Penetration of Moisture, CO₂, and Cl Ions in Concrete after Exposure to High Temperature

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Abstract
This study aims to understand how moisture, CO₂, and chloride ions penetrate usable postfire concrete by using electrical resistivity data. Mortar and concrete specimens with water-to-cement ratios (W/Cs) of 0.35 and 0.45. Polypropylene (PP) fibers were added to the specimens with W/C of 0.35. One surface of each specimen was placed on a hot plate and exposed to 350°C for 15 min. The moisture transfer in the specimens stored at 20°C and 60% relative humidity was assessed by measuring their electrical resistance. Then, the penetration of CO₂ and Cl ions in the mortar specimens was examined. The electrical resistance of the specimen surfaces was found to be greater than that at greater depths, and the unheated specimens were found to have the lowest resistance. This implies that the regions of the specimens heated with and without PP fibers were drier than those of the unheated specimens. In addition, the heated mortar specimens exhibited greater penetration of CO₂ and chloride ions compared to the unheated specimens. Thus, PP fibers and high W/C increased the rate of carbonation and chloride penetration into the mortar specimens after heating.

1. Introduction

1.1 Response of concrete to high temperature and moisture
One of the most extreme conditions that concrete structures, such as tunnels and buildings, can be exposed to is fire. Generally, when exposed to high temperatures, lower than 100°C, concrete is unaffected. When concrete is exposed to 300°C, its color changes to red or pink owing to the oxidation of ferric salts in the aggregates (Concrete Society 2008) and its compressive strength is reduced by about 15% – 40% because tiny cracks appear along the boundaries of calcium hydroxide (CH) crystals (Georgali and Tsakiridis 2005). Although the actual CH dehydration temperature is not yet established, there are several reports that it lies in the range of 350 – 550°C (Lin et al. 1996; Georgali and Tsakiridis 2005; Arioz 2007; Rongviriyapanich et al. 2016). At 550°C, the compressive strength is reduced by approximately 55% – 70% and aggregates begin to degrade; for example, the quartz in siliceous aggregates undergoes a phase transition at 573°C and expands (Georgali and Tsakiridis 2005; Concrete Society 2008). Large cracks appear within the cement paste and around aggregate particles when concrete is exposed to 600°C. At this temperature, the color of concrete begins to change to white or gray owing to the decarbonation of calcareous components in the cement matrix and fine aggregate (Concrete Society 2008). When concrete is exposed to 1000°C, the cracks increase, and at 1200°C, it completely decomposes and loses its binding properties owing to excessive cracking, spalling, and explosions (Lin et al. 1996; Omer 2007; Kalifa et al. 2001). Thus, postfire concrete structures should be repaired, strengthened, or demolished depending on the level of damage (Rongviriyapanich et al. 2016). However, they do not need repairing if their compressive strength is not affected (Jih 2008; Daungwilailuk et al. 2017; Concrete Society 2008).

Moisture as well as high temperature is also one of the factors related to the degradation and deterioration of concrete, such as steel corrosion, freeze–thaw attack, and carbonation. Generally, the permeability of postfire concrete rapidly increases after exposure to fire (Kalifa et al. 2001; Noumowe et al. 2009; Joakim 2015), which facilitates easier penetration of moisture and gas into postfire concrete (Poon et al. 2003). However, less attention has been paid to moisture transfer in postfire concrete structures where the mechanical and chemical properties are not considerably affected. At this level, the postfire concrete may not appear to need repair, as mentioned above, but some of its chemical and physical properties could have changed owing to factors such as dehydration reactions and degradation of modulus of elasticity. Consequently, such concrete structures exposed to high temperatures have a risk of deterioration

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owing to changes in mechanical properties and mineral compositions. Thus, the reliability of moisture state in usable postfire concrete is important to be observed. In addition, chloride ions and carbon dioxide can easily penetrate postfire concrete exposed to high temperatures. Thus, the diffusion of these two species is also necessary to understand the durability of concrete.

1.2 Response of electrical resistivity to moisture content
As a method for measuring the water content in concrete, gravimetric determination is a reliable method; however, this method needs the concrete to be cut for measuring its mass. Furthermore, many specimens are required to determine the changes in mass over time. On the other hand, the electrical resistivity of wet concrete is about $10^6 \, \Omega \cdot \text{mm}$, while that of dry concrete is about $10^{12} \, \Omega \cdot \text{mm}$. This variation in electrical resistivity between wet and dry concrete suggests that it is significantly affected by water evaporation (Madhavi and Annamalai 2016). Electrical measurement (resistivity and conductivity) is an alternative nondestructive method to monitor the in-place moisture in concrete (McCarter et al. 1995, 2001; Rajabipour et al. 2004). Additionally, this method is more economical because it requires only a few specimens. This method has been extensively used to monitor the moisture content at specific times and positions in mortar specimens. However, such data on postfire concrete are scarce in the literature. Thus, a nondestructive, in-place measurement method is required to assess the damage in postfire concrete. In this study, the electrical resistivity method is used to investigate the moisture content in mortar and concrete specimens after exposure to high temperature.

Elkey and Sellevold (1995), Layssi et al. (2015), and Madhavi and Annamalai (2016) have reported that the flow of current in concrete is due to the movement of ions within the pore structure and this movement is affected by temperature. An increase in temperature facilitates ionic movement, which in turn decreases the electrical resistivity (electrical resistance). It has been reported that a temperature change of 1°C at 21°C can result in 3% change in the electrical resistivity of saturated surface-dry concrete, with resistance increasing with decreasing temperature (Elkey and Sellevold 1995; Layssi et al. 2015). The effects of temperature, internal moisture content, and pore structure are also discussed in this paper.

1.3 Objectives of research
This study aims to investigate how moisture penetrates structurally sound postfire concrete by using electrical resistivity measurements in mortar and concrete specimens. In addition, the chloride and CO$_2$ penetration into postfire mortar specimens is investigated to assess the durability of postfire concrete structures.

2. Experiments

2.1 Materials and mixture proportions
In this study, ordinary Portland cement and crushed sand were used as cement (C) and fine aggregate (S), respectively, to develop the mortar specimens. The fine aggregate used in this study was quartz porphyry. Superplasticizer (SP) and air-entraining admixture (AE) were used to achieve the target air content of 4.5 ± 1.5% and appropriate workability for casting. Mortar specimens with water-to-cement ratios ($W/C$) of 0.35 and 0.45 were prepared. Polypropylene (PP) fibers were used in mortar specimens with $W/C$ of 0.35 at 0.34% by volume of mortar. This dosage approximately corresponds to 0.2% by volume of concrete, which is generally adopted from the industrial viewpoint (Behnood and Ghandehari 2009). The characteristics of the PP fibers used in this study are listed in Table 1. The target compressive strength of mortar specimens at the age of 28 days to obtain fire-resistant concrete was above 60 MPa. The mixture proportions of the mortar specimens are listed in Table 2.

For concrete specimens, crushed stone (G) was used as coarse aggregate besides the above materials. The coarse aggregate used in this study is again quartz porphyry. The target air content and slump values were 4.5 ± 1.5% and 14 ± 2 cm, respectively. The target compressive strength of the concrete specimens at the age of 28 days was also above 60 MPa. The mixture proportions of the concrete specimens are listed in Table 3, and the properties of the fresh mortar and concrete are listed in Table 4.

2.2 Preparation of specimens
(1) Mortar specimens
Mortar was mixed in a mortar mixer, and then casted and compacted in cylindrical and prismatic molds. Mor-
Mortar specimens of 50 mm in diameter and 100 mm high were prepared for compressive strength testing. For temperature monitoring, thermocouples were inserted at intervals of 20 mm in prismatic specimens of 40 mm width, 40 mm height, and 160 mm length, as shown in Fig. 1. For comparing the internal temperature between the mortar and concrete specimens, thermocouples were inserted at the same locations. An interval of 20 mm was selected to limit the effect of aggregates on temperature monitoring because the maximum size of the coarse aggregate used in this study was 20 mm. In addition, to measure the temperature near the exposed surface, the first thermocouple was inserted at 2.5 mm depth from the exposed surface. The embedded thermocouples were placed approximately 20 mm from the bottom of the specimens.

For moisture transfer examination, stainless-steel rods of 0.9 mm in diameter were arranged at intervals of 15 mm in the 40 × 40 × 160 mm prismatic specimens, as shown in Fig. 2. To limit the effect of fine aggregates on the measurement of electrical resistance, an interval of 15 mm, which is three times the maximum size of fine aggregates, was chosen. Prismatic specimens of 80 mm width, 40 mm height, and 160 mm length were prepared for the carbonation tests, as shown in Fig. 3, and the prismatic specimens of 40 mm width, 40 mm height, and 160 mm length were prepared for the chloride penetration tests.

### Table 4: Design and measured properties of fresh mortar and concrete.

| Name   | Design Slump (cm) | Design Air content (%) | Measured Slump (cm) | Measured Air content (%) | Temperature (°C) |
|--------|-------------------|------------------------|---------------------|--------------------------|------------------|
| M035   | -                 | 4.5 ± 1.5              | -                   | 4.5                      | 21.5             |
| M045   | -                 | 4.5 ± 1.5              | -                   | 4.5                      | 22.6             |
| M035PP | 14 ± 2            | 4.5 ± 1.5              | 16.0                | 5.0                      | 22.8             |
| C035   | 14 ± 2            | 4.5 ± 1.5              | 12.0                | 5.0                      | 19.2             |
| C035PP | 14 ± 2            | 4.5 ± 1.5              | 16.0                | 4.5                      | 21.3             |
casted and compacted in cylindrical and prismatic molds. Concrete specimens of 100 mm in diameter and 200 mm high were prepared for compressive strength testing. The temperature was monitored using thermocouples inserted at intervals of 20 mm in prismatic specimens of 100 mm width, 100 mm height, and 150 mm length, as shown in Fig. 4. Similar to the mortar specimens, the first thermocouple was inserted at 2.5 mm from the exposed surface to measure the temperature near the exposed surface. The embedded thermocouples were placed approximately 50 mm from the bottom of the specimens.

For studying the moisture transfer, stainless-steel rods of 0.9 mm in diameter were arranged at horizontal intervals of 20 mm and vertical intervals of 60 mm in prismatic specimens of 100 mm width, 100 mm height, and 150 mm length, as shown in Fig. 5. As in the mortar specimens, the stainless-steel rods were placed at 20 mm intervals to limit the effect of coarse aggregates on measurement of the electrical resistance.

(3) Curing and pretreatment
After casting, all top surfaces of the mortar and concrete specimens were covered with plastic sheets and wet cloths to prevent water evaporation, and then the specimens were stored at 20°C and 60% relative humidity (RH). Twenty-four hours after casting, they were demolded and cured in water at 20°C for 27 days, and then stored at 20°C and 60% RH for 30 days; this was done to reduce free water in the capillary pores, which would otherwise allow for a buildup of pore pressure during the heating tests, and consequently, spalling or explosion (Ozawa and Morimoto 2014; Lu 2015). In the case of fire, one surface of a concrete structure is generally exposed to fire. Therefore, one day before heating, five surfaces (all but one) of each prismatic specimen were covered with five layers of aluminum adhesive tape and insulation materials to simulate one dimensional heat transfer. For the cylindrical specimens, the top circle surface was an exposed surface and the other surfaces were covered by aluminum adhesive tape and insulation materials. The aluminum adhesive tape was applied to the first, third, and fifth layers to prevent moisture evaporation from the sides of the specimens. Two types of insulation materials, rock wool and silica aerogel, were used for high-temperature protection. The silica aerogel insulation material, which is a high-quality insulation material, was applied to the second layer, and rock wool was applied to the fourth layer to ensure that the high temperature did not affect the sides of the specimen.

The unheated specimens were cured in water at 20°C for 27 days and stored at 20°C and 60% RH for 30 days, similar to the heated specimens; subsequently, five surfaces of the unheated prismatic specimens, and the side and bottom surfaces of unheated cylindrical specimens were covered by one layer of the aluminum adhesive tape to prevent moisture absorption or migration from the sides, as a reference.

2.3 Heating regime
A hot plate was used to heat the specimen surfaces to 350°C to prevent CH dehydration. Furthermore, the Architectural Institute of Japan standard (AIJ 2015) suggests that concrete exposed to this temperature does not require repair.

After 58 days, the uncovered specimen surfaces were exposed to high temperature by being placed on the hot plate. The temperature of the hot plate was increased to 350°C at approximately 20°C/min and maintained for 15 min. Subsequently, the specimens were removed from the hot plate for testing. The total heating time was
approximately 31 min. The temperature of the hot plate was monitored using a thermocouple.

### 2.4 Scanning electron microscope (SEM) examination

The microstructure of heated and unheated mortar specimens was investigated by scanning electron microscope (SEM). The heated mortar specimens for temperature monitoring were collected three days after heating (i.e. at the age of 61 days) and cut at the depths of 2.5, 20 and 40 mm from the exposed surface into 10 mm width, 10 mm height and 20 mm length. For the unheated specimens, the specimens at the age of 61 days were cut into the same size at the center of the specimens.

### 2.5 Porosity examination

At the age of 58 days, after heating, all of the aluminum adhesive tape and insulation materials were removed from the mortar specimens, which were cooled naturally at 20°C and 60% RH. The mortar specimens were cut at intervals of 20 mm from the exposed surface, crushed to 2.36 – 4.75 mm, and then soaked in acetone and put in a desiccator at -0.1 MPa for 1 h to stop further hydration. Then, the specimens were kept in acetone before being measured by mercury intrusion porosimetry (MIP).

Subsequently, the acetone was drained from the sample by using a desiccator for 24 h. The 58-day-old mortar specimens before heating were prepared similarly. The porosity of the mortar specimens was studied using MIP.

### 2.6 Compressive strength test

The compressive strength of three cylindrical specimens was tested at 28 and 58 days as per the JIS A 1108 standard test method. At 58 days, the test was carried out on specimens before and after heating. After heating, all of the aluminum adhesive tape and insulation materials were removed from the specimens, which were then cooled at 20°C and 60% RH to prevent thermal shocking. In the unheated specimens, the aluminum adhesive tape was also removed.

### 2.7 Moisture transfer examination

After the aluminum adhesive tape of the third and fifth layers and all insulation materials were removed from the heated mortar and concrete specimens, the moisture transfer in the heated specimens was monitored at 20°C and 60% RH for 120 days. The unheated mortar and concrete specimens were covered with a single layer of aluminum adhesive tape and stored in the same place, and the moisture transfer was measured at the same time.

Because concrete conductivity is correlated with water content, the moisture transfer in the mortar and concrete specimens was assessed by measuring electrical resistance as a function of time through stainless-steel rods. The electrical resistance at each depth value was measured using an LCR meter, and was recorded at specific times.

### 2.8 Electrical resistance measurement

Concrete is a conductive material owing to the ionic movement occurring inside it; thus, it can hold electric charge. Electrical resistivity is measured from the resistance of concrete when electrical current passes through it. Direct current (DC) can induce polarization that affects the stainless-steel rod–concrete interface and pore solution to solid–phase interface. Therefore, the DC current cannot be measured reliably. On the other hand, when concrete is subjected to alternating current (AC), the dipoles of ions in the pore solution can direct the electric current (Layssi et al. 2015), resulting in stable measurements. Thus, AC is appropriate for measuring electrical resistance.

Madhavi and Annamalai (2016) and Layssi et al. (2015) reported many configurations to measure the electrical resistivity of concrete. The two-point uniaxial technique has been widely used for this purpose (Eldey and Sellevold 1995; Layssi et al. 2015; Madhavi and Annamalai 2016), and was also used in the present study. Layssi et al. (2015) reported that an electrical frequency of 0.5 – 10 kHz is appropriate to obtain the real resistivity of concrete using the two-point uniaxial technique. Elkey and Sellevold (1995) also reported that the difference in the electrical resistance of concrete for variable electrical voltage (V) disappeared when applying at least 1 kHz of electrical frequency. AC with 1 kHz frequency and 1 V was used in this study.

#### 2.9 Electrical resistivity calculation

In the two-point uniaxial technique, electric current between two electrodes, i.e., stainless-steel rods in this study, passes through concrete and the electrical resistance is measured. The stainless-steel rods (electrodes) in this study were inserted into the mortar and concrete specimens to ensure proper electrical connection during the measurements. Equation (1) describes the relation between resistivity and resistance:

\[ \rho = k \cdot R \]  

where \( \rho \) is the electrical resistivity (kΩ·cm), \( k \) is a geometrical factor (cm), and \( R \) is the electrical resistance (kΩ).

The geometrical factor depends on the size and shape of the specimen as well as the distance between the stainless-steel rods. In the two-point uniaxial technique, the geometrical factor is

\[ k = \frac{\pi \times l}{\log \left( \frac{d}{a} \right)} \]  

where \( l \) is the depth of the electrode (cm), \( d \) is the interval of the electrode (cm), and \( a \) is the electrode radius (cm). Finally, the electrical resistivity is expressed as

\[ \rho = \frac{\pi \times l}{\log \left( \frac{d}{a} \right)} \times R. \]
2.10 Accelerated carbonation test
Similar to the moisture transfer examination, after removal of the aluminum adhesive tape of the third and fifth layers and all insulation materials and then the cooling period, the heated mortar specimens were stored at 20°C, 60% RH, and 5% concentration of CO₂ for an accelerated carbonation test as per the JIS A 1153 standard test method of accelerated carbonation for concrete. The unheated specimens were also stored under the same conditions as the heated specimens. The specimens were cut at every 20 mm from the side edge perpendicular to the exposed surface (see Fig. 3) after 1, 4, 8, 13, and 26 weeks. Then, the carbonation depths of the cut surface were measured using phenolphthalein. The average of 10 measurements of carbonation depth was recorded.

2.11 Calcium hydroxide examination
The accelerated carbonation test method was used in this study to assess the durability of postfire concrete. Generally, CO₂ in the atmosphere diffuses into concrete and reacts with calcium hydroxide Ca(OH)₂ (CH) and calcium silicate hydrate 3CaO·2SiO₂·3H₂O, in the presence of moisture.

\[
\text{Ca(OH)₂} + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O} \quad (4)
\]

\[
3\text{CaO}·2\text{SiO}_2·3\text{H}_2\text{O} + 3\text{CO}_2 \\
\rightarrow 3\text{CaCO}_3 + 2\text{SiO}_2·\text{H}_2\text{O} + 2\text{H}_2\text{O} \quad (5)
\]

The availability of calcium oxide (CaO) also affects carbonation, as shown in Equation (6). Especially, when concrete is exposed to high temperature, it undergoes greater deterioration of the hydration products, thus potentially producing more CaO for the reaction, as seen in Equation (7).

\[
\text{CaO} + \text{CO}_2 \rightarrow \text{CaCO}_3 \quad (6)
\]

\[
\text{Ca(OH)₂} \rightarrow \text{CaO} + \text{H}_2\text{O} \quad (7)
\]

Therefore, in this study, we ensured that CH did not produce CaO after heating. There is a molecule of water in the chemical structure of CH that vaporizes at high temperature. Therefore, TG/DTA was used to determine the remaining amount of CH in the mortar specimens.

As in the compressive strength test specimens, all of the aluminum adhesive tape and insulation materials were removed after heating and the mortar specimens were left to cool at 20°C and 60% RH. The aluminum adhesive tape of the unheated mortar specimens was also removed. Powder samples of the heated mortar specimens were collected at depths of 2.5, 20, 40, 60, and 80 mm from the exposed surface by drilling. For the unheated specimens, samples were collected at the center of the specimens and then pulverized. The powder samples were passed through a 150 μm sieve, and then soaked in acetone and put in a desiccator at -0.1 MPa for 1 h to stop further hydration. Then, the specimens were kept in acetone. Subsequently, the samples were dried in a desiccator for 24 h before testing.

2.12 Accelerated chloride penetration
As in the compressive strength test, after removal of all of the aluminum adhesive tape and insulation materials, the mortar specimens were left to cool at 20°C and 60% RH. The aluminum adhesive tape of the unheated specimens was also removed. Five surfaces of both heated and unheated specimens were covered with epoxy resin so that the chloride ions penetrate the specimens in one direction. After coating, the specimens were stored at 20°C and 60% RH for 1 day to ensure the setting of the resin. The uncovered surface of both heated and unheated mortar specimens was then immersed in 3% sodium chloride (NaCl) solution for 1 day before being dried for 6 days. This cycle was selected because the pretest results suggested that this combination led to specimens with constant mass. These wet and
dry cycles were repeated 30 times. The chloride penetration depth in the mortar specimens was measured at the 15th and 30th cycles by using silver nitrate solution. The average of 10 measurements of the chloride penetration depth was recorded.

3. Results and discussion

3.1 Temperature history

Figures 6 - 8 show the temperature of the hot plate during heating and the internal temperature of the mortar specimens for 90 min after the beginning of heating. The temperature history of the concrete specimens is shown in Figs. 9 - 11. The temperature history of the hot plate is slightly different for each mixture because heating is controlled manually and separately for each mixture. When the mortar and concrete specimens are exposed to high temperature, the internal temperature at each depth gradually increases with exposure time. Compared to the C035 and C045 specimens, the temperature of the C035PP specimen fluctuates slightly from 150°C to 180°C at 2.5 mm depth. This is due to the melting of the PP fibers in the specimen because the melting point of the PP fibers used in this study is around 160°C. Table 5 lists the rates of temperature increase at depths of 2.5, 20, and 40 mm for the mortar and concrete specimens, which were determined by linear regression between 0-31 minutes of the heating time. Although the rate of temperature increase at 2.5 mm for the C035PP specimen is higher than that for the C035 specimen, the rates at 20 and 40 mm for the C035PP specimen are lower than those for the C035 specimen. Heating energy might be consumed by the melting of PP fibers in the C035PP specimen.

3.2 SEM observation

The microstructure of the mortar specimens is observed with an SEM, and the images are shown in Figs. 12 - 14. Figures 12(b) and (c), 13(b) and (c), and 14(e) show microcracks formed in the M035, M045, and M035PP specimens after heating, respectively. Cracking occurs in the mortar at depths of 2.5 and 20 mm, where the internal temperatures are approximately 200°C and 150°C, respectively. However, microcracks are not observed at a depth of 40 mm in the mortar specimens. Figures 14(a) – (e) show the PP fibers and microcracks in the M035PP specimen. The diameter of the PP fiber at depths of 2.5 and 20 mm decreases to approximately 35 and 32 μm, respectively, because a part of the PP fibers melts at depths of 2.5 and 20 mm, where the temperatures are approximately 200°C and 150°C, respectively, since the original diameter of the PP fiber is approximately 48 μm (Table 1). However, the temperature of 150°C is not consistent with the melting point of PP fibers, i.e., 160°C. The observed change in diameter in Fig. 14(e) and the temperature profile suggest that the temperature of the thermocouple in the M035PP specimen at 20 mm depth is affected by the partial melting of PP fibers, as mentioned in Section 3.1. At the depth of 40 mm, the PP fibers do not melt because their diameter is approximately 49 μm, as shown in Fig. 14(d).

| Name  | Rate at the depth from the surface (°C/min) |
|-------|--------------------------------------------|
|       | 2.5 mm | 20 mm | 40 mm |
| M035  | 6.57   | 4.03  | 2.64  |
| M045  | 6.99   | 4.25  | 2.62  |
| M035PP| 7.32   | 5.22  | 3.24  |
| C035  | 7.50   | 6.23  | 3.85  |
| C045  | 6.47   | 5.13  | 2.84  |
| C035PP| 8.96   | 4.34  | 3.37  |
Fig. 12 SEM images of the mortar specimen with W/C of 0.35 before and after heating.

Fig. 13 SEM images of the mortar specimen with W/C of 0.45 before and after heating.
The melting of PP fibers creates pressure-induced tangential spaces (PITS) (Ozawa and Morimoto 2014), as shown in Fig. 15.

3.3 Porosity of specimens

Figures 16(a) – (c) show the pore volume of the M035, M045, and M035PP specimens at 58 days, before and after heating. The diameter of the pores is divided into the following three ranges: 0.006 – 0.1, 0.1 – 1, and 1 – 10 μm. For the unheated specimens, the pore volume of the M045 specimen is higher than those of the M035PP and M035 specimens. After heating, the pore volume at
0 – 20 mm from the exposed surface for all heated specimens clearly increases. The volume increases in the pores of 1 – 10 μm in diameter for the heated M035, M045, and M035PP specimens are 200%, 174%, and 304%, respectively. This suggests that microcracks generated by pore pressure occur at this depth, and their widths, as estimated from the SEM images of all heated specimens, are approximately 2 – 3 μm. At 20 – 40 mm from the exposed surface of the M035 specimen, the pore volume also increases, especially in the range 0.1 – 1 μm, and the volume in this range is higher than that at the depth of 0 – 20 mm. However, the volume in this range at the depth of 20 – 40 mm is smaller than that at the depth of 0 – 20 mm, in the M045 and M035PP specimens. This suggests that the increase in pore volume is also due to pore pressure-induced cracks. The dense microstructure of mortar with a low W/C prevents water vapor from easily transferring during heating, increasing the pore pressure and generation of microcracks. Thus, the increase in pore volume is not observed in the M045 specimen. For the heated M035PP specimen, the increase in pore volume is caused by not only microcracks but also PITS. This explains why the volume increases in the M035PP specimen of pores with 1 – 10 μm in diameter are higher than those in the M035 specimen. However, the pore volume at 20 – 40 mm depth does not increase, which suggests that the PP fibers do not melt.

### 3.4 Compressive strength

| Name     | 28 days    | Compressive strength (MPa) (S.D.) | 58 days    |
|----------|------------|-----------------------------------|------------|
|          | Before heating | After heating | Before heating | After heating |
| M035     | 75.22 (3.71) | 75.87 (0.96) | 63.16 (0.64) |
| M045     | 38.97 (0.46) | 60.27 (1.35) | 43.31 (1.89) |
| M035PP   | 63.38 (2.19) | 77.70 (1.32) | 65.87 (1.33) |
| C035     | 66.98 (0.29) | 75.01 (1.32) | 56.10 (0.85) |
| C045     | 59.86 (0.80) | 63.66 (2.23) | 52.45 (1.92) |
| C035PP   | 69.20 (3.36) | 82.48 (0.58) | 70.52 (2.17) |

S.D.: standard deviation

The reduction in compressive strength of the mortar specimens after heating at 330°C is attributed to the pore pressure-induced microcracks during heating, as seen in the SEM images in Section 3.2.

For the concrete specimens, the compressive strength of the C035, C045, and C035PP specimens are listed in Table 6. For the unheated specimens, at 58 days, the compressive strengths of the C035, C045, and C035PP specimens are approximately 75, 63, and 82 MPa, respectively. Although the compressive strength of the C035PP specimen is higher than that of the C035 specimen, the difference in compressive strength between them is less than 10%. Apparently, the PP fibers do not affect the compressive strength of concrete with the same W/C.

After heating, the compressive strengths decrease and the residual compressive strengths of the C035, C045, and C035PP specimens are approximately 56, 52, and 70 MPa, respectively, which correspond to 75, 82, and 85% of the compressive strength of the unheated specimens. The reduction in compressive strength of the concrete specimen is due to pore pressure-induced cracks, as mentioned in Section 3.2.

Regarding the unheated specimens, the compressive strength at each age of the concrete specimens is higher than that of the mortar specimens with the same W/Cs except for the M035 and C035 specimens. Meanwhile, for the heated specimens, the percentage of residual compressive strengths of the C035 specimen is lower than that of the M035 specimen. The differential thermal expansion between cement paste and coarse aggregate at the internal temperature between 100 and 220°C is a reason for the reduction, which can affect the residual compressive strengths of concrete (Behnood and Ghandehari 2009; Yermak et al. 2017; fib 2007). However, the thermal incompatibility problem was mitigated by the free space generated by the melting of PP fibers. This is the reason why the residual compressive strength of the concrete specimen with PP fibers is higher than that of the concrete specimen without PP fiber and the residual compressive strength is almost the same in the mortar specimens.

### 3.5 Electrical resistivity and moisture transfer

(1) Electrical resistivity of mortar specimen

Fujioka et al. (2013) and Bui et al. (2015) reported that electrical resistance measurements using stainless-steel
rods can be used to determine the moisture content of the cement paste or mortar owing to the correlation between electrical resistivity and internal RH. Therefore, electrical resistivity is used in this study to examine the moisture transfer in mortar and concrete specimens.

Figure 17 shows the electrical resistivity of heated and unheated mortar specimens with time. It is observed that the electrical resistivity at 7.5 and 22.5 mm depths for all specimens with and without PP fibers suddenly increases after removal from the hot plate, while that at other depths suddenly decreases, except at 127.5 and 142.5 mm, for the M045 specimen.

The electrical resistivity at each depth for all specimens increases with time. The electrical resistivity of the M035 and M035PP specimens at depths between approximately 60 and 160 mm increases to nearly that of the unheated specimens at each age, except at 82.5 mm depth, for the M035 specimen. However, the electrical resistivity at 37.5 and 142.5 mm depths for the M045 specimen sharply increases to higher values than that for the unheated specimen. The electrical resistivity of the unheated specimens also increases constantly at 58, 118, and 178 days.

(2) Electrical resistivity of concrete specimen
The electrical resistivity of the concrete specimens is shown in Fig. 18, where the electrical resistivity of the concrete specimens at a depth of 7.5 mm exhibits a behavior similar to that of the mortar specimens. After being removed from the hot plate, the specimens’ electrical resistivity at 7.5 mm depth suddenly increases, while that at the other depths suddenly decreases.

The electrical resistivity inside the heated specimens increases, and is higher than that of the unheated specimens at the same age. The electrical resistivity of the unheated specimens also constantly increases at 58, 118, and 178 days.

(3) Discussion
The changes in the electrical resistivity of the concrete specimens show a similar trend to that of the mortar specimens. We observe that the microcracks in the SEM images and the increase in pore volume in the heated...
specimens are caused by thermal instability, melting of PP fibers, and high pore pressure. The increase in pore volume of the heated specimens favors the transfer of vapor. In other words, the extremely high electrical resistivity near the exposed surface, where the internal temperatures are approximately 150 – 220°C, suggests that moisture turns into vapor and escapes into the surroundings, while a part of vapor migrates to the greater depths, where the internal temperature is lower than 150°C. Consequently, the electrical resistivity at the greater depths is lower than that of the unheated specimen owing to the condensation of the vapor migrating from shallower depths.

The relations among microcracks, porosity, and electrical resistivity are explained as follows: the high porosity at 0 – 20 mm from the exposed surface of all heated specimens facilitates the transfer of vapor, which increases the resistivity at depths of 7.5 and 22.5 mm. On the other hand, at 20 – 40 mm depth in the heated M035PP specimen, the porosity changes slightly, as seen in Fig. 16(c). Therefore, at this depth, the resistivity of the heated M035PP specimen is lower than that of the M035 and M045 specimens. Compared to the heated M045 specimen at 0 – 40 mm from the exposed surface, the lower volume of pores 0.1 – 1 μm in diameter in the heated M035 specimen hinders the vapor transfer, resulting in lower electrical resistivity.

For the unheated specimens, the continuous increase in the electrical resistivity of the mortar and concrete specimens at 120 days suggests that the unheated specimens gradually dry when stored at 20°C and 60% RH. This trend is also observed in the heated specimens, at the approximate depth of 40 – 160 mm.

The unheated mortar and concrete specimens in this study were stored at 20°C and 60% RH after curing. Therefore, the unheated specimens are in a desorption phase when the electrical resistance of the specimens is measured. On the other hand, for the heated specimens, the migration and condensation of water vapor inside the heated specimens can result in an absorption phase in the inside of the specimens. Thus, it could be explained by the hysteresis effect that some electrical resistivities inside the heated specimens are higher than those of the unheated specimens at the same age.

An increase of 1°C at 21°C can reduce 3% of electrical resistivity in saturated surface-dry concrete. However, the moisture inside the mortar and concrete specimens changes during heating and the specimens do not remain saturated and surface-dry. The temperature of the heated specimens is increased to 350°C, but their resistivity is higher than that of the unheated specimens, and the electrical resistivity of the heated specimens at < 110°C suddenly decreases after heating. In this study, the electrical resistivity does not decrease with increasing temperature. As a result, the moisture transfer in the concrete and mortar specimens is consistent with the electrical resistivity data. The electrical resistivity increases when the moisture decreases at high temperature. Therefore, in this study, electrical resistivity can be used to investigate the moisture transfer inside the heated specimen without the reduction in electrical resistivity induced by the temperature increase.

3.6 Carbonation depth

Figure 19 shows the carbonation depths and rates of both heated and unheated M035, M045, and M035PP specimens. For the unheated specimens, carbonation is not observed for the M035 and M035PP specimens until 13 weeks (i.e., 3.6 √weeks) but it is observed for the M045 specimen after four weeks (i.e., 2 √weeks). The increase in carbonation depth for the unheated specimens is rather small compared to the heated specimens. The carbonation depth for the heated M035PP specimen is slightly smaller than that for the heated M035 specimen. Zhang and Li (2013) reported that the addition of PP fibers improves the carbonation resistance of concrete.

For the heated specimens, the carbonation depth for the M035 and M045 specimens is observed one week
after heating, while that for the M035PP specimen is observed immediately after heating. This suggests that CO₂ penetrates the heated mortar specimen more easily than the unheated specimen. The electrical resistivity data suggest the formation of a region with very low moisture near the exposed surface of the heated specimen. The pore moisture at this depth is eliminated owing to high temperature. In addition, the pore volume at the shallow depth is increased by high temperature. Therefore, the penetration of CO₂ into the heated mortar specimens through the shallow depth (i.e., depth of 0 – 40 mm) is easier than that into the unheated specimen.

The carbonation depths and rates for the heated M045 specimen are slightly higher than those for the M035 specimen because the total pore volume of the M045 specimen is higher than that of the M035 specimen. Especially, the volume of pores of 0.1 – 1 μm in diameter for the M045 specimen is higher than that for the M035 specimen, which increases the carbonation rate. The higher carbonation depth for the specimen containing PP fibers in this study, is attributed to the melting of the PP fibers, as suggested by the increase in pore volume (i.e., 1 – 10 μm in diameter). The free PITS facilitate the penetration of CO₂ and accelerate carbonation. This study suggests that the higher pore volume of a large pore diameter also affects the carbonation depth and carbonation rate.

**Figure 20** shows the residual amount of CH in both heated and unheated specimens. The amount of CH in the heated specimens is almost the same as that in the unheated specimens. This suggests that CH does not dehydrate within a temperature range applied in this study.

### 3.7 Chloride ion penetration

**Figure 21** shows the chloride penetration depths in both heated and unheated mortar specimens. Generally, the permeability of high-strength concrete is low because of the dense microstructure of concrete, especially concrete containing fiber (fib 2007). As a result, the chloride ion penetration depths of the unheated M035 and M035PP specimens are observed after 30 cycles and are found to be approximately 4 and 2 mm, respectively. Meanwhile, the chloride ion penetration depth of the unheated M045 specimen is observed after 15 cycles and is found to be approximately 7 mm.

The penetration depths of the heated M035, M045, and M035PP specimens after 30 cycles are approximately 13, 17, and 19 mm, respectively. As with carbonation, the chloride ion penetration depth of the heated specimens is larger than that of the unheated specimens owing to the low moisture content, high porosity, and melting of the PP fibers in the heated region. The region of low moisture content near the exposed surface absorbs more NaCl solution than that in the unheated specimen because of capillary suction, whereas the high porosity and melting of PP fibers facilitate the penetration of chloride ions.

The difference in chloride ion penetration rate between the unheated M035 and M045 specimens is attributed to differences in the pore volume, whereas the regions affected by heating are different in the heated specimens and affect the chloride ion penetration rate. In addition, the chloride ion penetration depth in both heated and unheated specimens increases with time.

The chloride ion penetration depth in the heated specimens with PP fiber is higher because of the generation of spaces owing to the melting of PP fibers.

### 4. Conclusions

In this study, penetration of moisture, CO₂, and chloride ions of usable postfire concrete was investigated considering detailed moisture transfer, which includes liquid water and vapor movement, obtained from electrical resistivity data.

The conclusions of this study can be summarized as follows:
Exposure to approximately 350°C reduced the compressive strength of mortars with W/Cs of 0.35, 0.45, and 0.35 with PP fibers by 17%, 28%, and 15%, respectively. It also reduced the compressive strength of concrete specimens with W/Cs of 0.35, 0.45, and 0.35 with PP fibers by 25%, 18%, and 15%, respectively.

PP fibers left PITS after heating and increased the porosity in the mortar and concrete specimens.

Electrical resistivity can be used to investigate the moisture content and moisture transfer in mortar and concrete after exposure to 350°C without a multiplying factor for reduction. There is also a strong correlation between the electrical resistivity and internal temperature of mortar and concrete specimens. The electrical resistivity increases when the internal temperature is higher than approximately 150°C.

The moisture content at 0 – 40 mm from the exposed surface of the heated mortar specimens with and without PP fibers is lower than that of the unheated specimens. For concrete specimens, the moisture content at depths approximately between 0 and 50 mm from the exposed surface in the heated specimen is lower than that at other depths. At depths far from the exposed surface, the mortar and concrete specimens gradually dry with time.

The low moisture content of the heated mortar specimen accelerates carbonation and chloride ion penetration. The total pore volume and pore diameter also significantly affect their acceleration.

Although the residual compressive strength of the heated specimens is greater than 70% and CH is not dehydrated, the heated specimens are degraded by heating.

Consequently, the moisture at depths close to the exposed surface of mortar and concrete specimens during heating evaporates, and then, part of the water vapor migrates to the interior and condenses in the specimen. This phenomenon can be observed by the electrical resistivity method. The latter is an in situ and nondestructive method that can be carried out in postfire concrete and mortar. The increase in pore volume caused by microcracking and the melting of PP fibers facilitates the penetration of CO₂ and chloride ions into the specimens after exposure to high temperature. Concrete with low W/C has greater strength and durability but develops more microcracks when exposed to high temperature. Although the addition of PP fibers prevents explosive spalling, PP fibers contribute to the degradation of fire-exposed concrete.

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