A Simple Method to Evaluate the Depth of Concrete Degradation by Fire

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Abstract

A method was developed to estimate the depth of concrete degradation caused by a fire using the rebound number measured with a compact Equotip hardness tester. The method was experimentally verified by measuring a core taken from a concrete specimen heated according to the RABT curve to confirm the distribution of the rebound number from the heating surface. The results were then compared with the distribution of the residual compressive strength estimated from the heated temperature of the concrete specimen and further measured with a core taken from the specimen. This confirmed that the distribution of the damage depth of concrete can be simply estimated by measuring the rebound number of test pieces obtained by cutting a core sample in half. The distribution of the damage depth coincides with the distribution of the measured compressive strength and the residual compressive strength estimated from the temperature data obtained in the fire resistance test.

1. Introduction

Fires caused by vehicular accidents in tunnels rapidly expose the tunnel-lining concrete to temperatures \( \geq 1000°C \) because of the burning of combustible materials in a closed space. Such extreme temperatures can cause explosive spalling and strength reduction in the concrete structure, resulting in tunnel collapse and hampering rescue efforts.

In Europe, studies have been conducted on anti-fire measures in response to accidents in large tunnels (Haack 1998). The Netherlands and Germany have specified heating curves, such as the RABT and RWS curves, for estimating explosive spalling resistivity and heat shielding of tunnels (Nordmark 1998). Measures such as applying a fire-resistant shotcrete and fire-resistant panel have been implemented to protect concrete from fire damage (ITA-AITES 2004; Kim et al. 2010). In Japan, a large fire occurred at the Nihonzaka Tunnel in the Tomei Expressway in 1979 that spalled lining concrete (Kawamura 1983). Since then, some shotcretes and panels have also been installed in Japan (Kiyomiya 2007).

When fire-resistant concrete is damaged by fire, the strength and durability near its surface deteriorate. Therefore, it is necessary to remove and repair degraded concrete. Precisely estimating the depth and degree of damage is important for proper repair work. Therefore, a simple method is needed to estimate the degraded depth quickly and efficiently.

Many methods have been proposed to measure the concrete degradation depth caused by fire (Kobayashi and Edahiro 2008; fib 2008). These methods can be roughly categorized into four types: (i) estimating the maximum exposed temperature from the color change on the concrete surface (Joongwon et al. 2009; Nabi et al. 2014; Sheng et al. 2018), (ii) estimating the altered calcium hydroxide [\( \text{Ca(OH)}_2 \)] depth using chemical methods such as neutralization depth measurement, scanning electron microscopy, differential thermogravimetric analysis, and X-ray diffraction (Heap et al. 2013; Lin et al. 1996; Pattamad and Danupon 2018), (iii) measuring the strength and hardness of the concrete via the compressive strength, Vickers hardness, and rebound number measured with a Schmidt hammer (Kubilay 2013; Muhammad and Raja 2013; Pattamad and Danupon 2018; Haddad et al. 2013; Cao 2017) and (iv) estimating the degraded depth from crack generation using the ultrasonic propagation velocity and impact echo (Chhauda 1976; Ercolani et al. 2017; Kubilay 2013; Heap et al. 2013; Iwano et al. 2017; Ufuk and Michael 2007).

These methods for investigating fire damage often use visual observation, neutralization depth measurement, and rebound number measured with a Schmidt hammer because of their ease. However, it is difficult to quantitatively estimate the degraded depth through visual inspection, although it can be roughly estimated. When measuring the neutralization depth, it is possible to specify an area where the maximum temperature reached 500°C or higher, but it is difficult to know the distribution of the degraded depth. As for using a Schmidt hammer to determine the rebound number, it is not effective to quantitatively estimate the degraded depth because of the high temperature exposure. Therefore, a simple method is needed to estimate the degraded depth quickly and efficiently.
difficult to estimate the degradation distribution in the depth direction, although the degree of degradation at one position can be measured. Therefore, each method has its own problems.

In recent years, several methods have been proposed to measure temperature and strength distributions. Sarai et al. (2012) proposed a borehole-point load test in which the damage depth is estimated from the penetration resistance obtained with an indenter inserted in a borehole. However, since this method can only be applied to areas of comparatively low compressive strength, it has not been used for evaluating an area heated according to the RABT curve.

Felicetti (2006) proposed determining the drilling resistance from the work per unit depth necessary to drill with a hammer drill. With this estimation method, it is possible to evaluate a relative difference from a sound area not degraded by heating. However, while accurate results can be expected from homogenous materials, the influence of cracks and aggregates makes it difficult to correlate the results with compressive strength.

Epasto et al. (2010) proposed a technique to non-destructively evaluate the fire damage depth from an impact-echo response using wavelet frequency. However, the technique requires special skills and expertise. Additionally, it was applied to an area with comparatively low compressive strength and has not been able to identify an area necessary to repair.

To evaluate the thermal properties of a material, conducting steady state tests for target temperatures may provide more reliable results. However, in actual situations such as fires, temperatures to which a material is subjected dramatically change with time. It is important to understand the thermal properties of a material subjected to temperature changes as shown by the RABT curve. Therefore, there is a need for a method to estimate the fire-damaged depth of tunnel concrete simply and precisely according to the RABT curve. This work thus proposes a method using a compact Equotip hardness tester to measure the rebound number and approximate the distribution of the remaining compressive strength. The validity of this estimation method is then verified by comparing rebound numbers of a core in a high-strength tunnel concrete exposed to sulfuric acid and salty environments (Aye et al. 2010; Coombes et al. 2013).

An Equotip hardness tester is shown in Fig. 1. Concrete hardness can be estimated from the ratio of the rebound velocity to the impact velocity when an impact body hits a concrete surface with a force specified with a fixed spring. The rebound number indicating the hardness of concrete can then be calculated by Equation (1) below. Test methods using this instrument have been adopted in the American and German standards (ASTM A956 1996; DIN EN 50156-1 2007). This instrument is compact, easy to operate, and enables measurement without damaging the concrete because the impact energy is as low as 11 N/mm, about 1/200 that of the Schmidt hammer. Unlike the Schmidt hammer, which is difficult to use for a core sample because of its large size, the Equotip tester can be used to measure the distribution of rebound numbers in the depth direction using a cross-sectional sample of the core. The rebound number is defined as:

\[ \text{HL} = \frac{V}{V_0} \times 1000 \]  

(1)

where \( \text{HL} \) is the rebound number, \( V \) the rebound velocity of the impact body, and \( V_0 \) its impact velocity.

(2) Rebound number measurement

After heating, the specimen was stored indoors at room temperature. A 100 mm-diameter core sample was taken from the specimen and cut in half in the depth direction measured using the Equotip tester are discussed in Section 2.1; measurements using the other three methods are discussed in Section 2.2. Cores used for measurement were taken from concrete specimens heated according to the RABT curve. Section 2.3 discusses the fire-resistance test used.

2.1 Proposed measurement method using an Equotip hardness tester

The Equotip hardness tester was originally developed in Switzerland in 1975 to non-destructively test the quality of metals (Ueno 1983). Since then, it has been used to measure the rebound number of plastics, rubber, and paper, and the hardness of pears to determine the optimal time to harvest and eat them. The instrument has also been used to study mechanical properties, such as compressive strength and elastic modulus, of rock materials (Hack et al. 1993; Muramiya et al. 2011). This tester has further been used to measure the surface hardness of concrete exposed to sulfuric acid and salty environments (Aye et al. 2010; Coombes et al. 2013).

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16 days after heating. Then, the rebound number was immediately measured. As specified by the Japan Society of Civil Engineers (JSCE 2013), measurements were made at intervals of 10 mm from the heating surface up to 200 mm and at 20 mm intervals thereafter. Twenty impact points were measured, as shown in Fig. 2; if a measured value did not fall within ±20% of the average value, it was rejected, and another measurement was taken. This procedure was then repeated for a total of three cores.

2.2 Existing measurement methods used for comparison

(1) Visual observation

The maximum temperature of the concrete was estimated on the basis of color changes in the specimens and cores. The relationship between concrete temperatures and colors is shown in Table 3 (JCI 2017; JSCE 2014).

(2) Measurement of neutralization depth

A 100 mm-diameter core was sampled from the specimen by cutting it without using water, split in half perpendicularly to the cross section, and then sprayed with a phenolphthalein solution on the split surface to measure the depth of the discolored area. The test was carried out in accordance with the Japanese standard (JIS A 1152 2018).

(3) Measurement of concrete compressive strength

Pieces were cut from varying depths of a 68 mm-diameter concrete core from a fire resistance test specimen, as shown in Fig. 3. The compressive strength of the pieces was measured in conformity with the Japanese standard (JIS A 1107 2012). The average compressive strength of three test pieces was calculated.

2.3 Fire resistance testing

The concrete specimens were subjected to high temperature in a fire resistance test before being measured with the different methods. High-strength concrete was prepared with a water-to-cement ratio of 0.35, which is typical for a shield tunnel deep underground. Currently, polypropylene (PP) fibers are used to prevent explosive spalling of tunnel-lining concrete (Bilodeau 2004; Zeiml 2006). Accordingly, 0.1 vol% PP fiber was mixed to suppress explosive spalling of concrete at high temperature (Tsuno et al. 2010, 2012). Sandstone and andesite were used for fine and coarse aggregates, respectively. The materials and mix proportions of this concrete are shown in Tables 1 and 2, respectively.

### Table 1 Materials used for concrete.

| Category       | Symbol | Type and property of materials          |
|----------------|--------|----------------------------------------|
| Water          | W      | Ground water                           |
| Cement         | C      | Portland blast-furnace slag cement type B, Density 2.98 g/cm³ |
| Fine aggregate | S      | Natural sand (Sandstone), Density (Surface-dry) 2.61 g/cm³, Fineness modulus 2.70 |
| Coarse aggregate | G      | Crushed stone (Andesite), Density (Surface-dry) 2.62 g/cm³, Solids content 60.0% |
| Admixture      | SP     | Superplasticizer                       |
| Short fiber    | PP     | Polypropylene short fiber, Density 0.91 g/cm³, Diameter 0.05 mm, Length 10 mm |

### Table 2 Mix proportions of concrete.

| W/C (%) | s/a (%) | Unit content (kg/m³) | SP (kg/m³) | PP (%) |
|---------|---------|----------------------|------------|--------|
| 35      | 54.5    | W 175                | C 500      | S 906  |
|         |         | G 760                | SP 6.5     | PP 0.1 |

※Volume ratio
The concrete specimen used in the fire resistance testing was 1700 mm wide, 1900 mm long, and 500 mm thick to simulate a tunnel lining. Fourteen prestressing steel bars were placed in the specimen and 14 N/mm² of compressive stress was applied. The outline of the testing is shown in Fig. 4.

The RABT curve (ZTV-TUNNEL 1995) was used for the fire resistance testing. This curve is used to simulate a tunnel-fire scenario (Kiyomiya 2007). The temperature in the testing furnace, controlled by thermocouples installed 100 mm away from the specimen, was raised to 1200°C in 5 minutes and then held constant for 60 minutes. The heating curve is shown in Fig. 5. The temperature history inside the concrete specimen was measured with thermocouples installed at depths of 0, 25, 50, 75, 100, 200, 300, and 500 mm from the heating surface. After the test, the concrete specimen surface was observed, and the explosive spalling depth was measured. The explosive spalling depth on the surface was measured using a Vernier caliper at intervals of 50 mm.

3. Results

3.1 Fire resistance testing

Figure 6 shows a surface image and the spalling depth distribution of the specimen after the test. The PP fiber prevented major spalling, and minor spalling was only observed at a few locations. The maximum explosive spalling depth was 3 mm, so explosive spalling likely had little or no effect on the temperature distribution. Thus, the effect of spalling on degradation depth can be considered small.

Figures 7 and 8 show the temperature history in the specimen during heating and the maximum temperature distribution in the concrete.
Table 3 Relationship between concrete temperatures and colors (JCI 2017; JSCE 2014).

| Heated temperature (℃) | Discoloration situation |
|------------------------|-------------------------|
| Over 1200              | Melting                 |
| 950 - 1200             | Light Yellow            |
| 600 - 950              | Grayish White           |
| 300 - 600              | Pink                    |

distributions in the depth direction, respectively. Calcium hydroxide [Ca(OH)$_2$], produced by cement hydration, dehydrates at 450 - 580℃, and calcium carbonate (CaCO$_3$) decomposes to form CaO and CO$_2$ at 750 - 900℃ (JCI 2012). The maximum temperature during testing reached 765℃ on the concrete surface and 450 - 580℃ at a depth of 21 - 35 mm. Therefore, both Ca(OH)$_2$ and CaCO$_3$ could have been altered on the concrete surface.

3.2 Damage depth measurement
(1) Visual observations
As shown in Fig. 9, the core surface after the fire resistance test was light yellow, which from Table 3 means it likely heated to about 950℃. At a depth of about 20 mm from the surface, the material was grayish white. Therefore, the temperature at this location was estimated to have reached 600℃, broadly coinciding with the results in Fig. 8. Additionally, a crack was found up to 60 mm in depth from the surface.

(2) Neutralization depth
The neutralization depth of the core test piece was 22 mm, as shown in Fig. 10. As Ca(OH)$_2$ decomposes to form CaO and H$_2$O at about 500℃, the pH of the concrete decreases. According to the distribution in Fig. 8, the maximum temperature reached about 500℃ at a depth of 20 - 30 mm, in agreement with the results of the neutralization testing. Therefore, neutralization testing is valid for estimating the depth of strength reduction of concrete exposed to temperatures above 500℃, as noted in previous studies (JCI 2012; JSCE 2014).

(3) Compressive strength
Figure 11 shows the compressive strength distribution at each depth from the heating surface of the core specimens. The depth of the horizontal axis in Fig. 11 indicates the shortest distance between the heating surface and core specimen, as shown in Fig. 3. The compressive strength decreases closer to the concrete surface. Deeper than 150 mm from the surface, the compressive strength is constant at around 70 N/mm$^2$. Concrete at less than 150 mm from the surface seems affected by heating. There is no noticeable difference in the variation in compressive strength regardless of the depth from the heating surface.

(4) Rebound number
The measured rebound numbers are shown in Fig. 12. As in the compressive strength tests, the rebound number increases with increasing depth until it reaches a constant value of about 830 at more than 150 mm from the heating surface. Figure 13 shows the relationship between the compressive strength and rebound number. The rebound number strongly correlates and increases with compressive strength.

Figure 14 is the distribution of the standard deviation of the 20 measurements for the rebound number. Although there are variations at each depth, the standard deviation and variation tend to be greater near the heating surface. As described in Section 2.1 (2), since a measured value that does not fall within ±20% of the average value is rejected in this study, all measured values are within ±20% of the average value. The standard deviation near the heating surface is comparatively large and averages approximately 60. Based on this standard deviation, the upper and lower limits meeting a significance level of
5% at this location are approximately ±100 of the average value, which corresponds to the allowable range of the measured values near the heating surface. Therefore, overall, the 20 measurements seem enough to obtain a highly accurate rebound number, as shown in Fig. 12.

4. Evaluation of validity of Equotip hardness test

4.1 Allowable temperature of concrete

According to the guidelines of the Japan Society of Civil Engineers, damage levels of heated concrete are classified into four categories depending on the maximum temperature, as shown in Table 4 (JSCE 2014). Concrete heated to less than 300°C falls into the category of no damage. Although previous studies on repairing damaged concrete have been summarized in detail in the guidelines of the Japan Concrete Institute, the maximum allowable temperature has not been clearly specified (JCI 2012). The design guidelines of the Metropolitan Expressway Company in Japan have set the maximum allowable concrete temperature at 350°C (Metropolitan Expressway Company 2008). The threshold temperature for repair is 300°C in the fib guidelines (fib 2008), whereas it is 380°C in the International Tunnelling and Underground Space Association Guidelines (ITA-AITES 2004). In Eurocode 4 (EN 1994-1-2 2005), the decrement rate of the residual compressive strength ratio increases above 300°C. Each standard and guideline adopts a different allowable maximum temperature.

4.2 Evaluation of residual compressive strength and damage depth after a fire

From the results for the compressive strength and rebound number, it was assumed that the concrete deeper than 150 mm from the heating surface was sound. The average of each measurement in the sound area was calculated, and the degree of concrete deterioration at each depth was evaluated using the ratio of the value at that depth to the average value in the sound area. To evaluate the validity of each method, this ratio was compared with the distribution of the residual compressive strength estimated from the temperature in the fire.
resistance test. The distribution of the residual compressive strength was estimated from that of residual compressive strength of general concrete under heating (Fig. 15) and the maximum temperature distribution obtained in the test (Fig. 8). The comparison between the measured and estimated values is shown in Fig. 16. The measured values for rebound number and residual compressive strength show a similar tendency to those of the estimated values for residual compressive strength. The concrete deterioration ratio greatly decreases at depths less than 50 mm for both the measured and estimated values.

The thermal data of the test (Fig. 8) show that the temperature reached 300°C, the maximum temperature to prevent significant strength reduction (Section 4.1), at a depth of 53 mm. The inflection points of the measured compressive strength and rebound number in Fig. 16 are at a depth of approximately 50 mm, which nearly coincides with the depth at which the maximum temperature reached 300°C. This confirms the validity of using the Equotip hardness tester to provide a quick and simple estimate of the depth of concrete degradation caused by a fire.

5. Conclusions

A method was developed to measure the rebound number with a compact Equotip hardness tester to estimate the degraded depth of concrete quickly and accurately. This would help maintain tunnel-lining concrete damaged by a fire. The validity of the proposed method was examined through a fire resistance test using the RABT curve. An Equotip tester was used to measure the distribution of the rebound number in the depth direction, and the data were compared with the residual compressive strength estimated from the temperature distribution in the test. The following conclusions can be made:

1. The damaged depth can be estimated by measuring the rebound number with a compact Equotip tester using cores sampled from heated concrete.
2. The reduction ratios of the compressive strength and rebound number in the heated area to those in the sound area had nearly the same distribution. In addition, they showed the same tendency as the distribution of the reduction ratio of the residual compressive strength estimated from the temperature data of the fire resistance test. The validity of the proposed method was thus confirmed.
3. Visual observations and neutralization depth testing corresponded with the results for the concrete temperature in the test, thus reconfirming the validity of these existing methods.

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