen for a meso scale 3-point flexural test. Then, the original specimens were cut into four 100×100×100 mm cubes, and the thin specimens whose thickness is approximately 10 mm were prepared following the geometry recommendations of the Japan Concrete Institute Standard: Method of test for fracture energy of concrete by use of notched beam, JCI-S-001-2003 [5]. In total, 10 layers, from heated to unheated faces, were created to understand the non-uniform degree of deterioration along the beam depth induced by one-directional fire. Additionally, the visual

observations would involve the visible damage on the top and bottom of the thin specimens, which was sometimes observed on the thin specimen nearby the heated face. Figure 2-5 shows the details of specimens for meso scale 3-point flexural test. The saw notches have been vertically set at the front and back sides along the thickness of thin specimens. By using this type of notch, the effect of effective beam's depth over the notch is negligible [6-7].

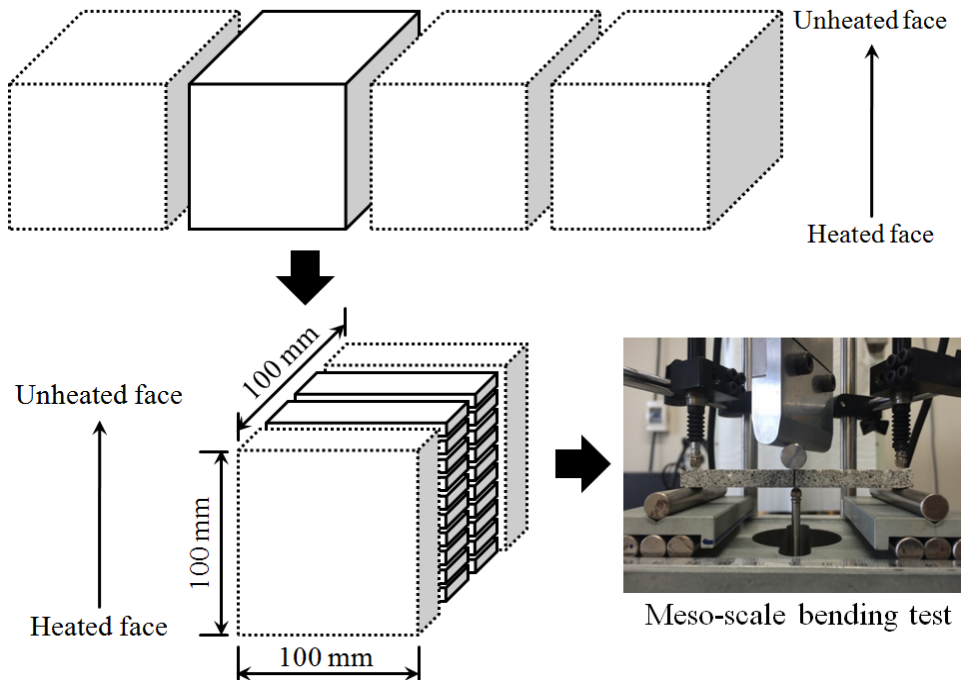


Fig. 2-5 Details of specimen for flexural test

In the meso scale 3-point flexural test, a single point load, with a constant displacement rate of $1 \mu\text{m/s}$, was applied to the top fiber at mid-span, and three LVDTs were installed at the middle and both ends during the entire period. The experimental data of load-deflection curves were recorded at 50 Hz until failure.

2.3 EXPERIMENTAL RESULTS OF CARBONATE MORTAR

In this section, both of quantitative and qualitative damage assessments focus on only the mortar made from fine aggregate whose mineral structure is carbonate. The experimental results involved in this section are developed temperature gradient, general condition of fire-damaged mortar and meso scale flexural strength. Table 2-5 shows the details of experimental results for all carbonate mortar series: JP ISO, JP ASTM and TH ISO.

Table 2-5 Detail experimentations of carbonate mortar

Mortar series	Temperature gradient	Physical condition	Flexural strength
JP ISO	Done	Done ¹⁾	Done
JP ASTM	Done	Done ²⁾	-
TH ISO ³⁾	Done	Done ²⁾	Done

Note: 1. Surface damage assessments of JP ISO series would be quantitatively reported.
 2. Both of JP ASTM and TH ISO series would be observed the general condition of fire-damaged mortar in comparison with JP ISO.
 3. Only 90 minutes of fire exposure was conducted in case of TH ISO.

2.3.1 Developing temperature in fire test

During the fire tests, temperatures were measured at several different locations in real time, such as the temperature of the oven and the surface and the developed internal temperature at the embedded thermocouples. Although one of the surfaces was directly exposed to fire, the temperature that was measured at the heated face of the specimen might not have been equal to the internal temperature of the oven for several reasons, such as thermal conductivity, the heat absorption of cementitious material, and the stability of the fire and furnace. Therefore, the temperature of the heated surface is a more appropriate value for describing the developed thermal gradients along a cross section rather than the oven's temperature.

When mortars were subjected to one-directional fire exposure, the internal temperature gradients started to gradually increase with elapsed exposure time. At a given distance from the heated face, the temperature tends to be higher when subjected to a longer duration. Along the cross section, the developed temperature gradually decreases at a greater distance from the heated face.

The temperature gradients were drawn from the maximum temperature at various depths from heated face. Figure 2-6(a) to 2-6(c) show a comparison of increased temperature of JP ISO and JP ASTM. Mortar specimens for these two series were exactly same condition before fire test. They were burnt with different fires and experimental conditions. The slight difference of developed temperature was observed because their experimental conditions were different. In case of JP ASTM, the side faces of mortar might be partially heated through fireproof material. However, the overall tendency was approximately same. Figure 2-7 indicates a comparison of JP ISO and TH ISO whose only difference is ordinary Portland cement used in mix proportion, i.e., C1 for JP ISO and C2 for TH ISO. In this case, the increased temperature was also approximately same.

Based on the developed temperature, it implies that the different thermal loading would not significantly affect the temperature gradients along the beam depth if accumulate fire severity was same. In addition, the significant of accumulate fire severity would affect the increase in temperature at various depths from heated face.

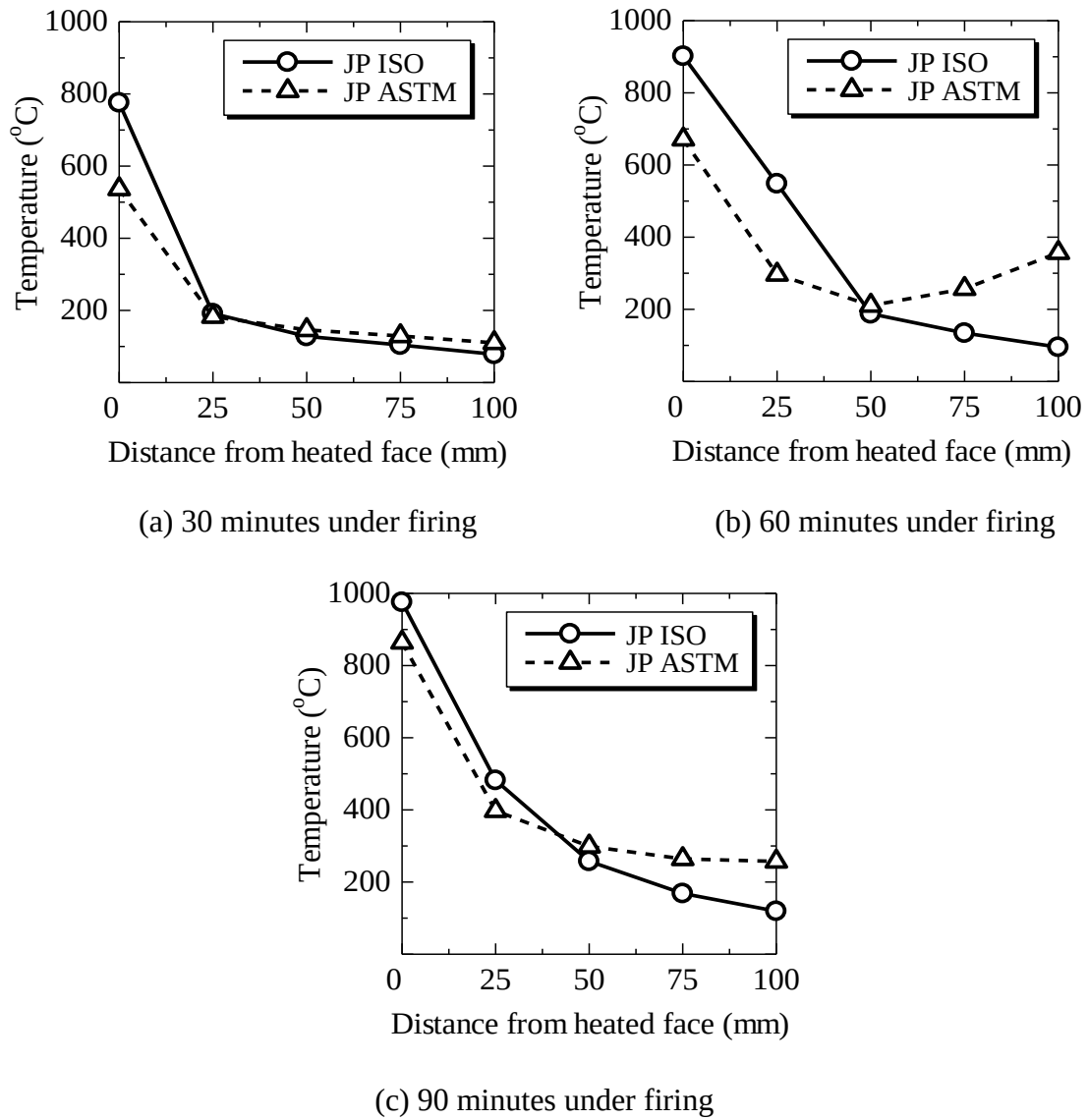


Fig. 2-6 Developed temperature gradients of JP ISO and JP ASTM

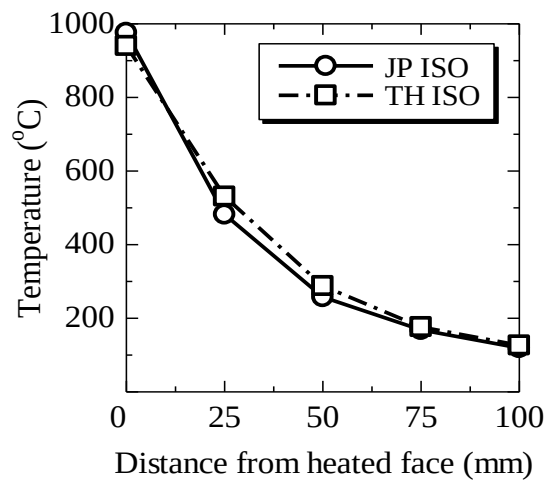


Fig. 2-7 Developed temperature gradients of JP ISO and TH ISO (90 minutes)

2.3.2 Post-fire physical damage assessments

When cementitious material was subjected to high temperature treatment, the crack might initiate and propagate due to the reduction of material strength and the development of thermal stress. Although it has been known that the different maximum temperatures to which specimens are exposed could introduce different degree of deterioration, no quantitative surface damage assessments have yet been reported. Therefore, this study aims to understand the general conditions of the mortar series and the quantitative surface damage assessment of JP ISO after heating and cooling regimes. In this study, there are two types of cracks: crazing on the heated face and cracking on side faces of the mortar prism. The physical condition of fire damaged carbonate mortars is illustrated in Fig. 2-8.

One-directional fire exposure was applied to the heated face, which experienced a drastically increased temperature. Meanwhile, the temperature of the internal layer of mortar might have been comparatively low. This means that there was a large difference in temperature between the heated and unheated faces at the beginning of the burning process. This could cause an expansion at the heated face, without corresponding expansion of the other sides. In this study, all specimens were instantaneously cooled in air after reaching the target duration. As a result of this, the temperature to which mortars were exposed, especially at the heated face, changed suddenly. An expanded surface in the heating process might suddenly shrink. Therefore, relatively straight cracks were introduced perpendicular to the heated face owing to the decrease in tensile strength under high temperature, as well as the rapidly developed tensile stress [8].

From the overview of the physical damage conditions in all carbonate mortars, it seems that the characteristics of crack induced by fire were approximately same. However, a horizontal crack was sometimes observed, e.g., JP ASTM and TH ISO. In the case of JP ASTM, this horizontal crack was just a craze cracking because specimens were partially heated through fireproofing material at side faces. It seemed to be a real cracking in the case of TH ISO, even though the specimen was subjected to perfectly one-directional fire exposure. In addition, there were very fine cracks existing near the heated border of TH ISO.

As for the general condition of fire damaged carbonate mortars, it is seen that the number of cracks increases with increasing time exposure. Moreover, the average length of these cracks tends to be higher for longer durations. To obtain a better understanding of this phenomenon, quantitative cracking assessments of the JP ISO series were conducted. Figure 2-9 shows the techniques of crack observations. The density of surface crazing at the heated face was determined by the number of interceptions of craze cracking on the virtual grids. These gridlines were in both horizontal and vertical directions. Meanwhile, the crack depth and spacing were determined on both side faces. The depth of cracking was measured from the border to the crack's tip, and the spacing was measured between single cracks. The relationship between crack density and temperature experience at the heated face, as illustrated in Fig. 2-10, tends to be higher for specimens that were exposed to higher temperature.

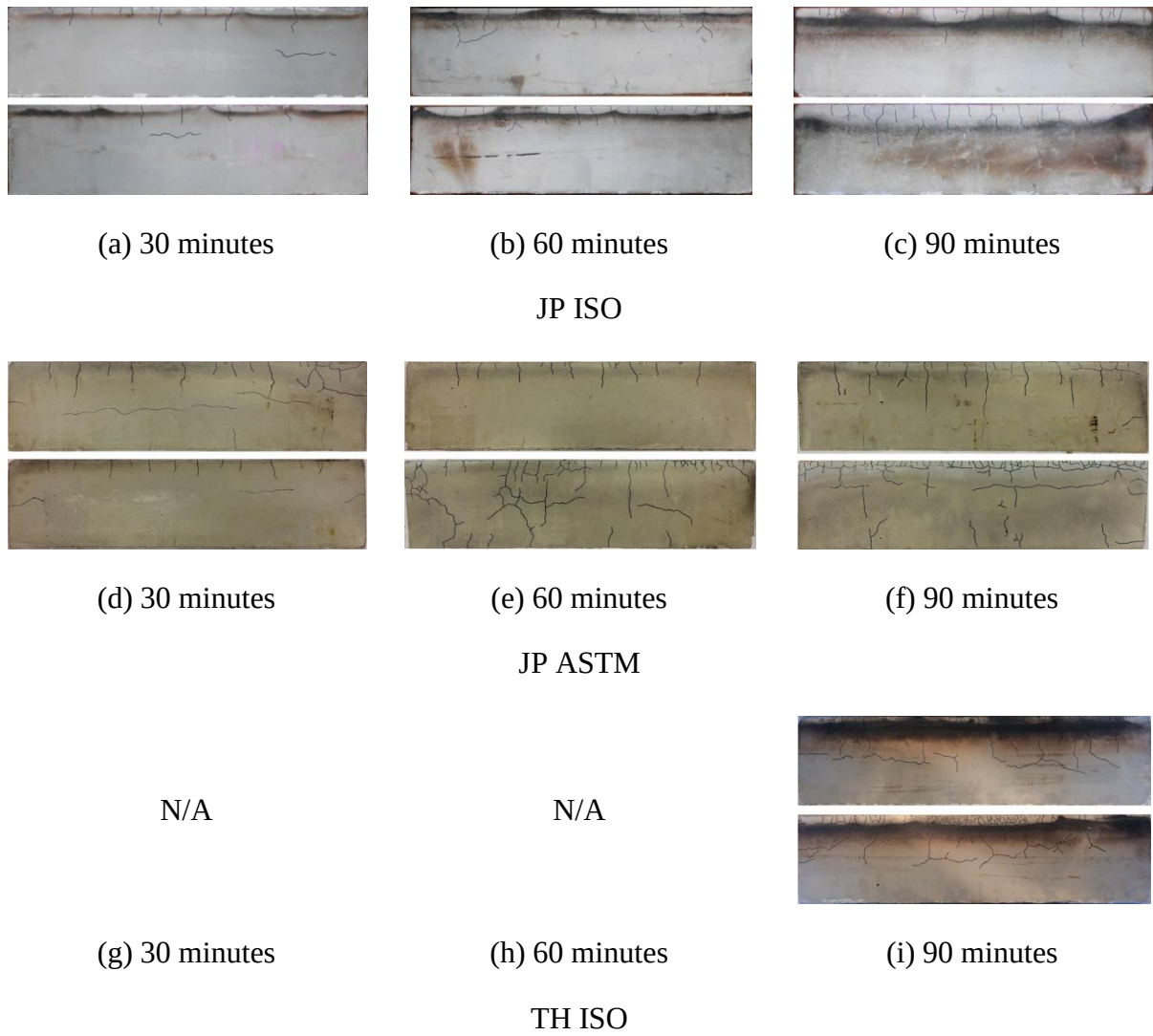


Fig. 2-8 General specimen cracking behavior of fire damaged carbonate mortars

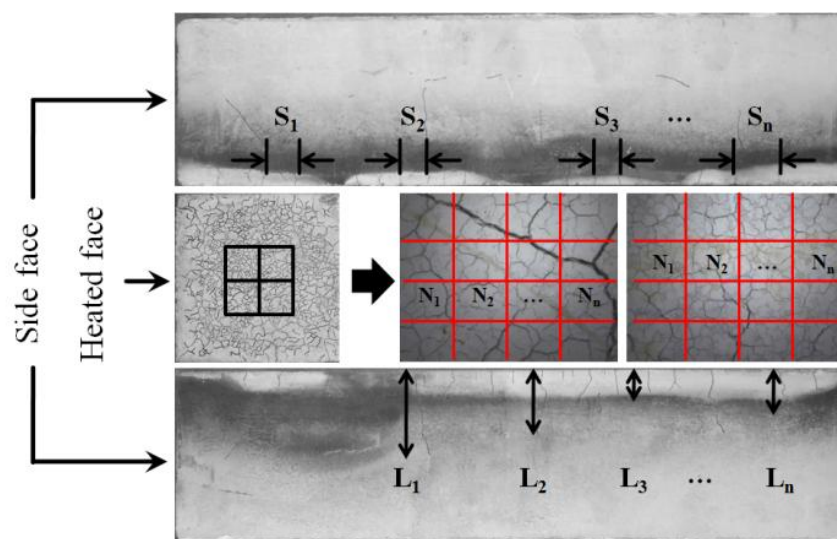


Fig. 2-9 Crack observations of specimen's faces

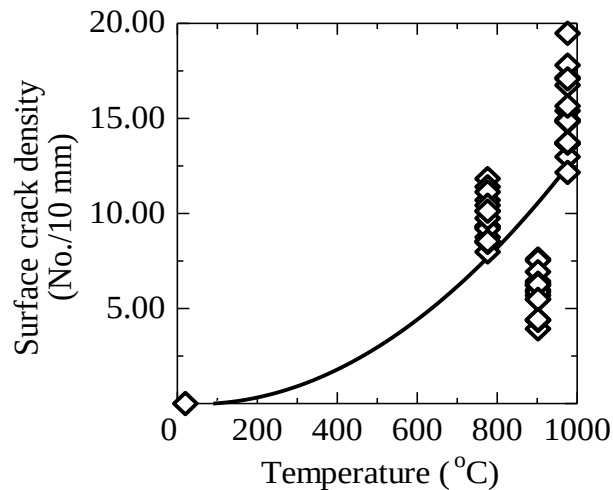


Fig. 2-10 Surface crack density-temperature relation

However, the characteristics of cracks on the side faces were different from the crazing found on the heated surface. Relatively straight cracks were seen on the side faces. The crack depth, which was measured from the edge of the side face to the tips of cracks, was not significantly different when comparing different cases and the distribution of spacing between single cracks became less scattered as the time exposure increased. The results of the crack depth and spacing are shown in Fig. 2-11(a) and 2-11(b), respectively. Although longer cracks could be observed when specimens were subjected to longer exposures, there is no clear relationship between average crack depth and exposure time. As seen from Fig. 2-11(b), the crack spacing could explain the progress of cracks more clearly. Because the mortar was allowed to cool down immediately in air, the external thermal loading at the heated face changed suddenly from high to ambient temperature. The increase in exposure time and temperature might cause more expansion in the mortar and decrease the resistance to crack initiation. Therefore, the number of cracks on the side faces is increased with increased exposure time. The high variance in the crack spacing is observed in mortar exposed to short-term firing, whereas scattering decreases with longer exposure.

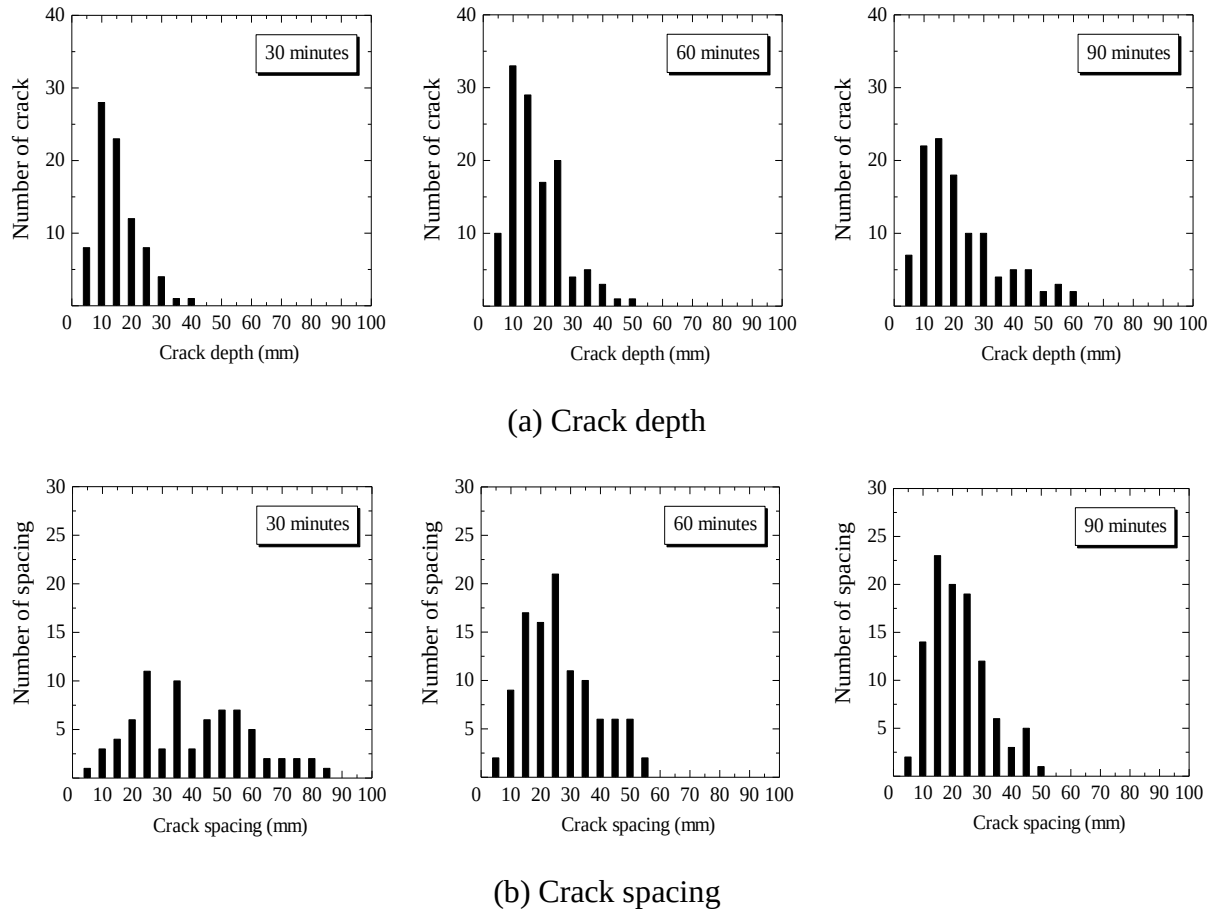


Fig. 2-11 Crack observations on side face

2.3.3 Post-fire flexural strength

In this section, the in-depth flexural strength of JP ISO and TH ISO, whose difference is only the cement used in mix proportions, is explained. The crack mapping of JP ISO and TH ISO was different, even though the developed temperature at various depths was similar. Therefore, a comparison between these two mortar series after 90 minutes of fire exposure can describe the influence of different cement.

The approximately 10-mm-thick testing specimens were prepared while avoiding straight visible cracks initiated by heating and cooling to measure the material strength along the beam depth after firing. However, visible cracks that propagated from the crazing at the heated face could be found on the bottom and top fiber of the thin specimens, especially for the specimens near the heated face. In case of the series of JP ISO, the damage evidence, i.e., visible cracks propagating from the crazing, still existed up to approximately 20 mm in case of 30-minute firing and 40 mm from heated face for 60- and 90-minute firings. The crack width, which ranged from 0.03 to 0.40 mm, was measured on the bottom and top faces of the thin specimens. Meanwhile, this kind of damage evidence on top and bottom surface of thin specimen of the TH ISO series also exists up to approximately 40.0 mm from heated face. The crack propagated from the heated face had a strong influence on the mechanical behavior of fire damaged mortar, especially for failure modes.

In the flexural test, the failure modes could be divided into two categories, as shown in Fig. 2-12. The pre-existing crack was vertically set at the front and back sides along the thin specimen's thickness. When applying a single point load at the top fiber up to the load limit, a real crack would occur. The bending failure locations of non-damaged specimens and specimens without visible cracks were usually found at pre-existing cracks, as illustrated in Fig. 2-12(a). On the other hand, the bending failure location was dependent upon the location of major fire crack, as shown in Fig. 2-12(b). The flexural strength was calculated using Eq. (2-3) in the case that the bending failure was observed at the pre-existing cracks.



(a) For non-damaged specimen and specimen without fire crack



(b) For specimen with existing fire crack

Fig. 2-12 Bending failure locations

$$F_b = \frac{3 \cdot P \cdot L}{2 \cdot b \cdot h^2} \quad (2-3)$$

where F_b represents flexural strength (N/mm^2); P , L , b , and h are peak loading (N), span length (mm), section width (mm) and depth (mm), respectively.

Practically for the fire damaged series, the bending failure might not be occurred at the mid-span due to the existence of fire cracks. In that case, the flexural strength would be calculated using the actual bending moment obtained at the actual bending failure location.

The average flexural strength on non-damaged mortar is 7.20 and 7.86 N/mm^2 for JP ISO and TH ISO, respectively. The flexural strength along the beam depth for JP ISO exposed to three durations, including reference specimens, is illustrated in Fig. 2-13(a). Also, the in-depth flexural strength of TH ISO exposed to 90 minutes firing is shown in Fig. 2-13(b).

In case of the JP ISO series, the flexural strength tended to be reduced in all fire-exposed specimens, especially for the layer that was directly exposed to fire at the bottom. The flexural strength of those layers was reduced by 66%, 72%, and 81% of non-damaged strength for 30, 60, and 90 minutes under firing, respectively. The loss of flexural strength of those layers was not significantly different when compared between cases because the

existing crack caused a weak point and a bending failure location. At a greater distance from the heated surface, the visible damage disappeared. Therefore, the flexural strength gradually became similar to the flexural strength of the non-damaged material. Although the flexural strength of the layer that was directly exposed to fire at bottom of TH ISO series was a large variation, the minimum value was approximately same as JP ISO. However, it could be also observed that the variation of flexural strength of the TH ISO series is higher than the series of JP ISO.

Based on the measurements of flexural strength, the loss in strength was up to approximately 30 mm from the heated face, the same as the existence of damage evidence on the surface of the thin specimens. Therefore, the influence of cracking on post-fire material strength should be taken into account. We also observed a slight increase in strength in some layers next to the severely damaged zone. This is probably because of the rehydration of the unhydrated cement particles within the appropriate range of temperature.

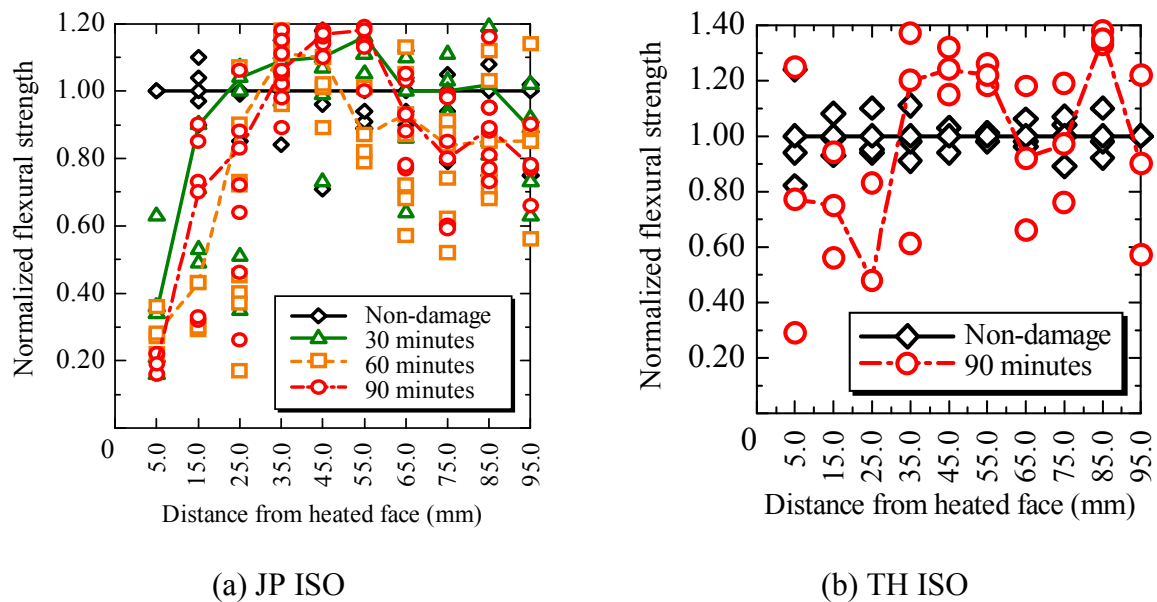


Fig. 2-13 Meso scale flexural strength

2.4 EXPERIMENTAL RESULTS OF SILICEOUS MORTAR

The experimentations of siliceous mortar focus on only qualitative experimentations in order to understand the influence of different types of fine aggregate used in mix proportion, i.e., carbonate and silica. In this section, the results of TH ASTM series would be mentioned and would be compared with carbonate mortar series.

2.4.1 Developing temperature in fire test

As previously mentioned in Section 2.3.1, the increase in temperature was influenced by the accumulate fire severity. Also, the post-fire physical damage assessments of carbonate mortar showed that the cracking conditions were different even though the developed temperature gradient was approximately same. Therefore, the influence of raw materials used made

mortar might play a dominant role on the fire damage condition of cementitious material. In this section, a comparison of developed temperature between carbonate and siliceous mortar will be discussed.

Figure 2-14 shows the comparison between carbonate mortars, i.e., JP ISO and JP ASTM, and siliceous mortar (TH ASTM). At a given distance from the heated face, the temperature tends to be higher when subjected to a longer duration. Along the cross section, the developed temperature gradually decreases at a greater distance from the heated face. In the case of carbonate mortars, the developed temperature gradients were approximately similar despite being exposed to different temperature histories. For 30 and 60 minutes under firing, the developed temperatures had approximately the same tendencies in all mortar series. However, there were prominent differences between series when the exposure time was 90 minutes. In addition, the developed temperature gradients of TH ISO and TH ASTM which was exposed to 90 minutes of fire exposure are shown in Fig. 2-14(d).

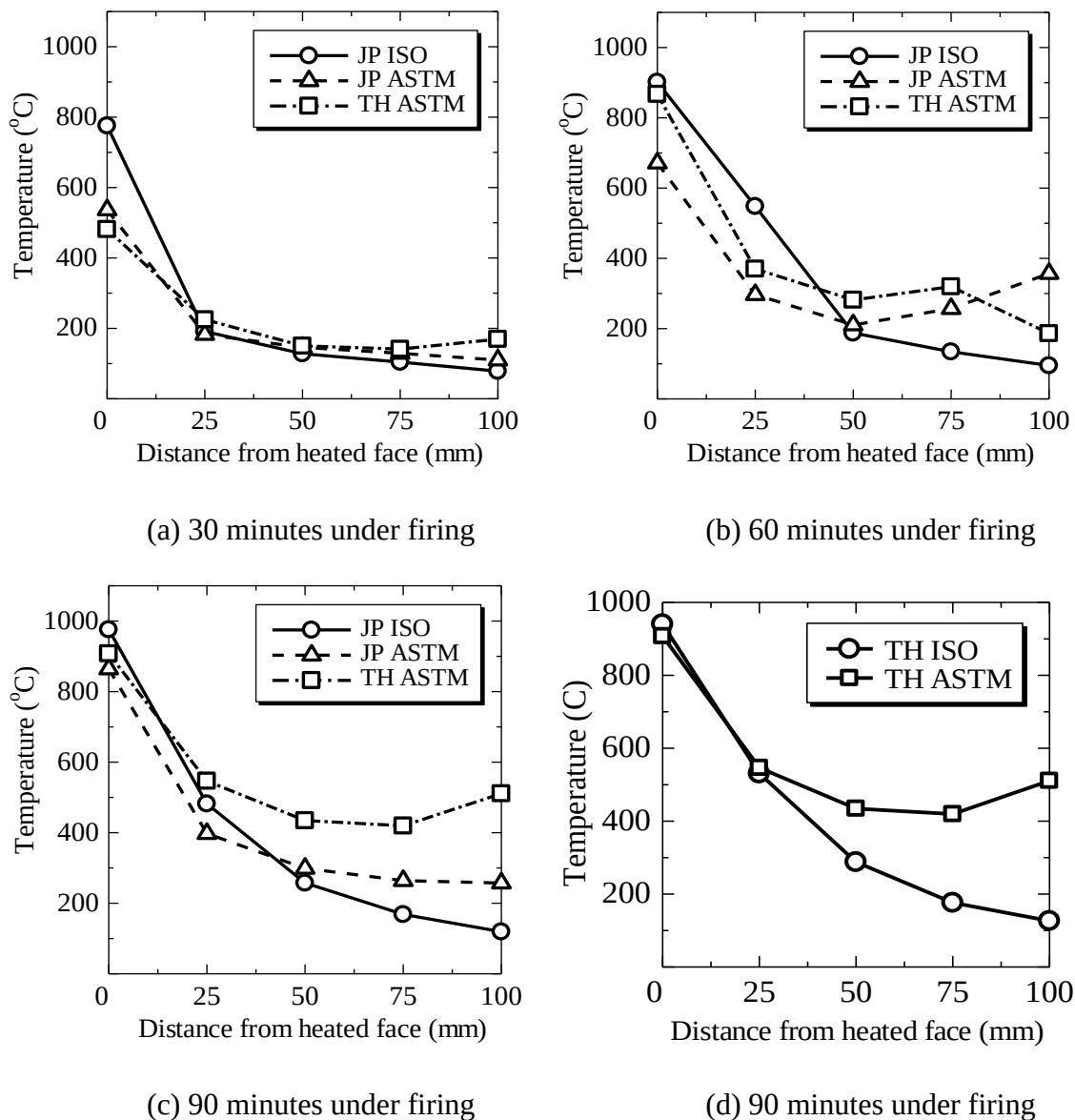


Fig. 2-14 Comparison of developed temperature between carbonate and siliceous mortar

As seen from the developed temperature gradients, the types of raw material used in mix proportions, rather than the external thermal loading, might play a dominant role in the development of internal temperature, especially for long-term exposure. For cementitious materials exposed to fire, the initiation and propagation of a crack and its intensity probably cause a non-uniform temperature gradient along the cross section. Therefore, the significant difference in temperatures between calcareous and siliceous mortar under the same fire history could be described by the different crack mappings.

2.4.2 Post-fire physical damage assessments

As same as the physical condition of carbonate mortar, Figure 2-15 shows the general damage condition of the TH ASTM series. The horizontal cracks were obviously observed as well as perpendicular crack. It became more severe and the binding property was also ruined. The characteristics of these horizontal cracks seem to indicate an expansion crack in firing. This difference in cracking pattern may reflect the significant difference in developed temperature gradients.

By comparing the developed temperature gradients along the cross section and the visual observations, it can be seen that the degree of deterioration of cementitious material progresses as exposure time, or temperature to which the mortar is exposed, increases. Moreover, the difference in raw materials used in mix proportions may be a key parameter for understanding general physical damage to cementitious materials exposed to fire, whose influences will be discussed elsewhere. Based on the results of developed temperature and the crack assessments, the existence of fire cracks could demonstrate how fire deterioration progresses in cementitious material and must be taken into account to achieve the mechanical properties of fire damaged cementitious material more precisely.

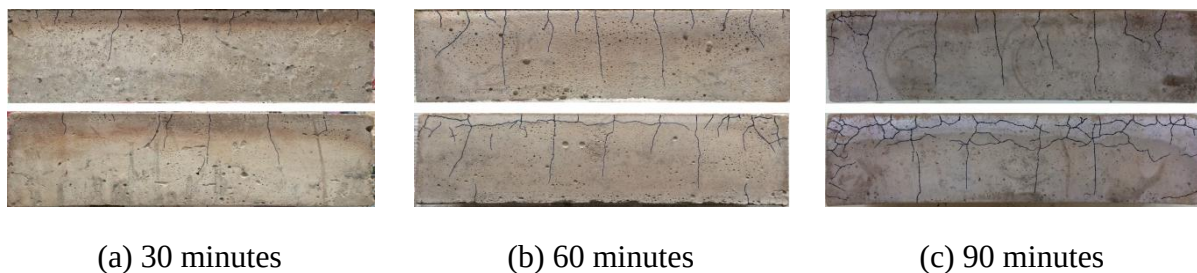


Fig. 2-15 General specimen condition of fire damaged siliceous mortars

2.5 RELATIONSHIP OF FIRE DAMAGED CEMENTITIOUS MATERIAL

Since fire exposure is related to thermal loading, temperature is probably one of the appropriate primary indices for predicting the fire damage characteristics of cementitious material. Several studies have investigated the effect of temperature background on fire-damaged material properties. Figure 2-16 shows the compressive strength of normal weight concrete at elevated temperature which is reported in Eurocode 2 [9]. In this design code, only material strengths which were evaluated by the classical methods have been mentioned. Although it was diminished with respect to an increase in temperature in both siliceous and

calcareous aggregates, there was no report regarding the influence of fire cracks on those material properties. In addition, the concrete made from different types of fine aggregate had a different response to fire exposure. This implies that the raw materials used in mix proportions are supposed to have an effect on the fire damage characteristics.

As previously discussed, the degree of deterioration of cementitious material in fire problem is non-uniform distribution regarding the distance from fire origin. Therefore, the material properties in small scale can achieve the actual damage condition more precisely. Also, the existence of fire cracks on specimens strongly affects the material strength and failure modes. Therefore, the relationship between material strength in small scale considering the influence of fire crack and temperature should be discussed. Figure 2-17 shows the comparison of flexural strength-temperature relation of two mortar series, i.e., JP ISO and TH ISO.

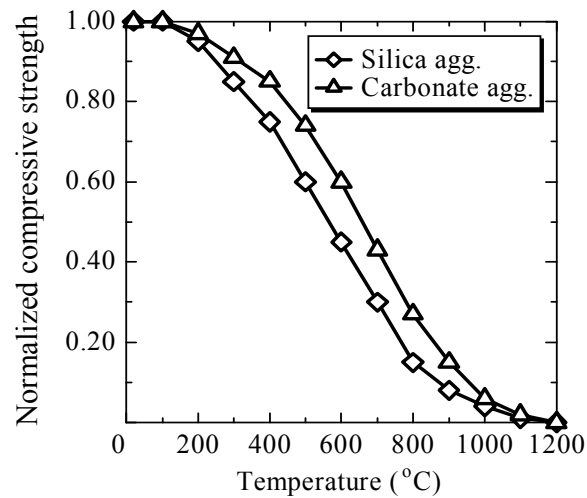


Fig. 2-16 Variation of compressive strength at elevated temperature [9]

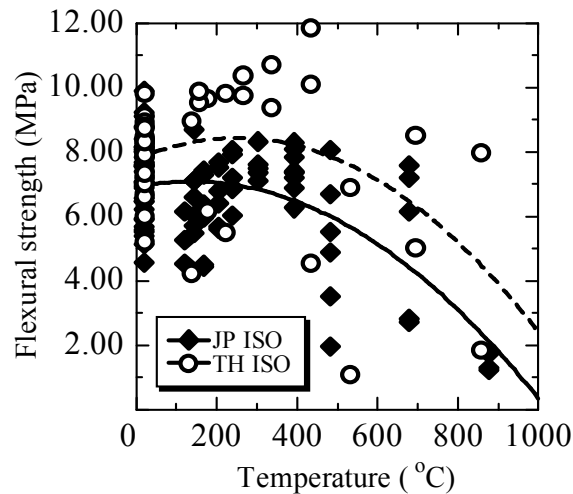


Fig. 2-17 Flexural strength-temperature relations

In the early stage of burning, the flexural strength is slightly increased compared with the strength without any damage. After that, a rapidly decreasing gradient is observed. To compare with the result of [9], the relationship between flexural strength and temperature

obtained in this study is slightly different from that of the Eurocode because the existence of a fire crack has been taken into account and the meso-scale damage assessment could obtain the post-fire properties more precisely than conventional methods of evaluation. Therefore, it would show more realistic degree of deterioration induced by one-directional fire exposure along the beam depth. With respect to an increase in temperature, the flexural strength would be more scattered because of the existence of cracks induced by fire. The flexural strength-temperature relation According to the flexural strength-temperature relation, the TH ISO series had a higher strength and variation at the same temperature experience compared with the JP ISO series.

2.6 SUMMARY

This study expresses the progress of fire damage of mortar in fire problem, as well as the influence of different thermal loadings and influence of raw materials used in mix proportions.

The raw materials used in mix proportions, i.e., cement and fine aggregate, might play more dominant role compared with an influence of external thermal loadings.

The initiation and propagation of fire damage depends on the accumulate fire severity applied to cementitious material.

Because of the non-uniform degree of fire deteriorations along the cross section, the residual performance of fire damaged material should be evaluated in small scale rather than the average response by the conventional methods of evaluation.

The crack induced by fire exposure strongly affects the strength of fire-damaged mortar. Therefore, it should be taken into account in damage evaluation in order to obtain the actual damage properties more precisely.

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CHAPTER 3

MESO SCALE DAMAGE ASSESSMENT

- **Meso Scale Experimentations**
- **Invert Calculation**
- **Relationship of Meso Scale Material Properties**

CHAPTER 3

MESO SCALE DAMAGE ASSESSMENT

3.1 INTRODUCTION

To the best of our knowledge, the fire damage characteristics in meso scale of cementitious material have not been fully understood. In addition, the material properties in various scales, e.g., chemical structures, pore structure, and mechanical behaviors, are supposed to change due to high temperature treatment. Even though much of existing research found that the mechanical behavior of fire damaged material would be changed from the non-damaged one, very few studies have focused on the relationship between these basic properties. Therefore, several meso scale experimentations are mentioned in this study in order to obtain the better understanding of fire damage mechanisms in cementitious material.

3.2 MESO SCALE EXPERIMENTATIONS

The meso scale experimentations in this chapter involved modulus of elasticity, porosity by water absorption, and determinations of calcium hydroxide (CH) and calcium silicate hydrate (CSH). The result of modulus of elasticity would be reported for two mortar series, i.e., JP ISO and TH ISO. Meanwhile, only JP ISO series would be conducted the porosity test and chemical analysis. The specimens for these two experimentations were same specimens with the flexural test.

Figure 3-1 shows the overall use of a specimen hewed from the original prism for quantitative damage assessments, including 3-point flexural test, porosity, and chemical analysis. The thin specimen was first used for the bending test. Approximately 10×10×10 mm cubes were extracted from both sides of the bending failure location for the porosity test, while the remaining part was ground into a powder with a diameter of approximately 150 μm for chemical testing. This technique could eliminate the major damage on the specimen for porosity test because the bending failure should be obtained at the existing location of major damage induced by fire exposure. However, the specimen for porosity test might contain some damage aspects, such as minor cracks, chemical decomposition due to its temperature background.

Since the quantitative damage assessments were conducted with same specimens, the physico-chemical and mechanical properties at each layer can be related together without any bias. Also, the temperature background of specimens that was interpolated at the mid-point of each thin layer were same for all assessments; therefore, the temperature might be one of the good index to describe the fire-damaged mesoscale material properties, as same as the relationship between flexural strength and temperature in Section 2.5.

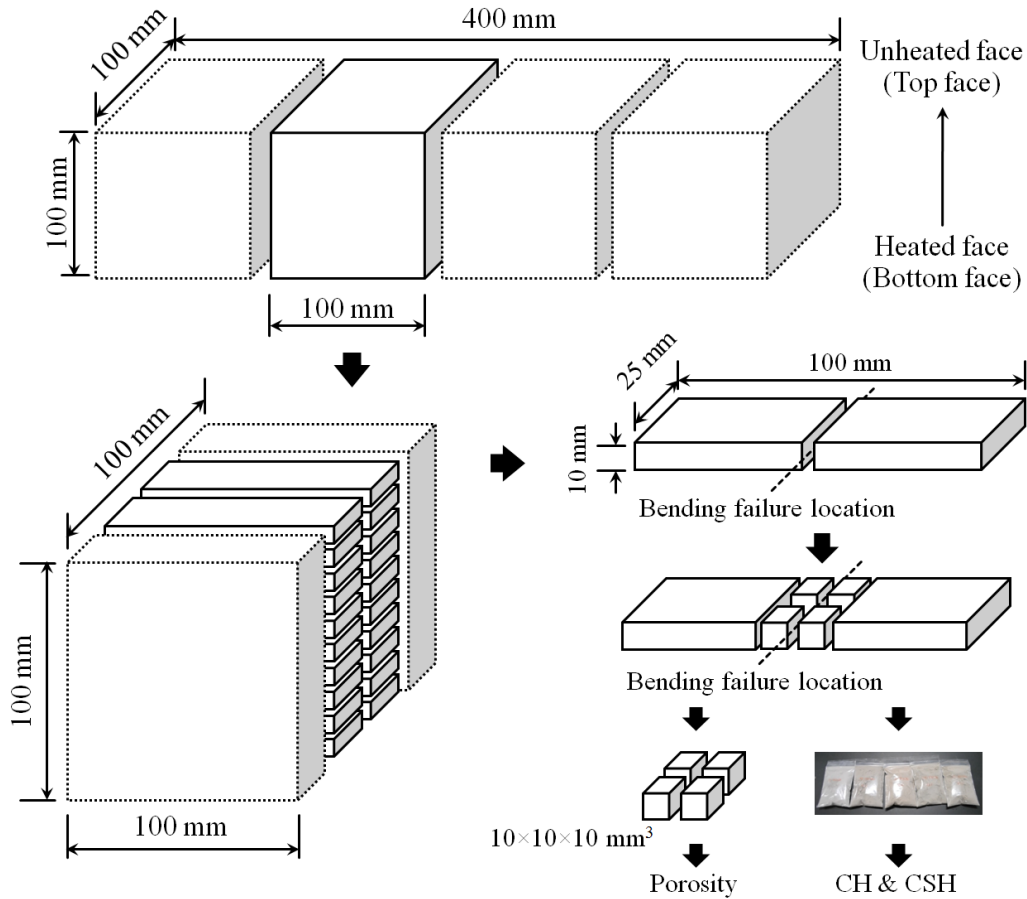


Fig. 3-1 Use of specimen for damage assessments along the beam depth (only JP ISO)

3.2.1 Modulus of elasticity

By using the experimental data of load-deflection curves, flexural strength, modulus of elasticity and theoretical fracture energy using the concept of RILEM recommendation [1] could be calculated. In this section, modulus of elasticity of JP ISO and TH ISO series would be calculated using Eq. (3-1). Meanwhile, the theoretical fracture energy will be discussed in the further section.

$$E = \frac{P_{1/3} \cdot L^3}{4 \cdot \delta_{1/3} \cdot b \cdot h^3} \quad (3-1)$$

where E represents Young's modulus (N/mm^2); $P_{1/3}$ and $\delta_{1/3}$ are loading (N) and displacement (mm), respectively at one-third of the peak load. Meanwhile, L , b , and h are peak loading (N), span length (mm), section width (mm) and depth (mm).

Figure 3-2(a) and 3-2(b) show the average modulus of elasticity along the beam depth of the JP ISO and TH ISO series, respectively. These results of two mortar series show the significant decrease in modulus of elasticity along the specimen depth. This reduction was not same as the flexural strength which was obviously recovered at the greater distance. As discussed in previous chapter, the flexural strength became similar to non-damaged material

beyond approximately 35.0 mm from heated face. However, the residual stiffness of fire-damaged mortar was still less than half of non-damaged material. Although the modulus of elasticity would be increased at the greater distance from the heated face, it does not become similar to the non-damaged material. It might imply that the stiffness of fire-damaged material was more severely diminished compared with the strength of cementitious material in fire problem.

In existing research, it has been discovered that the stiffness of material was gradually diminished at elevated temperature and was fully diminished at the temperature above 1200 °C [2]. At this temperature, the explosive spalling due to the excessive fire cracks could be also observed [3]. This implies that the existence of fire crack would significantly affect the modulus of elasticity of fire-damaged mortar. Therefore, the influence of fire crack on mechanical properties should be taken into account.

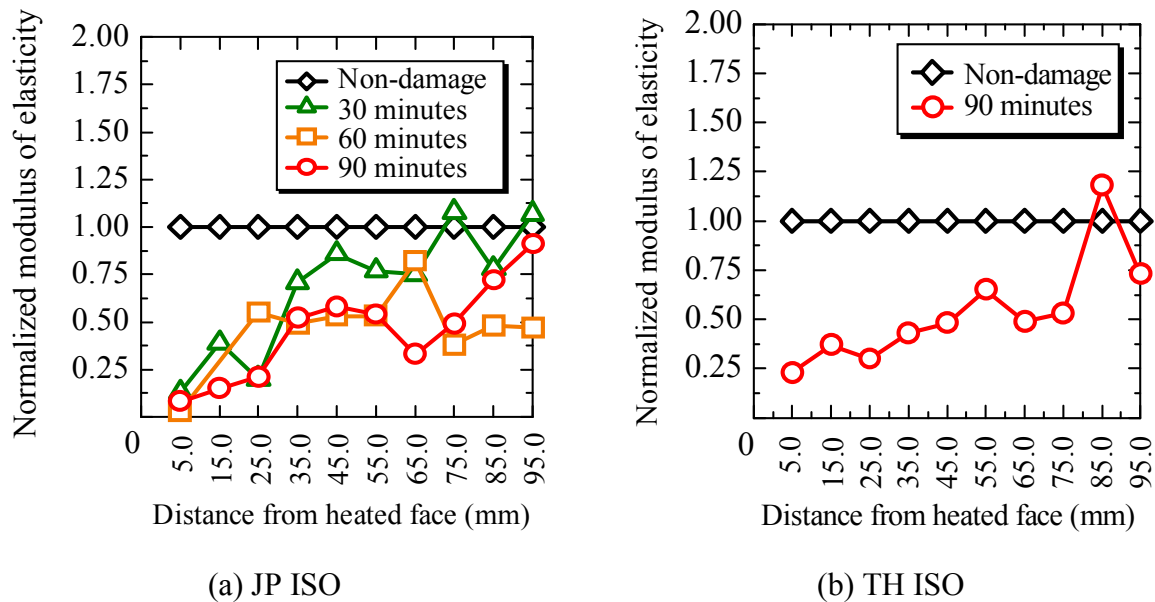


Fig. 3-2 Modulus of elasticity

3.2.2 Porosity by water absorption

In this study, the porosity of 10×10×10 mm cubic specimens was determined by only water absorption technique. The specimens were first dried in the oven at 105 °C for 24 hours and then immersed in water until fully saturated. Although the isolated pore could not be counted in calculation by water absorption, there was no additional and unexpected damage due to applied pressure in Mercury Intrusion Porosimetry (MIP) [4-7]. Equation (3-2) shows the calculation of porosity.

$$P = \frac{(m_s - m_d)}{V_s \times \rho_w} \times 100 \quad (3-2)$$

where P represents porosity (%V/V), and ρ_w , m_s , m_d and V_s are water density (g/mm³), weight of the saturated specimen (g), weight of the oven-dried specimen (g), and volume of the specimen (mm³), respectively.

To obtain an overview of the changes in porosity, the porosity trends induced by short and long durations of firing (30 and 90 minutes) are discussed in this section. Figure 3-3 shows that the porosity along the beam depth of fire-damaged specimens is not significantly different compared with reference series. In existing researches [4-6, 8-9], they have discovered the increase in porosity of fire-damaged concrete but they have not eliminated the effect of fire crack on porosity. However, the effect of major cracks was negligible in this study due to the preparation technique for fire-damaged mortar. Therefore, the porosity of fire-damaged material without existing fire crack has not been changed by fire exposure. Because the porosity was sensitively affected by the existence of fire crack, as well as the additional cement hydrates; therefore, porosity might not be an appropriate index for understanding the material strength and mechanical behavior of fire-damaged mortar. Although the fire did not introduce a change in porosity value, it might introduce a change in pore structure in other ways, such as pore structure coarsening.

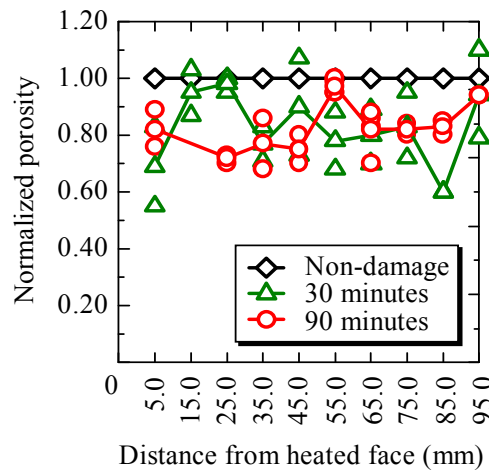


Fig. 3-3 Porosity by water absorption

3.2.3 Cement hydration products

At elevated temperature, the free water in pore system was firstly escaped out; then, the fraction water would be released by dehydration, such as cement hydration products. Then, the molecular structure of chemical compositions has been changed. In this study, only calcium hydroxide (CH) and calcium silicate hydrate (CSH), which are known to have an influence on a material's performance and its durability, are discussed. During firing, the compounds still exist up to a certain temperature, i.e., approximately 450-500 °C for CH and 500-550 °C for CSH, while the rehydration process could re-generate where the temperature ranges between 100 °C and 300 °C. The analysis of residual chemical contents would be done at the location where the temperature is sufficiently high for decomposition, as well as the location where the material strength has been recovered. In this study, the residual chemical compounds refer to the remaining amount in specimens after heating and cooling.

The residual amounts of CH and CSH were determined using a thermogravimetric/differential thermal analyzer (TG/DTA) and heavy liquid separation and methanol-salicylic acid solution, respectively.

TG/DTA was used to calculate the weight of CH by using the weight of water evaporated from the powder specimen during the test, as shown in Eq. (3-3). This concept was used in TG/DTA to determine the remaining amount of CH in the powder based on the law of mass conservation.



In the case of CSH, the molecule of water could be liberated at high temperature as in CH. Therefore, it should be decomposed during fire exposure. Generally, CSH can be dissolved in a solution made from methanol and salicylic acid. In order to prevent the dissolution of other chemical compositions containing in fine aggregate, heavy liquid separation was used to separate the coarser and finer phases of the raw powder specimen. Then, the residual amount of CSH in the finer phase could be determined based on the dissolved weight in methanol-salicylic acid solution.

The results of the remaining amount of CH and CSH were shown in Fig. 3-4(a) and 3-4(b), respectively. The amount of CH at directly heated layer was reduced by 51%, 67%, and 65% compared with the non-damaged specimen after 30, 60, and 90 minutes under firing, respectively. The average temperatures of 659 °C, 831 °C, and 877 °C for each case are sufficiently high for the decomposition of those layers. At a greater distance from heated face, the residual amount of CH tends to be higher. In the case of CSH, the decomposition occurred in all fire-exposed specimens. In the layer that was directly heated at the bottom fiber, CSH was decomposed by 29%, 63%, and 55%, compared with the non-damaged specimen after 30, 60, and 90 minutes under firing, respectively. A substantial decrease in CSH could also be observed even at greater distances from the heated side.

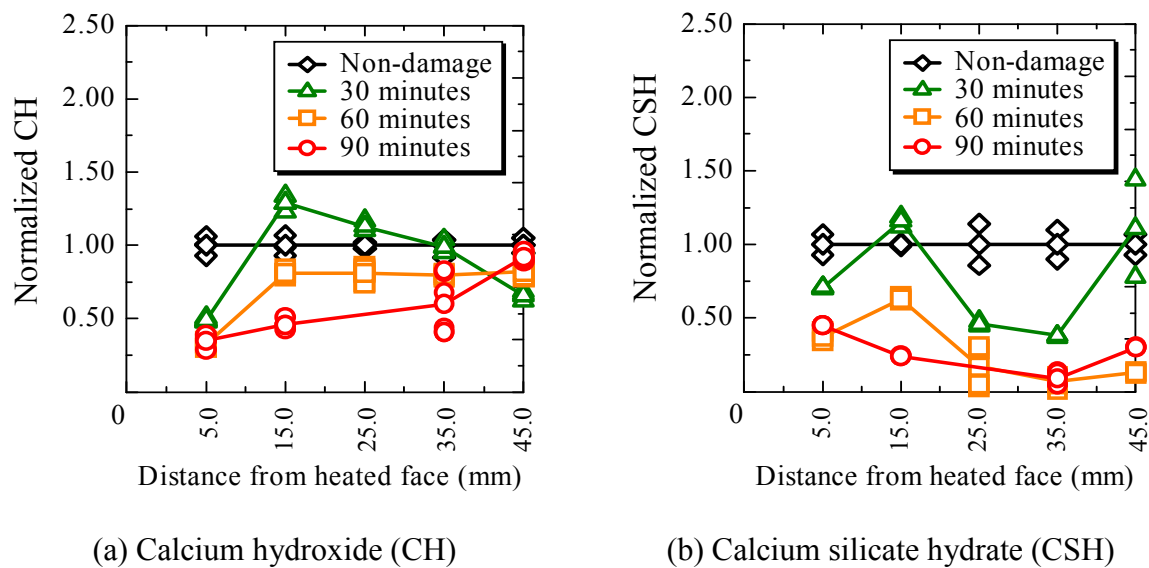


Fig. 3-4 Residual amount of cement hydration products

3.3 INVERT CALCULATION PROCEDURES

The invert calculation is based on the program of multi-linear approximation method of JCI-S-001-2003. The tensile strength, the fracture energy, and the tension softening curve would be obtained from the experimental load-displacement curves of notched beam under 3-point flexural test.

3.3.1 Mesh arrangement

The calculation of JCI-S-001-2003 was conducted on the concept of symmetry. Therefore, only specimens whose bending failure location obtained at the pre-existing crack can be conducted this invert calculation. The meshing design of half specimens was generated by using the triangle element whose sign convention of nodal number is counterclockwise. Figure 3-5 shows the typical meshing design for inverted calculation. At the bending failure location, the meshing size was recommended to be smaller than other points for calculation accuracy.

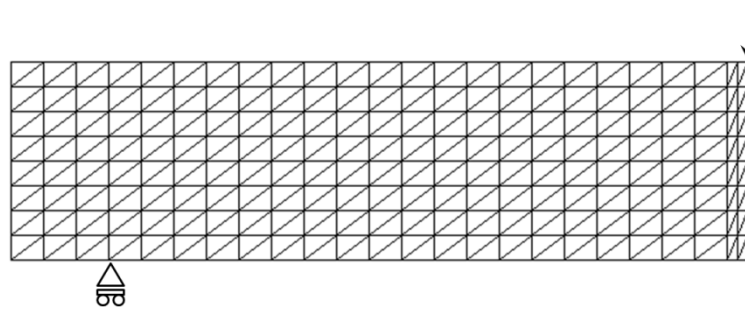


Fig. 3-5 Mesh arrangement of half specimen

3.3.2 Details of calculation

Poly-linear approximation is a method of estimating a tension softening curve by inverted analysis using load-deflection curves of 3-point flexural test. In crack growth analysis using a fictitious crack model, the bridging effect could be considered as a cohesive stress. This cohesive stress was changed according to the change in fictitious crack width. The tension softening curve could be explained by reducing the cohesive stress with an increment of fictitious crack width. The total area under cohesive stress-crack width represents the fracture energy.

3.4 RESULTS OF INVERT CALCULATION

3.4.1 Tensile strength and fracture energy

By using the multi-linear approximation method of JCI-S-001-2003, the tensile strength could be obtained from experimental data. However, only specimens whose bending failure was obtained at pre-existing crack could be conducted. In case of specimen whose bending failure was found in random location, the tensile strength would be favorably calculated using

the relationship proposed in [10]. Equations (3-4) and (3-5) show the relationship between flexural strength and tensile strength of mortar.

$$\frac{F_b}{F_t} = 1 + \frac{1}{0.85 + 4.5 \left(\frac{h}{l_{ch}} \right)} \quad (3-4)$$

$$l_{ch} = E \cdot \frac{G_f}{F_t^2} \quad (3-5)$$

where F_b and F_t represent flexural strength (N/mm²) and tensile strength (N/mm²), and h is specimen's depth (mm). E and G_f are modulus of elasticity (N/mm²) and fracture energy (N/mm).

The average tensile strength on non-damaged mortar is 5.32 and 6.00 N/mm² for JP ISO and TH ISO, respectively. The tensile strength along the beam depth for JP ISO exposed to three durations, including reference specimens, is illustrated in Fig. 3-6(a). Also, the in-depth tensile strength of TH ISO exposed to 90 minutes firing is shown in Fig. 3-6(b).

Tensile strength was obviously diminished at the location nearby heated face. At the greater distance, it gradually increased and became similar to non-damaged material. As widely known, the tensile strength should have a same tendency with the flexural strength. This study also shows the good agreement between those two mechanical properties. At the distance where the flexural strength became similar to non-damaged material, the tensile strength is also observed the same trend.

However, the tensile strength of all burnt series was also similar to non-damaged specimen. It could be said that those burnt specimens did not contain any major cracks, and might be similar to non-damage one. As a result of this, the existence of crack could have an influence on mechanical characteristics in the fire problem of cementitious material.

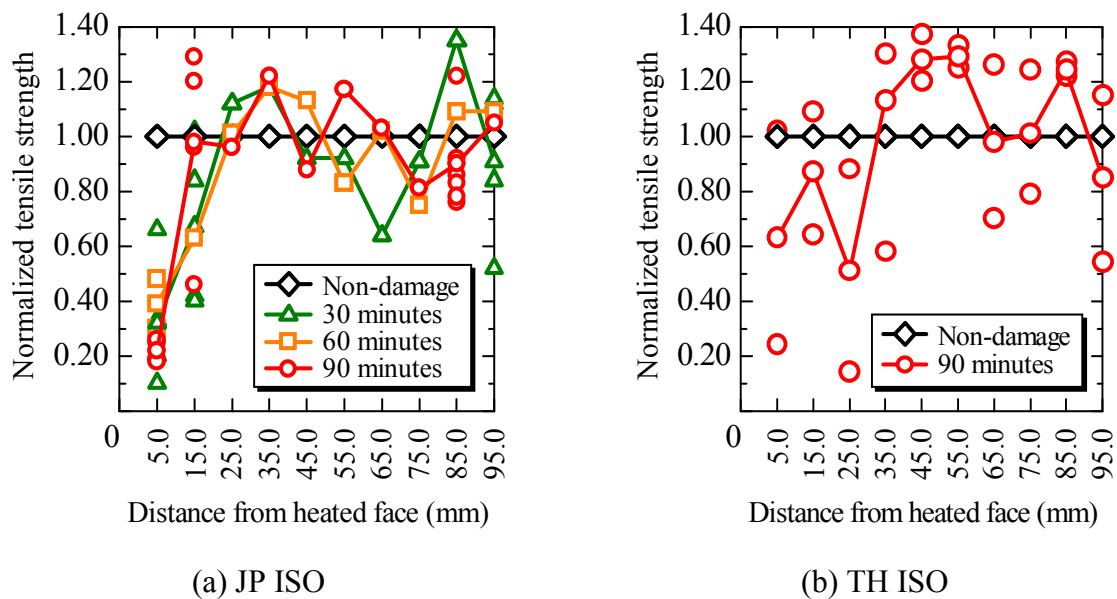


Fig. 3-6 Tensile strength

There are two techniques for calculating the fracture energy: an accumulate area under tensile stress-crack width curves, and a calculation following the recommendation of RILEM. Eqs. (3-6) and (3-7) show the calculation of fracture energy following the recommendation of RILEM.

$$G_f = \frac{W_0 + W_1}{A_{lig}} \quad (3-6)$$

$$W_1 = \left(\frac{L_s}{L} \cdot m_1 + 2 \cdot m_2 \right) \cdot N \cdot \delta_{tu} \quad (3-7)$$

where G_f represents fracture energy (N/m); W_0 , W_1 are area under load-displacement curves up to the rupture of specimens (N-mm) and work done by deadweight of specimen and loading jig (N-mm). Also, cross-sectional area at mid-span (A_{lig}), length of the specimen (L_s), span length (L), dead weight (m_1), weight of equipment (m_2), gravitational acceleration (N), and displacement at 2 N of the descending branch (δ_{tu}) are required.

Figure 3-7 shows the result of fracture energy, G_f , which was calculated based on the concept of the RILEM recommendation. The average G_f of the non-damaged specimens is 24.78 N/mm. As seen from the result, the fracture energy of all fire-damaged series was not significantly different compared with that of the reference specimens.

Figure 3-8 shows the comparison of fracture energy calculated by two techniques. It is seen that both approaches are in completely good agreement.

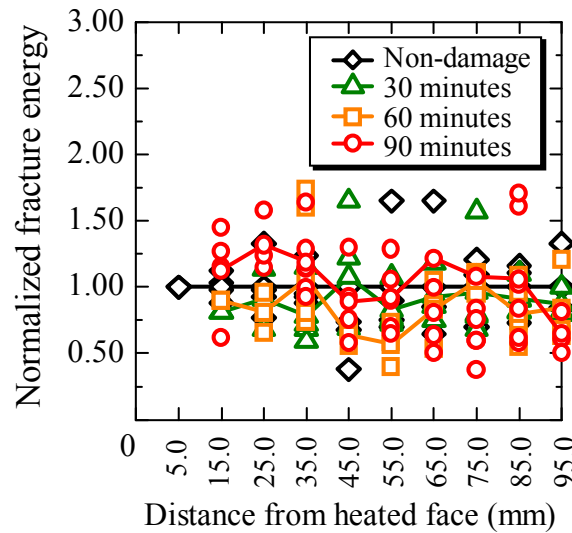


Fig. 3-7 Theoretical fracture energy

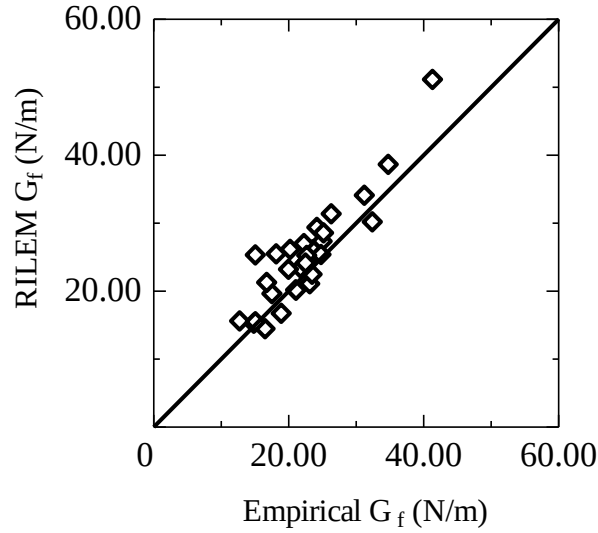


Fig. 3-8 Fracture energy using calculation of JCI and RILEM

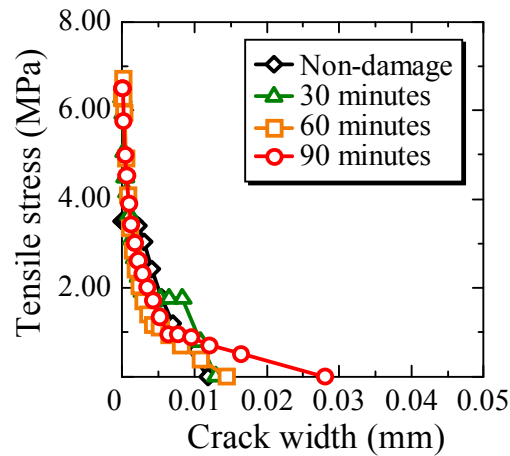
3.4.2 Tensile softening model

The tensile softening model is the relationship between tensile stress and crack width after first cracking. The tensile strength was called initial cohesive stress (F_t). The tensile softening model was proposed following the Reinhardt model [11], as shown in Eq. (3-8).

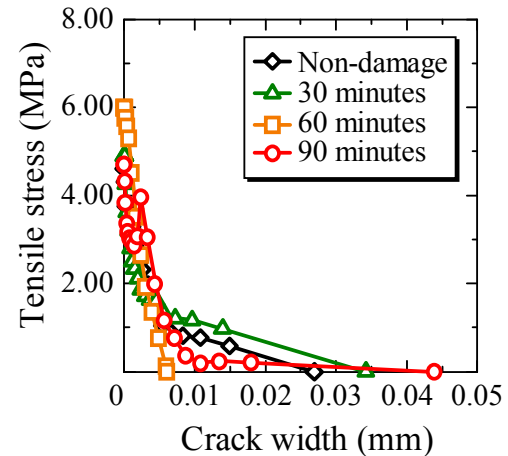
$$\frac{\sigma}{F_t} = \left(1 + \left(c_1 \frac{w}{w_c}\right)^3\right) e^{\left(-c_2 \frac{w}{w_c}\right)} - \frac{w}{w_c} (1 + c_1^3) e^{-c_2} \quad (3-8)$$

where σ and F_t are tensile stress (N/mm^2) and tensile strength (N/mm^2), respectively. The crack width (mm) and maximum crack width (mm) are represented by w and w_c , while c_1 and c_2 are arbitrary constant.

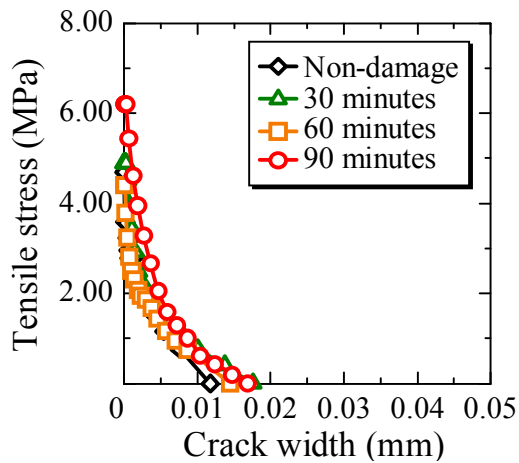
By means of multi-linear approximation techniques of JCI-S-001-2003, this technique is applicable for only the symmetric specimens. Therefore, only specimens whose bending failure location was obtained at the pre-existing crack can be used in this calculation. The mechanical response, as shown in Fig. 3-9(a) to 3-9(d), can confirm the similarity to non-damaged material of specimens without major cracks.



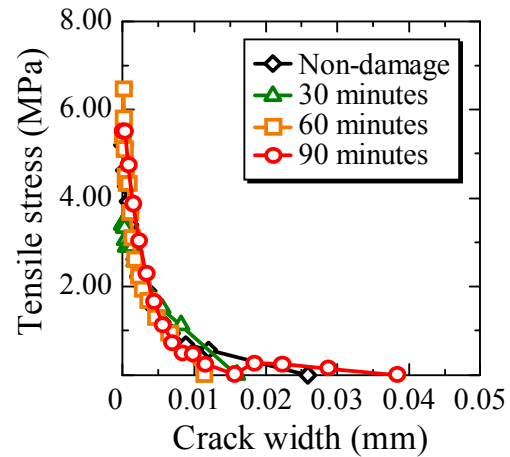
(a) 35.0 mm from heated face



(b) 45.0 mm from heated face



(c) 55.0 mm from heated face



(d) 65.0 mm from heated face

Fig. 3-9 Tensile stress-crack width curves

3.5 RELATIONSHIP OF MESO SCALE MATERIAL PROPERTIES

As for the flexural strength-temperature relation, the modulus of elasticity-temperature and tensile strength-temperature relations could be discussed. Figure 3-10 and Figure 3-11 show the modulus of elasticity-temperature and tensile strength-temperature relations of JP ISO and TH ISO mortar series, whose difference is only cement used in mix proportion. It can be seen that the modulus of elasticity is strongly related to temperature experiences. Meanwhile, it was approximately same for both mortar series. This relation could confirm that the stiffness of fire-damaged material was more severely diminished compared with its strength. In case of tensile strength-temperature relation, the relationship of TH ISO is slightly higher than JP ISO. As a result, it implies that the influence of cement might play an important role on material strength rather than modulus of elasticity of mortar in fire problem.

Because both of flexural strength and modulus of elasticity have a strong relation with temperature, they are supposed to have a mutual relation. Figure 3-12 shows that the flexural

strength has a strong relationship with modulus of elasticity for both mortar series. An obviously decrease in modulus of elasticity can be seen when the flexural strength was also comparatively low, i.e., the flexural strength of specimens with and existing fire crack. However, the modulus of elasticity of thermal-experienced specimens was still in decreasing, even though the flexural strength was similar to that of the non-damaged material. The relationship of TH ISO between flexural strength and modulus of elasticity is slightly higher than JP ISO. Therefore, it implies that the mortar made from different raw material has a different response in fire problem.

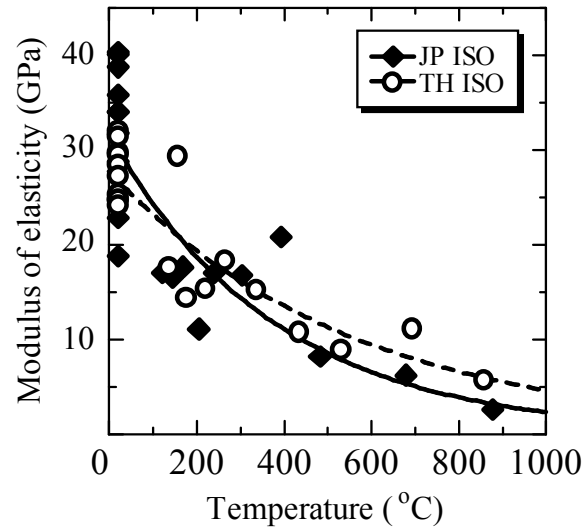


Fig. 3-10 Modulus of elasticity-temperature relation

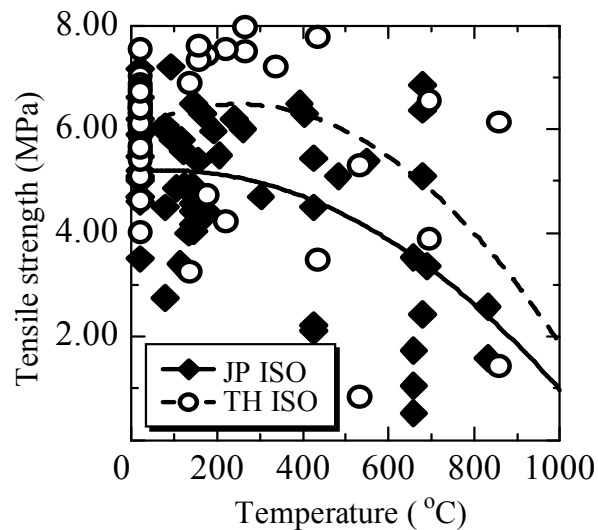


Fig. 3-11 Tensile strength-temperature relation

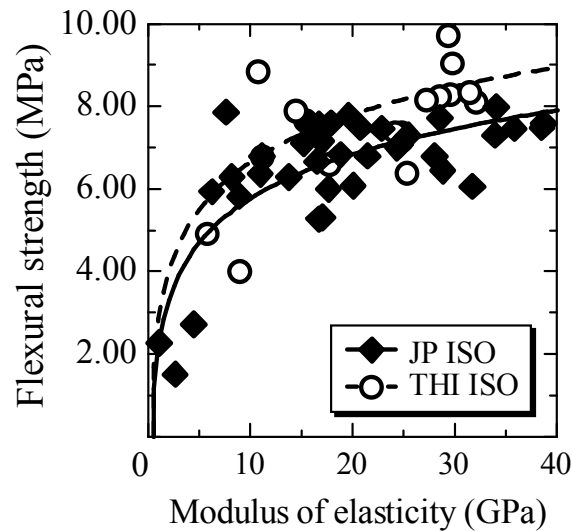


Fig. 3-12 Flexural strength-modulus of elasticity relation

Even though the mechanical response is the major evaluation factor of concrete structures, fire exposure can introduce the deterioration to cementitious material in various scales. Therefore, the relationship between mechanical properties and other meso scale material properties, i.e., flexural strength-porosity and flexural strength-cement hydrates, should be discussed in order to obtain the better understanding of fire damage mechanisms.

Although the increasing trend of porosity with temperature is expected due to chemical decomposition, the porosity by water absorption does not differ from the non-damaged mortar. The explanation for this phenomenon is, the change in porosity due to chemical decomposition mainly affects by the calcium leaching of cement hydration products, not the liberation of water molecule. Figure 3-13 shows that the porosity did not show a strong relation with temperature, as for the mechanical properties, i.e., flexural strength and modulus of elasticity. Therefore, porosity is not a good index for understanding the strength of cementitious material in the fire problem.

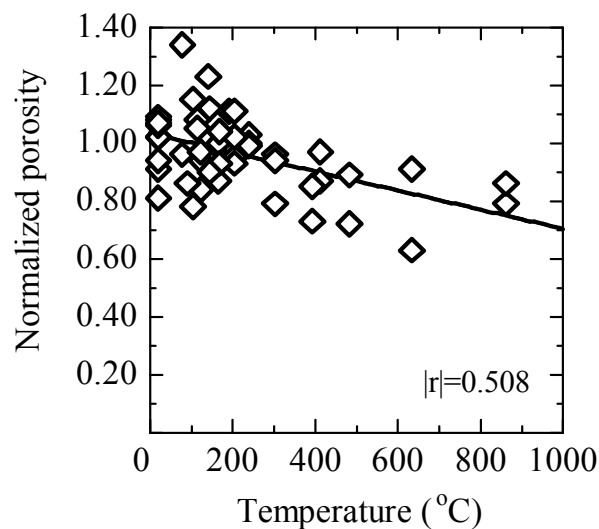


Fig. 3-13 Porosity-temperature relation

To understand the effect of cement hydrates on the mechanical strength of fire-deteriorated cementitious material, the relationships between chemical compounds and flexural strength are shown in Fig. 3-14(a) and Fig. 3-14(b) for CH and CSH, respectively. The individual relation of each chemical compound to flexural strength does not show a clear tendency. However, the integration of the decomposed amount of chemical compounds also does not clearly describe the loss in flexural strength. Moreover, the change in porosity caused by the chemical decomposition is mainly affected by the calcium leaching, not by the evaporation of chemically bound water from the molecular structure. Consequently, the individual influence of porosity and the physico-chemical characteristics might not have a strong relation with the mechanical characteristics of cementitious material in the fire problem.

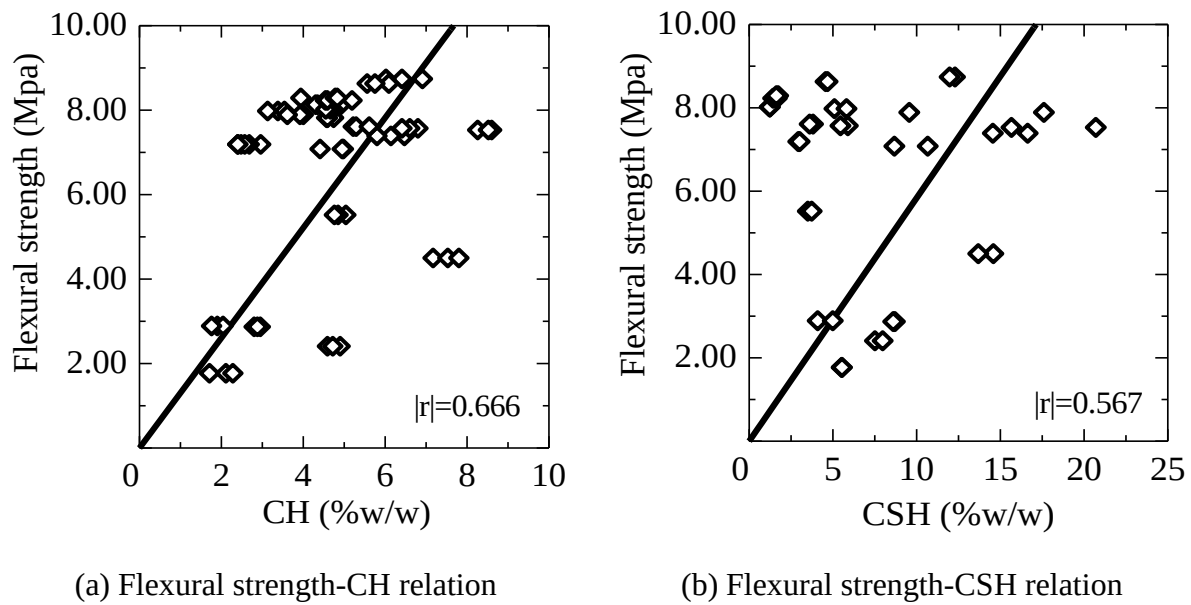


Fig. 3-14 Flexural strength-cement hydrates relations

3.6 SUMMARY

In this chapter, the meso scale damage assessments can be summarized as follows:

All of the experimental results, including mechanical characteristics, porosity, and chemical compositions, show non-uniform distribution of the degree of fire deterioration, which is dependent upon the distance from the fire origin. These findings could confirm that assessment at a small scale can describe fire damage characteristics more precisely than a macro-scale structural response.

The relationships between material strength and chemical compositions show that they are not able to describe the reduction of strength and stiffness of fire-damaged mortar, while the porosity after heating and cooling also does not have clear tendency. In addition, the crack induced by fire which has a stronger effect to the material strength and failure mode can also be treated as a kind of porosity. Therefore, the porosity and hydration products are inappropriate indices for cementitious material in fire problem.

According to the strong relationships of mechanical characteristics and temperature, as well as the crack assessments, the temperature is the most appropriate index to describe how the damage of cementitious material in fire problem progresses and to understand the post-fire mechanical properties, and it could be involved in all aspects of damage.

Because of the strong influence of the existence of fire cracks on mechanical behavior of post-fire mortar, the cracks must be taken into account in order to achieve the strength and stiffness more precisely. Therefore, the relationship between mechanical properties and temperature experiences, considering the effect of fire crack is powerful and has a wide applicability range. In addition, the influence of fire crack on mechanical properties implies that the cementitious material with different fire crack characteristics could have different mechanical responses.

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CHAPTER 4

ANALYTICAL SIMULATION OF DAMAGE

- **Coupled Analysis System**
- **Temperature Distribution**
- **Crack Mapping**
- **3-point Bending Simulation**

CHAPTER 4

ANALYTICAL SIMULATION OF DAMAGE

4.1 INTRODUCTION

Much of existing researches and experimentations on fire damaged cementitious material have been conducted the laboratory works using the conventional methods of evaluation. However, it has been confirmed by the degree of deteriorations was not uniform in the case of mortar subjected to one-directional fire exposure. This study provides the knowledge of meso scale fire damage assessments. As a result, the fire damage characteristics of cementitious material are now relatively well understood.

Besides the evaluation of residual performance by the laboratory works, it is obvious that much less attention has been paid to numerical studies of response of structural concrete after fire exposure in comparison to the experimentations. In addition, the coupled analysis system between heat transportation and structural analysis has not yet been well-proposed. Therefore, this analytical study aims at to simulate a temperature distribution along the beam section, as well as a fire crack mapping of mortar after exposed to one-directional fire.

In this study, the analytical simulations were firstly conducted the analysis of heat transportation. Then, the increase in temperature could introduce the thermal strain as an initial strain for structural analysis.

4.2 RIGID BODY SPRING MODEL (RBSM)

The rigid body spring model (RBSM) is one of the discrete analytical methods. In this study, RBSM was used as a structural analysis because of its simplicity to model a continuum material like mortar. By using this approach, the continuum material like mortar can be modeled as an assemblage of rigid particles interconnected by zero-length spring along their boundaries, as shown in Fig. 4-1. There are two kinds of spring at each boundary: normal and shear spring. The properties of these springs control the fracture criteria of mortar. Each rigid particle has three degree of freedom defined at the center of gravity of particle: two translations and one rotational degree of freedom. The coefficients of spring are expressed in Eq. (4-1) and Eq. (4-2) for normal and shear spring, respectively. In order to prevent the bias of meshing design on fracture direction, Voronoi element whose geometry is random was used to model the continuum material.

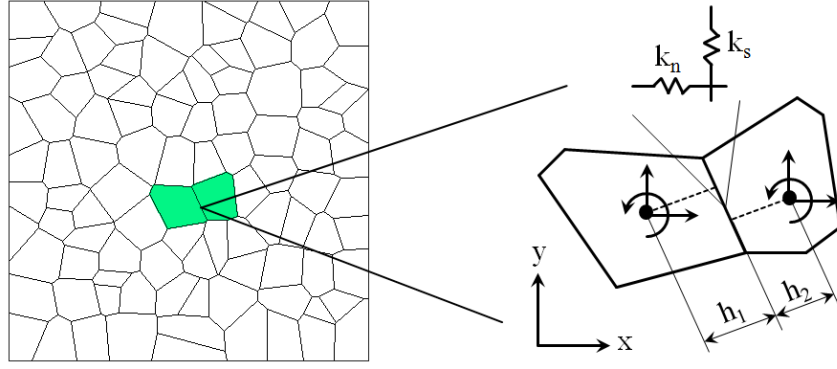


Fig. 4-1 Voronoi element and springs

$$k_n = \frac{E}{1-\nu^2} \quad (4-1)$$

$$k_s = \frac{0.5 \cdot E}{1+\nu} \quad (4-2)$$

where k_n and k_s are the coefficients of normal and shear spring, respectively. E and ν are modulus of elasticity of Voronoi element and Poisson's ratio.

The modulus of elasticity and Poisson's ratio of each element are given by a weighted average of the material properties in two particles according to their perpendiculars, as shown in Eq. (4-3) and Eq. (4-4), where h_1 and h_2 are the perpendiculars from the center of gravity to the interface between particles.

$$E = \frac{E_1 h_1 + E_2 h_2}{h_1 + h_2} \quad (4-3)$$

$$\nu = \frac{\nu_1 h_1 + \nu_2 h_2}{h_1 + h_2} \quad (4-4)$$

Since the material constitutive law is non-linear, non-linear solving method is needed to solve the force-displacement equation. This study employs the Modified Newton-Raphson method for non-linear solving. Generally, convergence criterion greatly affects the analytical result. Therefore, it must be carefully determined. The convergence criterion in this analytical study follows Eq. (4-5).

$$\frac{\sum \{R\}^2}{\sum \{Q\}^2} \leq \eta \quad (4-5)$$

where η and N_{max} are value for convergence criterion and maximum iterative calculation number. $\{R\}$ and $\{Q\}$ are the un-balanced force vector and the internal force vector, respectively. In this study, a value of η and N_{max} were set to 1×10^{-5} and 500, respectively.

The behavior of mortar in tension was assumed to be linear elastic, with a modulus of elasticity up to tensile strength. When the tensile strength was reached, a transverse crack has been initiated. A fictitious crack model was subsequently used to define the cohesive tensile

stress as a function of crack opening, as shown in Eq. (4-6). Therefore, both ascending and descending curves were defined, as shown in Fig. 4-2.

$$\frac{\sigma}{f_t} = \left\{ 1 + \left(C_1 \frac{w}{w_c} \right)^3 \right\} \exp \left(-C_2 \frac{w}{w_c} \right) - \frac{w}{w_c} (1 + C_1^3) \exp(-C_2) \quad (4-6)$$

where σ and f_t are tensile stress (N/mm²) and tensile strength (N/mm²), respectively. w_c is a maximum crack width where no stress can be transferred in μm . h is

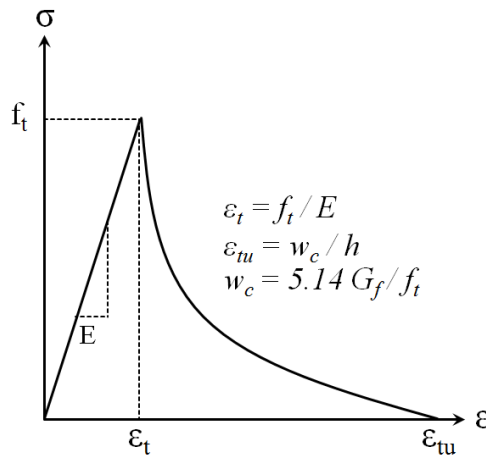


Fig. 4-2 Constitutive law of normal spring [2]

4.3 HEAT TRANSFER USING FINITE VOLUME METHOD (FVM)

Finite volume method (FVM), firstly introduced by McDonald, MacCormack and Paullay in 1970, is a method for the solution for partial differential equations (PDEs), especially for those that arise from physical conservation laws [3]. This method has gained wide-spread acceptance for robustness, intuitive formulation, and computational advantages.

The heat transportation in mortar relates to the heat conduction, in which thermal loading was applied to boundaries. When mortar is subjected to fire exposure, heat is transferred thorough material by both conduction and convection. The free water begins to evaporate, as well as the release and evaporation of chemically bound water by dehydration. The vapor and water transportation is governed by the pressure gradient, moisture and temperature gradients. Also, heat and moisture transfer in porous materials like mortar is a coupled phenomenon. In existing research [4-5], moisture migration was caused by gradient of moisture content, temperature and pressure.

According to the oven-dried condition of mortar in this study, the moisture transportation is negligible because there was no free water. In addition, there was no diffusion of bound water because it was rapidly evaporated only after released as free water [6]. Therefore, only heat conduction would be considered in this study. The governing equation of heat transfer in porous bodies was derived based on the energy conservation equation. Equation (4-7) shows the governing equation considering the heat conduction, heat capacity and required energy to release and evaporate the chemically bound water by dehydration.

$$\rho C(T) \frac{\partial T}{\partial t} + (\lambda_E + \lambda_D) \frac{\partial \bar{\rho}_D}{\partial t} = k(T) \frac{\partial^2 T}{\partial x^2} \quad (4-7)$$

where ρC , λ_E , λ_D are effective heat capacity of mortar ($\text{J/m}^3 \cdot ^\circ\text{C}$), latent heat of evaporation (J/kg), and latent heat of dehydration of bound water (J/kg), respectively. Also, $\bar{\rho}_D$ is mass of released bound water per unit volume of mortar (kg/m^3), while T , t , x are temperature ($^\circ\text{C}$), time interval (sec) and distance from heated face (m). $\partial T / \partial t$, $\partial \bar{\rho}_D / \partial t$ and $\partial^2 T / \partial x^2$ are increased of temperature per time interval ($^\circ\text{C/sec}$), amount of released bound water ($\text{kg/m}^3 \cdot ^\circ\text{C}$), and rate of changed heat per unit length ($^\circ\text{C/m}^2$).

Since the mortar was oven-dried condition, the effective heat capacity was determined on only the solid phase. The specific heat of solid phase, $C_s(T)$, thermal conductivity, $k(T)$, as temperature dependence [6-7], are described by Eq. (4-8) and Eq. (4-9). Equation (4-10) shows the approximation of released bound water by dehydration [8].

$$C_s = 900 + 80 \left(\frac{T}{120} \right) - 4 \left(\frac{T}{120} \right)^2 \quad (4-8)$$

$$k = 2.0 - 0.24 \left(\frac{T}{120} \right) + 0.012 \left(\frac{T}{120} \right)^2 \quad (4-9)$$

$$\begin{aligned} \bar{\rho}_D &= 0 & ; T \leq 200 \text{ } ^\circ\text{C} \\ &= \bar{\rho}_{\text{cement}} \times 7.0 \times 10^{-4} (T - 200) & ; 200 \text{ } ^\circ\text{C} < T \leq 300 \text{ } ^\circ\text{C} \\ &= \bar{\rho}_{\text{cement}} \times 0.4 \times 10^{-4} (T - 300) + 0.07 & ; 200 \text{ } ^\circ\text{C} < T \leq 800 \text{ } ^\circ\text{C} \\ &= \bar{\rho}_{\text{cement}} \times 0.09 & ; T > 800 \text{ } ^\circ\text{C} \end{aligned} \quad (4-10)$$

where $\bar{\rho}_{\text{cement}}$ is cement content in mix proportion (kg/m^3).

4.4 DETAILS OF COUPLED ANALYSIS

Figure 4-3 shows the fire condition of 100×400 mm of mortar section. Fire exposure was applied to the bottom face of mortar, while other faces were free of thermal loading. The initial value of temperature at any points was set to $20 \text{ } ^\circ\text{C}$ before heat analysis.

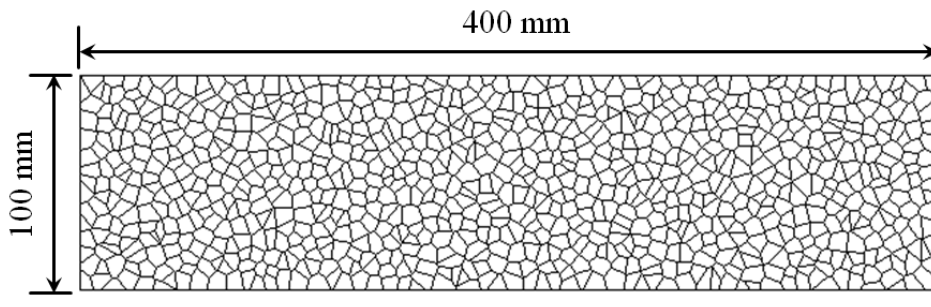


Fig. 4-3 Fire condition of coupled analysis system

The boundary elements at bottom face was applied the thermal loading. There was a thermal equilibrium between all interconnected phases within an infinitesimal volume. The temperature difference at any location would be calculated for every time steps. Then, the actual temperature would be updated by summary of temperature at previous step and temperature difference.

The increase in temperature would introduce an expansion strain as a function of temperature, as well as the deteriorated material properties as a function of temperature. This thermal strain which could be treated as an initial strain was used to adjust the total strain in normal spring of each Voronoi in RBSM analysis. In this study, the thermal strain was given in Eq. (4-11), for carbonate aggregate.

$$\begin{aligned}\varepsilon_{\text{Temp}} &= -1.2 \times 10^{-4} + 6 \times 10^{-6}T + 1.4 \times 10^{-11}T^3 && ; 20^\circ\text{C} \leq T \leq 805^\circ\text{C} \\ &= 12 \times 10^{-3} && ; 805^\circ\text{C} < T \leq 1200^\circ\text{C}\end{aligned}\quad (4-11)$$

The deteriorated material properties, e.g., tensile strength, modulus of elasticity, flexural strength, were updated for all temperature-experienced Voronoi elements following the experimental results.

Although this method did not consider the effect of crack in heat conduction, it was able to simulate the temperature distribution along the cross section induced by applied thermal loading at one face of mortar.

4.5 DEVELOPING OF TEMPERATURE DISTRIBUTION

Table 4-1 shows the developed temperature gradient along the cross section. In order to prevent the size effect of aggregate particle, the size of Voronoi element should be approximately 3-4 times of maximum aggregate. Therefore, three average sizes of Voronoi element were chosen to model the mortar, i.e., 5.00 mm, 6.67 mm and 10.00 mm.

As seen from this table, the temperature of each element was increased with increasing duration of exposure. The fineness of Voronoi element also affects the calculated temperature within an infinitesimal volume by heat transfer. At same duration of exposure, the smaller element was supposed to have a slightly higher temperature within particle.

Figure 4-4 shows the comparison of temperature gradients along the beam depth between experimental results (JP ISO) and analytical results. The temperature of each element was defined at the center of gravity of Voronoi, while the average temperature shown in figure was calculated by average temperature of all elements at same distance from heated boundary. The analytical results gave the underestimation in the location nearby the heated face. As previously mentioned in Chapter 2, the visible fire crack still existed up to approximately 20 mm in case of 30-minute firing and 40 mm from heated face for 60- and 90-minute firings. The analytical results of heat transfer were observed the approximately same trend of underestimation.

During the fire test, cracking was initiated and gradually propagated at elevated temperature. When the real cracks opened, the fire might go through these cracks to crack tips. The temperature at the crack tip was probably accumulated from heat conduction and fire exposure through the crack. Therefore, the temperature at the crack tip was supposed to be higher than the increased temperature by heat conduction. However, the temperature within infinitesimal volume using the analysis system in this study was computed by heat conduction without the effect of crack. Therefore, the underestimation of temperature in each element within the distance that fire crack exists was observed.

It implies that the behavior of heat transfer in mortar is supposed to be different if the crack exists. In order to obtain the temperature distribution along the beam depth more precisely, the influence of crack at elevated temperature should be taken into account.

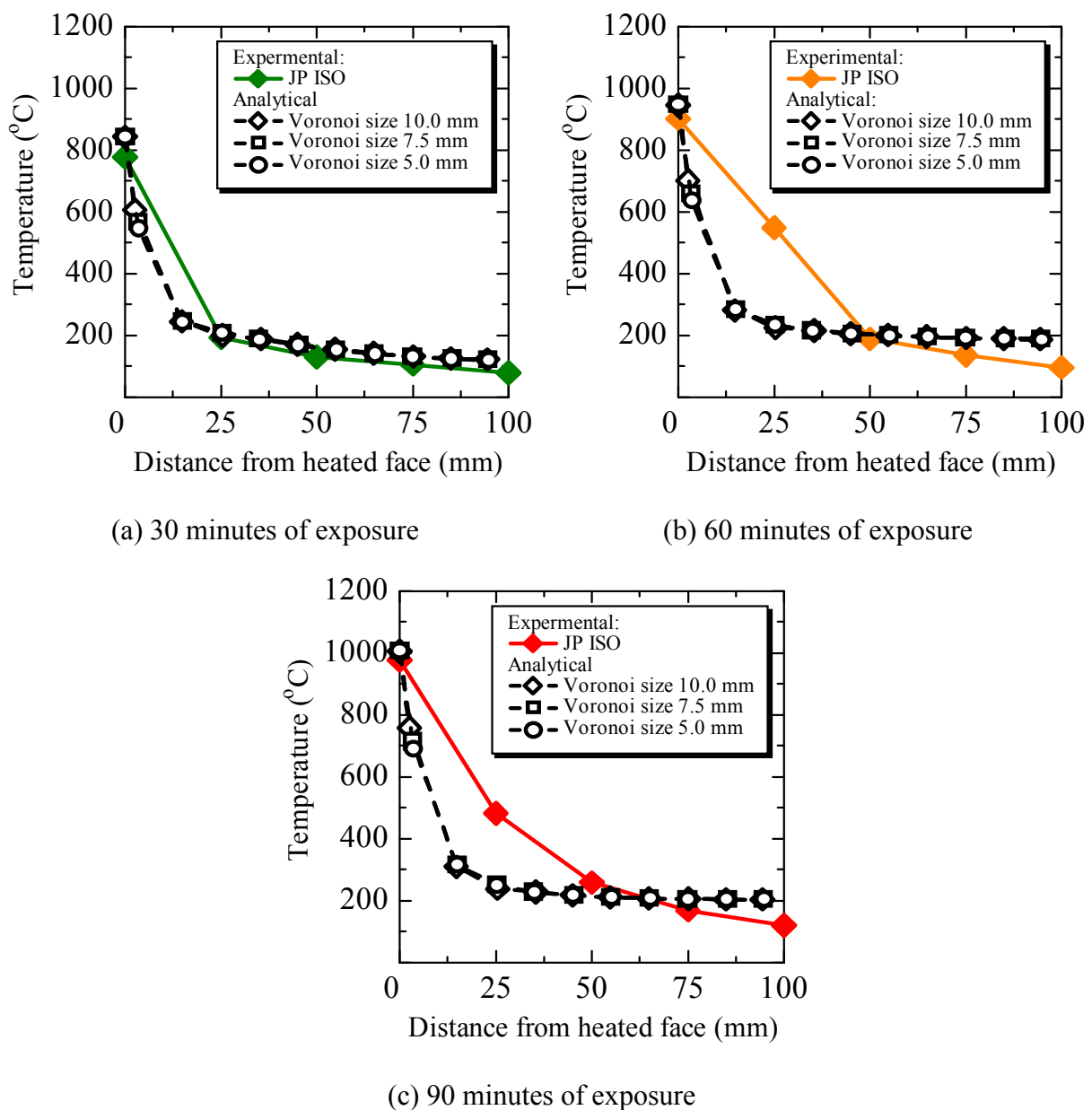
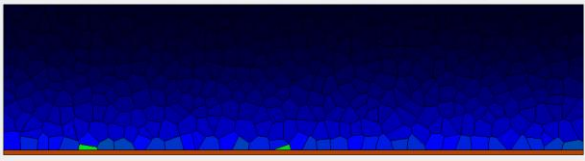
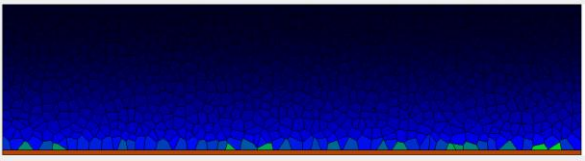
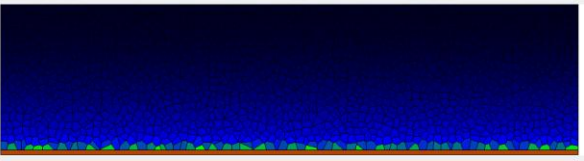
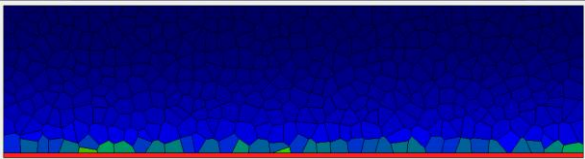
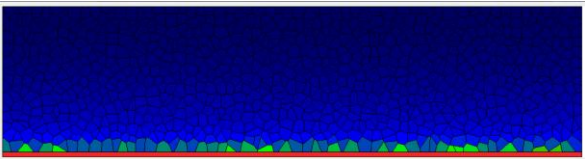
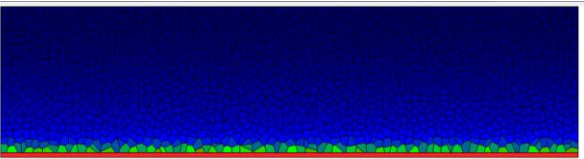
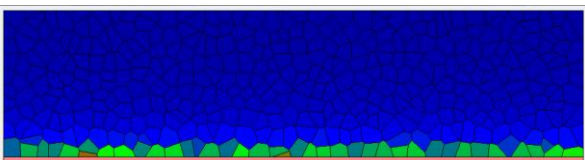
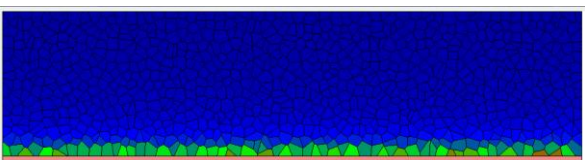
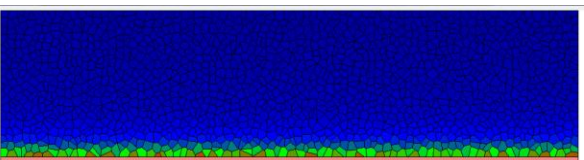
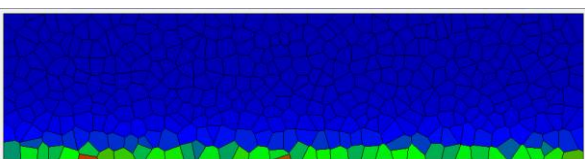
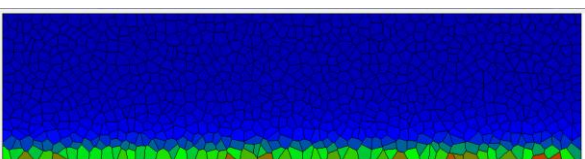
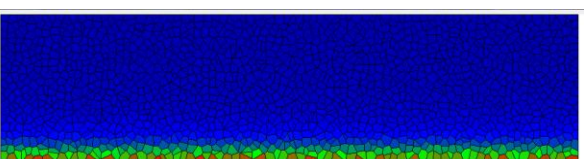


Fig. 4-4 Temperature distributions along the beam section

Table 4-1 Temperature distribution

Duration (min)	Average size of Voronoi		
	10.00 mm	6.67 mm	5.00 mm
15			
30			
60			
90			

4.6 CRACK MAPPING OF MORTAR EXPOSED TO UNI-DIRECTIONAL FIRE

In order to simulate the actual condition of mortar exposed to one-directional fire, parametric analysis should be conducted to obtain the best combination among several parameters for crack mapping of fire-damaged mortar. However, the parameters in this study were chosen based on the experimental conditions, decrease in strength of damaged material properties, as well as the maximum size of aggregate in mortar. Therefore, author would like to compare the crack condition of fire-damaged mortar with three parameters, i.e., meaning of strength-temperature relation, boundary conditions and size of Voronoi element.

Figure 4-5 shows the detail of specimen's condition during fire test. Although a gap was left between mortar specimen and wooden frame in order to prevent the movement constraint, the expansion of specimen during fire test might occur. Therefore, the actual boundary condition of specimen during fire test might not be completely free movement at both left and right ends of specimen. Table 4-2 shows the details of parametric analysis for obtaining the best combination among the chosen parameters. Firstly, the influence of change and un-change mechanical properties-temperature relations would be clarified, as shown in Table 4-3.

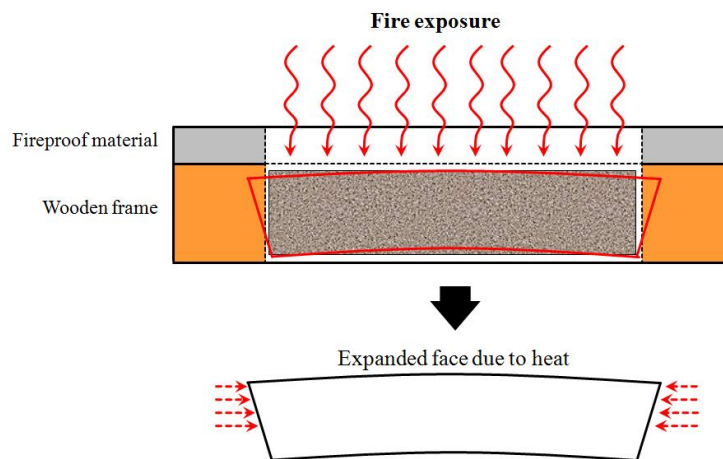


Fig. 4-5 Detail of specimen's boundary condition

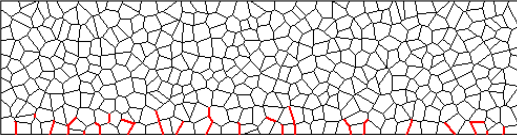
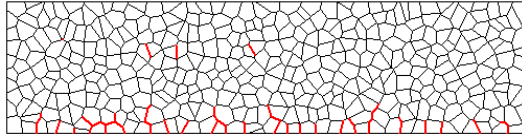
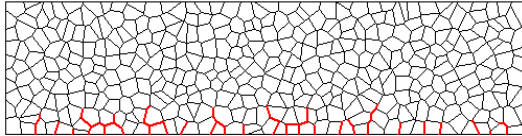
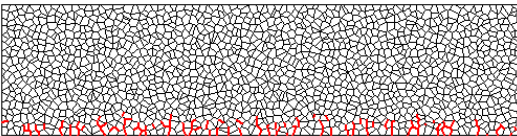
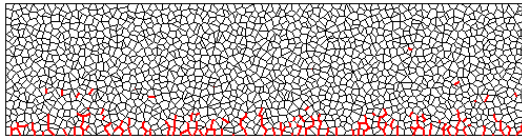
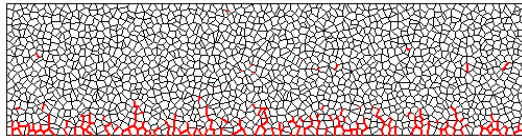
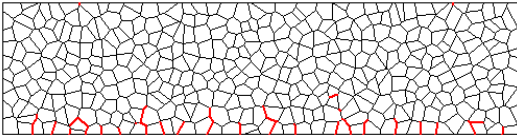
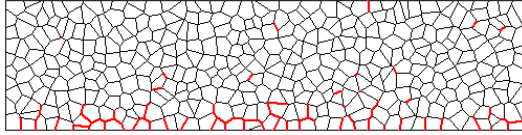
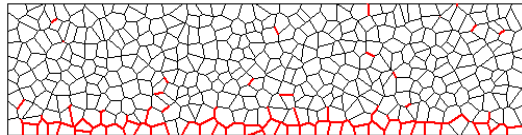
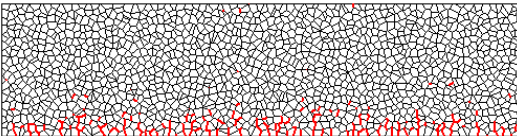
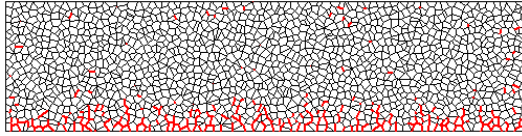
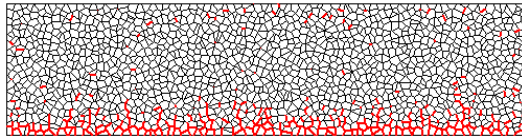
Table 4-2 Detail of parametric analysis

Duration (min)	Constant material properties		Deteriorated material properties	
	Free end	Fixed end	Free end	Fixed end
30	✓	-	✓	✓
60	✓	-	✓	✓
90	✓	-	✓	✓

Note: 1. *Deteriorated material properties* means the mechanical properties-temperature relations was considered in the coupled analysis system, while *Constant material properties* means the material properties of each Voronoi does not affect by temperature.

2. *Fixed end* condition means a completely fixed boundary at both ends of specimen.

Table 4-3 Fire crack mappings (material properties-temperature relations)

Condition	Duration of exposure (minutes)		
	30	60	90
Experiment			
Deteriorated material properties	 10.00 mm	 10.0 mm	 10.00 mm
	 5.00 mm	 5.00 mm	 5.00 mm
Constant material properties	 10.00 mm	 10.00 mm	 10.00 mm
	 5.00 mm	 5.00 mm	 5.00 mm

The fire crack mappings, shown in Table 4-3, show that the insignificant difference of crack mappings at the short fire exposure. Meanwhile, the analytical result gave the difference characteristics of fire crack, such as spalling due to excessive crack in the case of 90 minutes of exposure, in comparison with experimental results. In addition, the mechanical strength and stiffness of fire-damaged mortar were supposed to have a relation with temperature experience that was exposed to. Therefore, the relationships between mechanical properties and temperature must be considered in order to simulate the fire crack mappings more accurately.

As previously mentioned that the boundary condition of mortar during fire test might not be completely free of movement constraint, author would like to conduct the boundary conditions at upper bound and lower bound: completely free BCs and completely fixed BCs at both ends of specimen, as shown in Fig. 4-6, together with the material properties-temperature relations. In the case of both ends have been completely fixed, it represent the case that mortar specimen was exactly fit with the size of openings. Therefore, the horizontal movement was completely restrained.

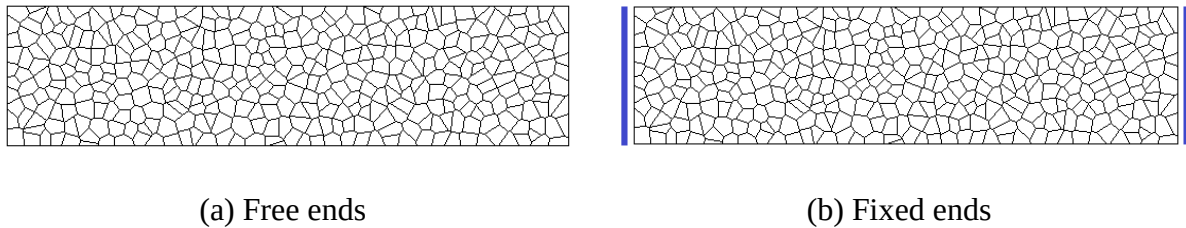
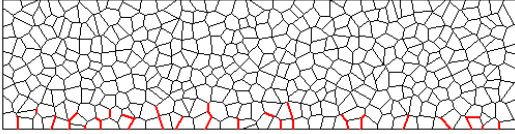
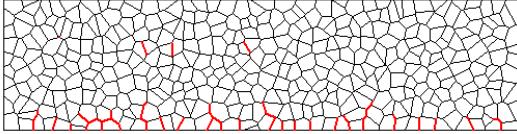
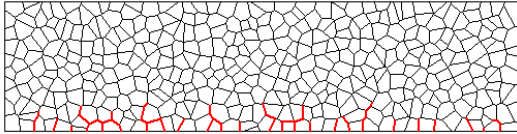
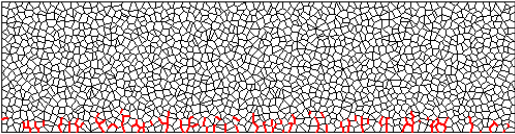
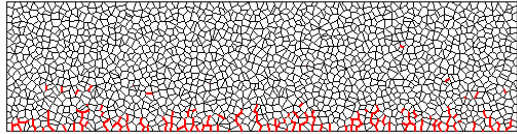
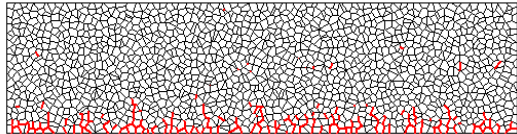
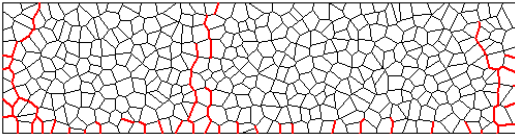
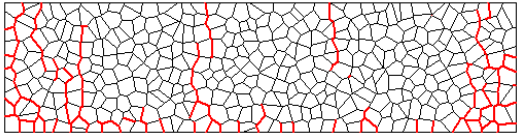
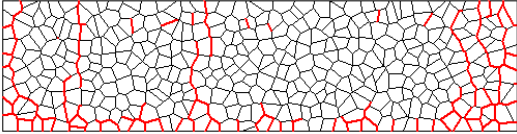
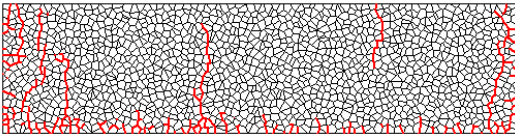
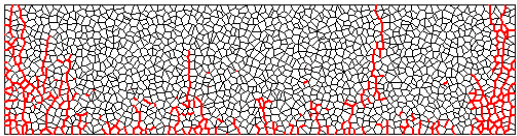
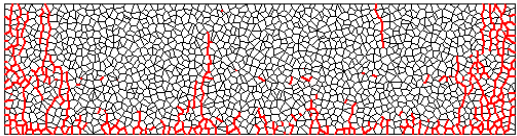


Fig. 4-6 Boundary conditions of mortar during fire

Table 4-4 shows the influence of boundary conditions on fire crack mapping. The explosive spalling due to movement constraints was obviously founded in case of completely fixed ends. Also, the crack was also observed nearby both ends of specimens. To compare with experimental results, the crack nearby both ends of post-fire mortar was sometimes observed, together with the existence of horizontal cracks. These situations might be explained by the boundary conditions at both ends of mortar during fire test, as well as some other aspects. As for the analytical results, it implies that the actual boundary condition of mortar placed in wooden frame during fire tests is a condition between completely free and fixed boundary conditions.

By viewpoints of temperature distribution and fire crack mappings, it could be roughly said that the change in material properties with temperature within an infinitesimal volume must be taken into account. Meanwhile, the smaller Voronoi elements can provide the higher temperature within elements and spacing between single cracks is much finer than larger size of Voronoi. However, the crack can exist at only element's boundary where the fracture criterion of springs was set. Therefore, the finer crack in small Voronoi elements would represent the deteriorated of material properties with temperature background for larger element. Also, the actual degree of specimen's movement constraints was within the range of completely free and fixed boundary conditions.

Table 4-4 Fire crack mappings (boundary conditions)

Condition	Duration of exposure (minutes)		
	30	60	90
Experiment			
Completely free ends	 10.00 mm	 10.0 mm	 10.00 mm
	 5.00 mm	 5.00 mm	 5.00 mm
Completely fixed ends	 10.00 mm	 10.00 mm	 10.00 mm
	 5.00 mm	 5.00 mm	 5.00 mm

4.7 SEMI-MACRO SCALE DAMAGE ASSESSMENT

Semi-macro scale damage assessment was conducted by the analytical study on 3-point bending test of $100 \times 100 \times 400$ mm fire-damaged mortar (JP ISO) as a part of full-scale structure, but the cementitious material was mortar instead of concrete. The material properties-temperature relations and thermal strain components are taken into account.

Figure 4-7 shows the 3-point bending test of $100 \times 100 \times 400$ mm mortar after exposed to 30-, 60- and 90-minute of fire exposure. The loading point was set to 0.02 mm/step as displacement control, while horizontal translation of loading point was completely fixed. The support settlement at two supporting points was negligible by fixed movement in y-direction.

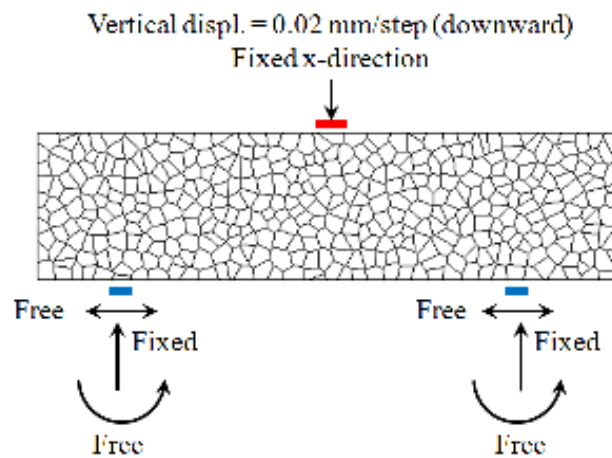


Fig. 4-7 Schematic 3-point bending simulation

Figure 4-8 shows the load-displacement curves obtained from the analytical simulation. The mechanical properties-temperature relations were taken into account. The strength and stiffness of fire damaged mortar was significantly decreased comparing with non-damaged mortar. Meanwhile, they were approximately same in all Voronoi case.

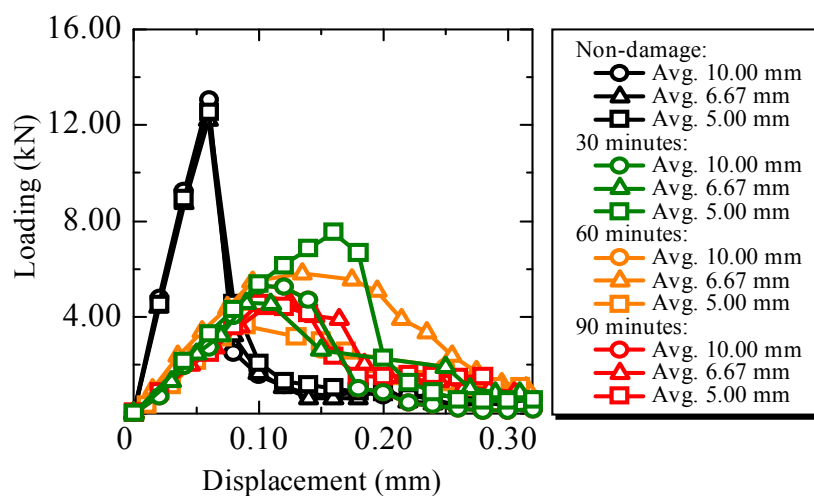
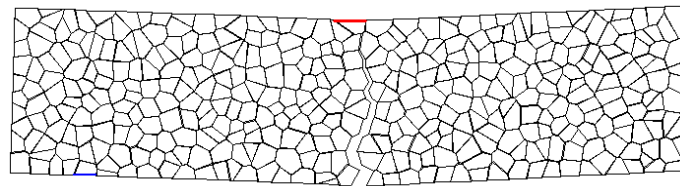
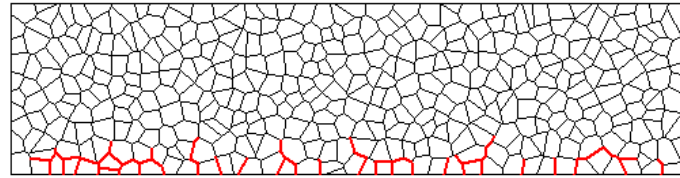
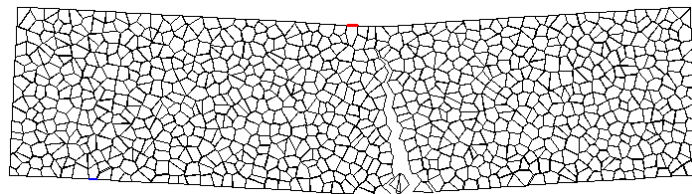
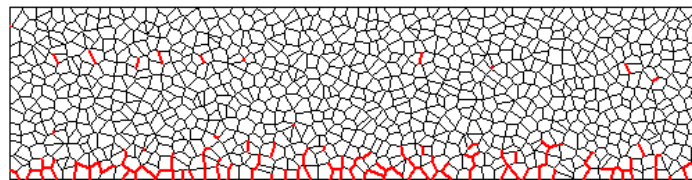


Fig. 4-8 Analytical load and displacement curves

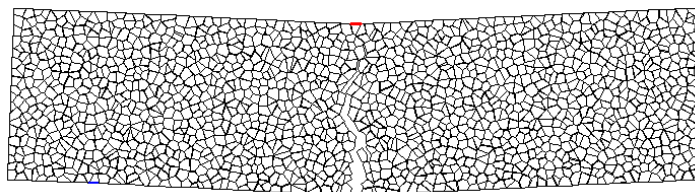
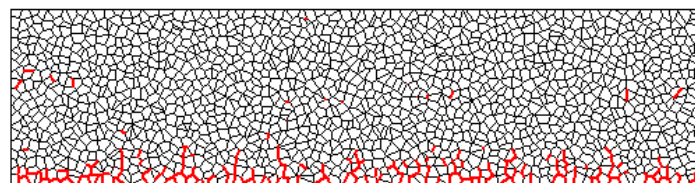
Figure 4-9 shows the propagation of bending failure location and existing fire cracks. It was obviously seen that the bending crack was initiated at the tip of existing fire cracks in all cases. It implies that the fire crack is weak point and can affect the mechanical characteristics.



(a) Avg. Voronoi size of 10.00 mm



(b) Avg. Voronoi size of 6.67 mm



(c) Avg. Voronoi size of 5.00 mm

Fig. 4-9 Propagation of bending failure

4.8 SUMMARY

The present analytical study was conducted a series of fire-damaged mortar that was made from carbonate aggregate and locally available Ordinary Portland cement in Japan.

Due to the underestimation of temperature distribution, the influence of crack on heat transportation must be taken into account in order to perform heat analysis in fire-damaged mortar.

Although there was a small gap between mortar and wooden frame, the expansion of heated face might occur during fire exposure. This can cause the movement constraint. Therefore, the boundary conditions strongly affect the crack pattern of fire-damaged mortar. In this study, the actual boundary condition was supposed to be at the degree of constraints between completely free and fixed ends condition.

The fineness of Voronoi element also affects the crack location of fire-damaged mortar. Although the finer mesh could give the higher quantitative results, the deteriorated material properties were approximately same due to same temperature distribution. In practical, the average size of meshing should be 3-4 times of maximum aggregate size.

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CHAPTER 5

GENERAL CONCLUSIONS AND FUTURE PROSPECTS

- **General Conclusions**
- **Future Prospects**

CHAPTER 5

GENERAL CONCLUSIONS AND FUTURE PROSPECT

5.1 GENERAL CONCLUSIONS

In this study, efforts have been given to investigate the fire damage characteristics and its progress to mortar made from different raw material and exposed to different fire curves. To understand the influence of each parameter, the experimentations were designed. Also, the numerical simulation for temperature distribution and crack mappings was also developed to perform the coupled analysis system of heat transfer considering heat conduction and energy required for dehydration, and structural analysis.

Based on the experimental study, the general conclusions were drawn as follows:

1. The mortar was significantly deteriorated by fire exposure. The general damage conditions after heating and cooling confirms the different response to fire exposure in the case that mortar was made from different raw materials.
2. According to the experimental results in this study, the non-uniform degree of deterioration along the beam depth has been verified by the existence of crack on the meso scale specimens, as well as other mechanical properties. Therefore, the fire-damaged material properties must be evaluated by means of small scale assessment method rather than the conventional methods of evaluation.
3. The experimental results of in-depth fire-damaged material strength and stiffness imply that the stiffness of material was significantly diminished rather than material strength. Meanwhile, both of them are strongly related to temperature experiences that mortar was exposed to.
4. The crack induced by fire is a weak point and has a strong influence on the mechanical response of fire damaged mortar, such as strength, stiffness and failure mode of flexural test; therefore, it must be taken into account in order to achieve the actual fire damage condition of cementitious material more precisely.
5. The relationships between material strength and chemical compositions show that they are not able to describe the reduction of strength and stiffness of fire-damaged mortar, while the porosity after heating and cooling also does not have clear tendency. In addition, the crack induced by fire which has a stronger effect to the material strength and failure mode can also be treated as a kind of porosity. Therefore, the porosity and hydration products are inappropriate indices for cementitious material in fire problem.
6. According to the strong relationships of mechanical characteristics and temperature, as well as the crack assessments, the temperature is the most appropriate index to

describe how the damage of cementitious material in fire problem progresses and to understand the post-fire mechanical properties, and it could be involved in all aspects of damage.

For the numerical simulation, the general conclusions were drawn as follows:

1. The temperature distribution along the cross section induced by one-directional fire exposure was simulated by heat conduction equation considering the energy required for dehydration of chemically bound water.
2. The average size of rigid particles affects the interior temperature of each element, while the average temperature at certain depth does not significantly different.
3. Due to the underestimation of temperature distribution governed by heat conduction equation in this study, the influence of crack on heat transportation must be taken into account in order to perform heat analysis in fire-damaged mortar.
4. To simulate the accurate fire crack mappings, the deteriorated material properties as a function of temperature must be taken into account.
5. As for the analytical results in this study, the boundary conditions also affect the propagation of fire cracks and fire crack mappings.
6. In semi-macro scale simulation of 100×100×400 mm fire-damaged mortar, the response of structure was simulated by using the meso scale material relations. Also, the bending failure location is dependent upon the existence of fire crack

5.2 FUTURE PROSPECTS

The following points are recommended for future study:

1. The analytical scheme should be applied to a coupled phenomenon of heat and moisture transportation during fire exposure for representing the in-operated concrete structure.
2. The influence of fire cracks on heat transfer.
3. The mechanical response to fire of cementitious material made from different raw materials.
4. The influence of experimental conditions, e.g., partially heated phenomenon through fireproof material, on the surface crazing.
5. The scale effect of experimentations, e.g., meso-macro scale relations.

APPENDIX A

- **Flow Chart of Analysis**
- **Results of Analytical Cases**

APPENDIX A

A.1 FLOW CHART OF ANALYSIS

The computational works were done according to the following input data and flow chart.

Step 0: Constant and initial values

All necessary parameters that are not varied with temperature would be set at this step.

Mortar:

$$\text{Cement content, kg/m}^3: \quad \bar{\rho}_{\text{cement}} = 624$$

$$\text{Density (Solid phase), kg/m}^3: \quad \rho_s = 2100$$

Initial condition:

$$\text{Initial temperature, } ^\circ\text{C}: \quad T_0 = 20 \text{ at any points}$$

Thermal loading:

$$\text{Fire curve of ISO 834, } ^\circ\text{C}: \quad T = 345 \log(8t + 1) + T_0$$

Constant material properties:

$$\text{Latent heat of evaporation, J/kg:} \quad \lambda_E = 2300 \times 10^3$$

$$\text{Latent heat of dehydration, J/kg:} \quad \lambda_D = 2400 \times 10^3$$

Step 1: Determining of temperature dependence variables at time step n

The value of temperature at time step n-1, T_{n-1} , will be used to calculate the coefficients required for the calculation at time step n.

$$\text{Thermal conductivity, J/m}\cdot\text{s}\cdot^\circ\text{C}: \quad k(T) = 2.00 - 0.24 \left(\frac{T}{120} \right) + 0.0012 \left(\frac{T}{120} \right)^2$$

$$\text{Specific heat, J/kg}\cdot^\circ\text{C}: \quad C_s(T) = 900 + 80 \left(\frac{T}{120} \right) - 4 \left(\frac{T}{120} \right)^2$$

$$\text{Effective heat capacity, J/m}^3\cdot^\circ\text{C}: \quad \rho C(T) = \rho_s C_s(T)$$

Released bound water, kg/m³:

$$\begin{aligned}
 \bar{\rho}_D &= 0 & ; T \leq 200 \text{ }^\circ\text{C} \\
 &= \bar{\rho}_{\text{cement}} \times 7.0 \times 10^{-4} (T - 200) & ; 200 \text{ }^\circ\text{C} < T \leq 300 \text{ }^\circ\text{C} \\
 &= \bar{\rho}_{\text{cement}} \times 0.4 \times 10^{-4} (T - 300) + 0.07 & ; 200 \text{ }^\circ\text{C} < T \leq 800 \text{ }^\circ\text{C} \\
 &= \bar{\rho}_{\text{cement}} \times 0.09 & ; T > 800 \text{ }^\circ\text{C}
 \end{aligned}$$

Step 2: Solve the systems of partial differential equations

The new value of temperature at time step n, T_n , will be obtained.

Step 3: New time step

At every time steps, the increment of interval time, Δt , is 0.25 seconds. Then, Step 1 to Step 2 will be repeated until the total time of fire simulation.

Step 4: Computation of deteriorated material properties and thermal strain

After calculating the temperature at target duration, the deteriorated mechanical properties will be computed.

JP ISO:

$$\begin{aligned}
 \text{Flexural strength, MPa:} & \quad F_b(T) = -9 \times 10^{-6} T^2 + 2 \times 10^{-3} T + 6.68 \\
 \text{Modulus of elasticity, MPa:} & \quad E(T) = 30199 e^{-0.003 T} \\
 \text{Tensile strength, MPa:} & \quad F_t(T) = -5 \times 10^{-6} T^2 + 9 \times 10^{-4} T + 5.16
 \end{aligned}$$

TH ISO:

$$\begin{aligned}
 \text{Flexural strength, MPa:} & \quad F_b(T) = -1 \times 10^{-5} T^2 + 5.3 \times 10^{-3} T + 5.97 \\
 \text{Modulus of elasticity, MPa:} & \quad E(T) = 27692 e^{-0.002 T} \\
 \text{Tensile strength, MPa:} & \quad F_t(T) = -8 \times 10^{-6} T^2 + 4.1 \times 10^{-3} T + 7.77
 \end{aligned}$$

Also, the thermal strain as a function of temperature will be computed and used as an initial strain component.

Carbonate aggregates:

$$\begin{aligned}
 \varepsilon(T) &= -1.2 \times 10^{-4} + 6 \times 10^{-6} T + 1.4 \times 10^{-11} T^3 & ; 20 \text{ }^\circ\text{C} \leq T \leq 805 \text{ }^\circ\text{C} \\
 &= 12 \times 10^{-3} & ; 805 \text{ }^\circ\text{C} < T \leq 1200 \text{ }^\circ\text{C}
 \end{aligned}$$

Siliceous aggregates:

$$\begin{aligned}\varepsilon(T) &= -1.8 \times 10^{-4} + 9 \times 10^{-6}T + 2.3 \times 10^{-11}T^3 && ; 20^\circ\text{C} \leq T \leq 700^\circ\text{C} \\ &= 14 \times 10^{-3} && ; 700^\circ\text{C} < T \leq 1200^\circ\text{C}\end{aligned}$$

Step 5: Structural analysis using deteriorated material properties and initial strain

The structural analysis will be performed by rigid body spring model (RBSM) considering deteriorated material properties and adjusting a strain component in normal spring by thermal strain.

A.2 RESULTS OF ANALYTICAL CASES

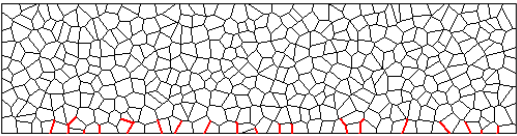
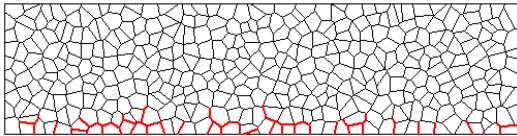
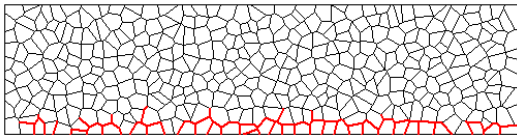
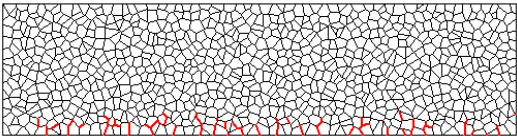
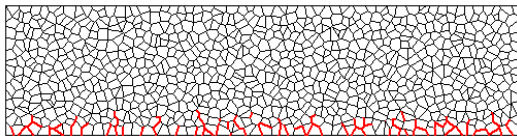
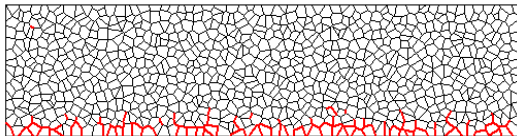
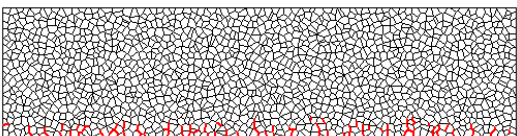
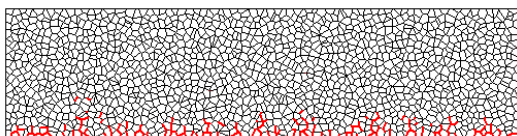
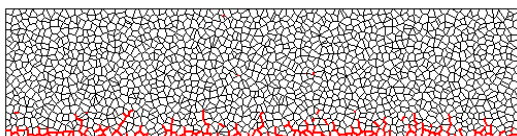
Besides the analytical results in Chapter 4, some of analytical cases have been done. The following figures show the analytical results of crack simulation using different raw materials.

These analytical results might not be able to directly compare with the experimental results. However, they would show the difference of fire crack mappings introduced by different types of aggregate used in mix proportion.

As seen from Table A-1 and Table A-2, the crack mappings were supposed to be different in the case of mortar made from different types of aggregate. The spalling due to excessive crack might be observed in siliceous type of aggregate more obviously than carbonate mortar due to its higher expansion strain.

As for these results, it implies that the cementitious materials made from siliceous aggregate are supposed to have the higher degree of deterioration compared with calcareous type of aggregate.

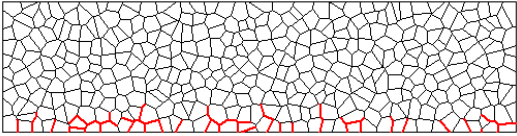
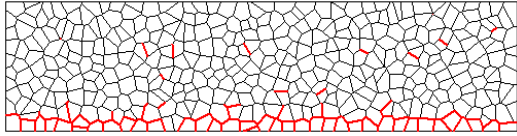
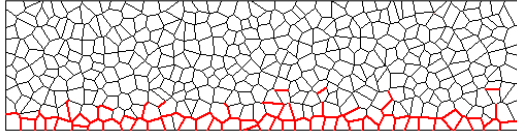
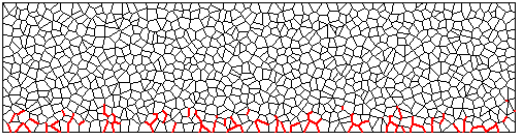
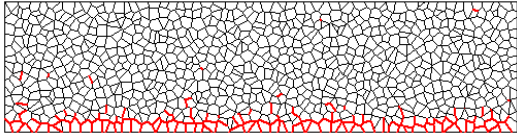
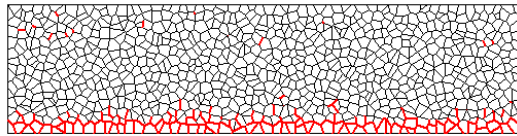
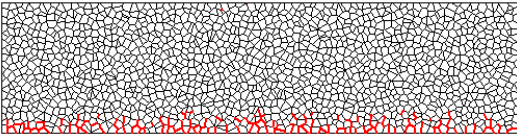
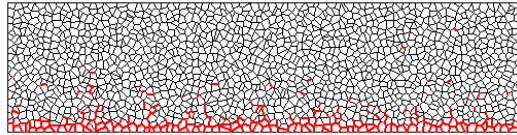
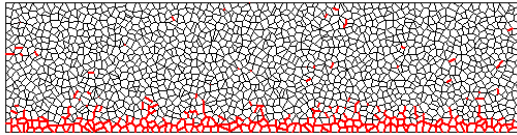
Table A-1 Fire crack mappings (Using results of TH ISO with calcareous aggregate)

Voronoi size (mm)	Duration of exposure (minutes)		
	30	60	90
10.0			
6.67			
5.00			

Note: 1. *Voronoi size* means the average value of Voronoi elements.

2. *TH ISO* means the mortar made from cement that is locally available in Thailand and calcareous aggregate.

Table A-2 Fire crack mappings (Using results of TH ISO with siliceous mortar)

Voronoi size (mm)	Duration of exposure (minutes)		
	30	60	90
10.0			
6.67			
5.00			

Note: 1. *Voronoi size* means the average value of Voronoi elements.

2. *TH ISO* means the mortar made from cement that is locally available in Thailand and calcareous aggregate.