

# System for Diagnosing Concrete Deterioration with Spectroscopic Analysis

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The most popular method for inspecting concrete structures for deterioration (for example, due to chloride attack) is sampling. But sampling inspections are destructive and only point out which structures need repairs. On the other hand, spectroscopic analysis can display chloride ion distributions with contour lines. It is better to diagnose concrete structures with spectroscopic analysis, rather than by using point-by-point sampling. This paper presents the results of diagnosis of structures in service affected by chloride ions from the sea and snow-melting agents.

## 1. Introduction

Methods for diagnosing concrete structures in ascending order of precision are: ① visual inspection, ② non-destructive inspection, and ③ sampling, that is, taking concrete core samples. However, the scope of measurement of these methods is limited. Moreover, sampling is not suitable for newly built structures as it involves additional requirements such as confirming the positions of reinforcing bars in an area before a sample is taken from there and concrete patching after extracting the sample. Spectroscopic analysis is a new diagnosis system that is non-destructive yet capable of outputting the distribution of chloride ion concentration on a concrete surface in a short period of time.<sup>(1)</sup> Application of this system makes possible non-destructive measurements, such as the half-cell potential method, and screening of the sampling sites. It is also an effective way to determine the repair area and selecting repair methods.

IHI Group has already reported research findings on the spectroscopic diagnosis system.<sup>(2)-(5)</sup> This paper describes the application of the spectroscopic diagnosis system to three in-service bridges in different surrounding environments and of different structures in order to verify the precision of non-destructive inspection by means of spectroscopic analysis versus the precision of destructive inspection.

## 2. Spectroscopic analysis system

### 2.1 System overview

Spectroscopic analysis is a multiple regression analysis technique with chemometrics as illustrated in the flowchart in Fig. 1. This system is already established as a non-

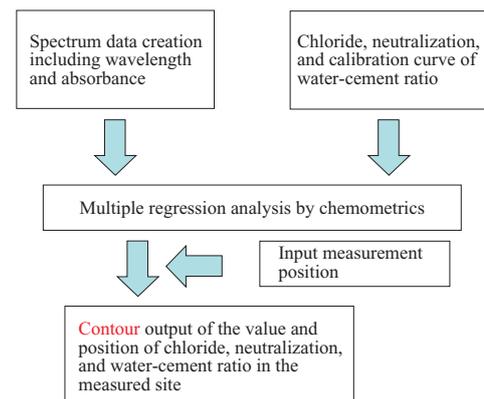


Fig. 1 System output flowchart

destructive inspection technology extensively used for measuring the sugar content of fruits. The system described in this paper applies the same technology so that a contour map of saline concentration is displayed once the measurement position is input. In principle, it is also possible to diagnose chemical neutrality by employing a calibration curve of calcium carbonate concentration, etc. Furthermore, diagnosis can be performed with alkaline aggregate reaction and other chemical deteriorations once correlations can be found between non-destructive and destructive inspections.

The spectroscopic analysis system performs measurements by scanning the concrete surface with an approximately 150 × 100 mm device called a probe head, as illustrated in Fig. 2. Measurement is made in a closed system without ambient light such as sunlight while the surface of the concrete is illuminated by a halogen lamp, the reflected light of which is collected into an optical fiber.

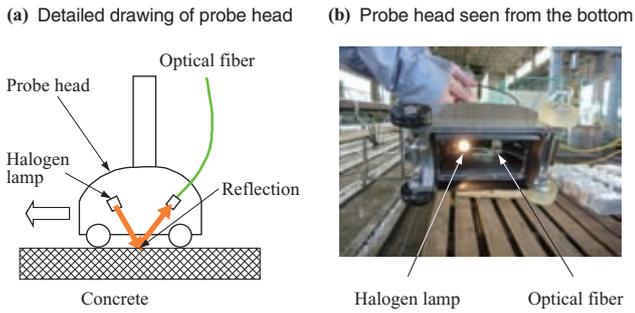


Fig. 2 Outline of probe head

## 2.2 Plotting calibration curves

The high alkaline property present on the surface right after the placing of concrete is lost by its reaction with carbon dioxide in the air over time. This phenomenon triggers dissolution of the Friedel's salt ( $3\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot\text{CaCl}_2\cdot 10\text{H}_2\text{O}$ ) in the concrete, which reacts with chloride ions.<sup>(6)</sup> Even concrete with a large amount of chloride ions may demonstrate a significantly reduced chloride ion level on the surface, posing a problem for the estimation of chloride ion concentration inside the concrete.

The Chemometrics method offers a solution to this problem. A calibration curve with clear correlation as shown in Fig. 3 can be obtained by selecting multiple peaks corresponding to the chloride ion concentration and calcium hydroxide. The results can be used for correctly measuring the surface chloride ion concentration without being influenced by neutralization.

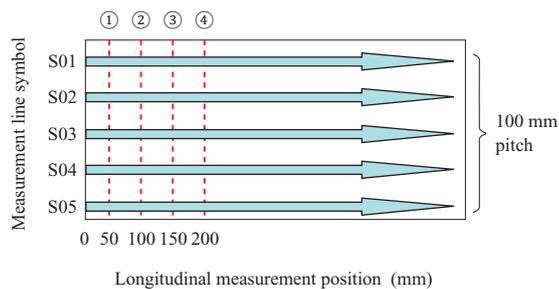
## 2.3 Measurement method

Figure 4 shows the actual measurement situation (-(a)) and the data output method (-(b)) according to the system.

(a) Actual measurement



(b) Data output method



(c) Output of wavelength and intensity of light received for each spot (50 mm pitch)

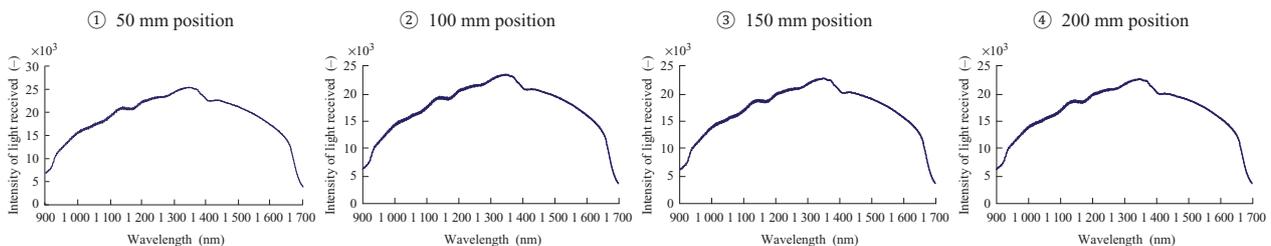


Fig. 4 Measurement method

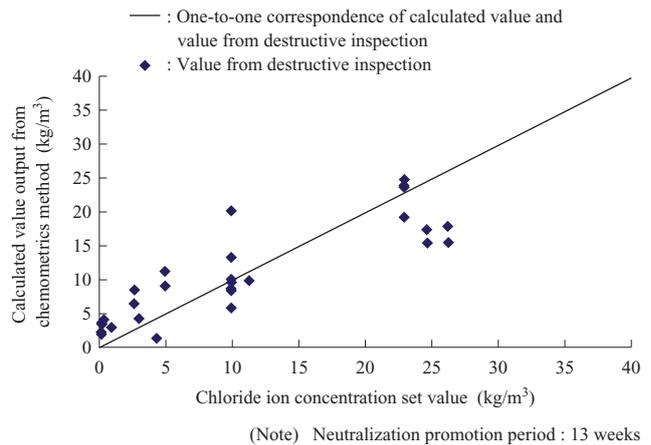


Fig. 3 Plotted calibration curve

The example here shows the measurement of the bottom surface of the Pre-stressed Concrete (PC) bridge beam. The beam has a width of 500 mm, which can be measured in five lines because of the width of the probe head. Data on the wavelength and intensity of light received (Fig. 4-(c)) can be obtained longitudinally every 50 mm. Chloride ion concentration can be output for the measured area.

## 2.4 Output method

Since the probe head used in this system has a built-in encoder which can output the scanned distance, a graph of chloride ion concentration over the distance can be produced as shown in Fig. 5. By merging this information with CAD-generated data of the measured area, a contour map as shown in Fig. 6 can be produced. As a result, spots with higher chloride ion concentration in the measured site become visible at a glance.

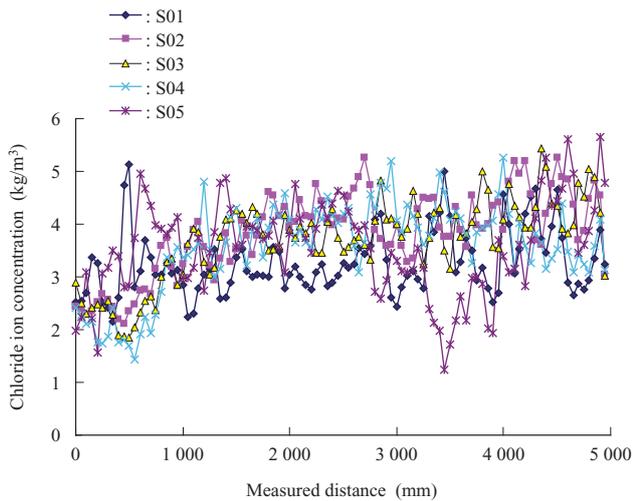


Fig. 5 Profile of chloride ion concentration versus measured distance

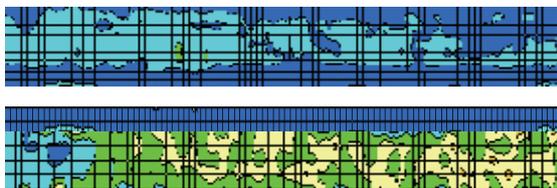


Fig. 6 Example of contour map output

### 3. Overview of measured bridges

This chapter describes the three in-service bridges that were measured.

#### 3.1 Bridge A – reinforced concrete (RC) slabs affected by salt from the sea

Figure 7 shows the appearance of measured bridge, bridge A. The bridge faces the Sea of Japan, 250 m from the coast. The bridge is 19.9 m long and 8.3 m wide and has a single-span steel beam structure with RC slabs.

The bridge is exposed to seasonal winds in the winter. It has been in service for 38 years. The surface of the slabs is impregnated with silane-siloxane aqueous emulsion to protect against salt damage. As to deterioration of



Fig. 7 Appearance of bridge A

the concrete surface, some cracks and some spalling in concrete sections, caused by salt from the sea and snow melting agent are observed in the overhang parts. Slabs in the section between beams were sound without noticeable deterioration.

#### 3.2 Bridge B – PC beams affected by salt from the sea

Figure 8 shows the appearance of a measured bridge, bridge B. This bridge also faces the Sea of Japan and stands on the coast. The bridge is 991.6 m long and 11.25 m wide and has a simple post-tensioned T-beam structure with 31 spans. The measured area is on a span on the land section. It has been in service for 37 years. In the parts where concrete is exposed, cracks and deterioration of repaired sections due to salt damage were observed.

#### 3.3 Bridge C – RC slabs affected by snow melting agent

Figure 9 shows the appearance of a measured bridge, bridge C. This bridge stands 1 km inland from the mouth of the river and therefore is not affected by salt from the sea. Nevertheless, a large amount of snow melting agent is sprinkled on it in the winter. The bridge is 264.6 m long and 26 m wide and has a 2-span box beam and 3-span continuous steel beam structure. It has been in service for 28 years. No conspicuous deterioration is observed except for cracks in some places which were most likely caused by drying shrinkage.



Fig. 8 Appearance of bridge B



Fig. 9 Appearance of bridge C

## 4. Measurement results

This chapter discusses the measurement results from the three in-service bridges.

### 4.1 Bridge A – reinforced concrete (RC) slabs affected by salt from the sea

Figure 10 shows the chloride ion concentration measurement results of bridge A. The overhang and beam on the side facing the sea show high chloride ion concentration. This finding indicates the influence of salt from the sea that adhered to the bottom of the slabs. For this reason, spalling of concrete sections due to corrosion of reinforcing bars was observed in overhang segments with small covered areas. As to the slabs, because they are largely covered, no impact from reinforcement corrosion was observed.

In addition, the chloride ion concentration on the concrete surface measured by spectroscopic analysis was compared with the estimates from the sampling method in order to verify the accuracy. Comparison was made in three areas which resulted in the negligible difference of  $0.6 \text{ kg/m}^3$ . Thus, it was confirmed that the value obtained from the spectroscopic analysis can be directly regarded as the actual chloride ion concentration on the concrete surface.

### 4.2 Bridge B – PC beams affected by salt from the sea

Figure 11 shows the chloride ion concentration measurement results of bridge B. It was initially expected

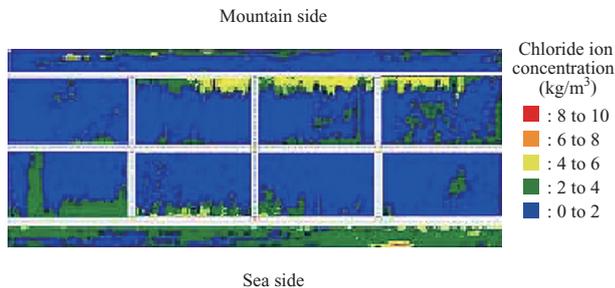


Fig. 10 Chloride ion contour map for bridge A

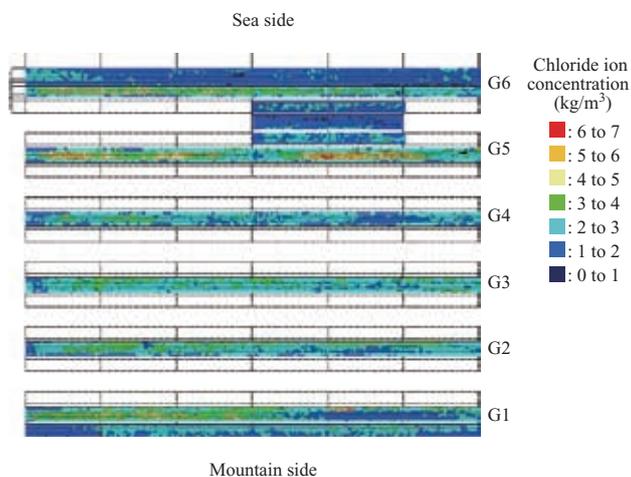


Fig. 11 Chloride ion contour map for bridge B

that the side of beam G6, which faces the sea, would demonstrate the highest chloride ion concentration. In actuality, it was the bottom of the beam that was detected as having the highest concentration. Moreover, it was not beam G6, which is the closest to the sea, but beam G5, which is one span inland, that had the highest chloride ion concentration. This is believed to be the result of the cleansing effect of rain water that falls on the beam on the outside. The inner side of the beam and slab had a lower concentration compared to the bottom of the beam. This finding revealed that the structure of bridge B experiences more adhesion of salt from the sea on the bottom of the beams, but not between the beams.

### 4.3 Bridge C – RC slabs affected by snow melting agent

Figure 12 shows the chloride ion concentration measurement results of bridge C. The bridge is not affected by salt from the sea, as it is located inland. The chloride ion concentration on the surface, therefore, is below  $3 \text{ kg/m}^3$  almost everywhere without any particular sites with significantly high concentration. The highest concentration was observed in a concrete joint with a maximum measurement of  $4.8 \text{ kg/m}^3$ . According to this finding, this bridge requires more consideration for the effect of local application of snow melting agent because of the inland location, rather than the effect of salt from the sea.

## 5. Method for estimating salt concentration inside concrete

Spectroscopic analysis provides estimated values on the surface of concrete. Meanwhile, determination of reinforcement corrosion requires estimation of chloride ion concentration at places where there are reinforcing bars. This estimation is usually made by applying Equation (1), which is defined in the standard specifications for concrete structures in Japan Society of Civil Engineering (Design).<sup>(7)</sup> The covering depth is determined from the drawings or reinforcing bar radar. The diffusion coefficient can be obtained either through curve fitting of chloride ion concentration versus depth measured by sampling or calculation based on the types of cement and water-cement ratio.<sup>(8)</sup>

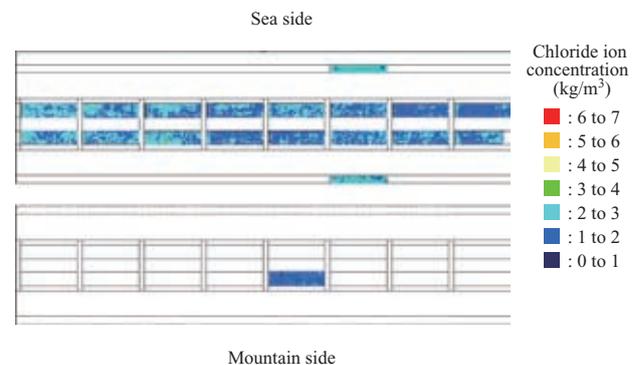


Fig. 12 Chloride ion contour map for bridge C

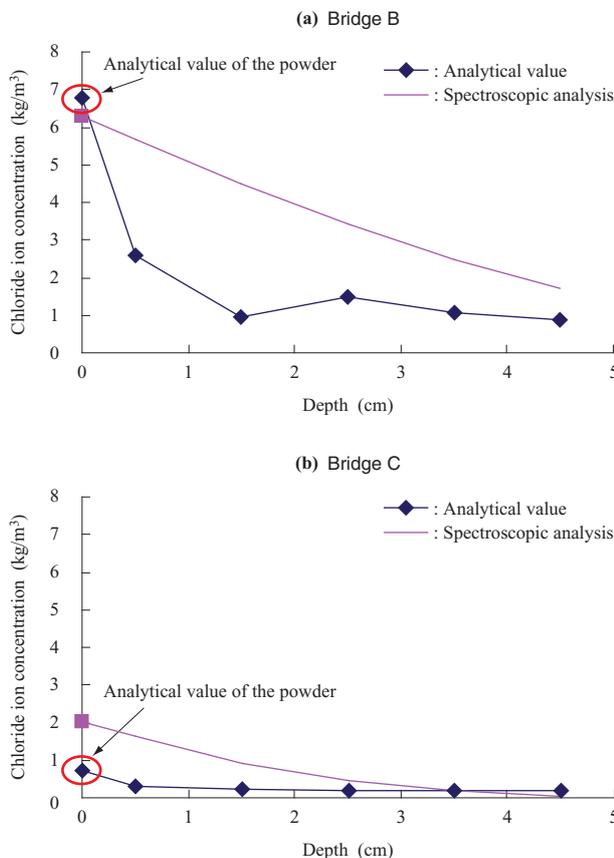
$$C(x,t) = \gamma_{cl} \cdot C_0 \left( 1 - \operatorname{erf} \frac{x}{2\sqrt{D_{ap} \cdot t}} \right) \dots\dots\dots (1)$$

- $C(x,t)$ : Chloride ion concentration corresponding to cover  $x$  cm and  $t$  years in service ( $\text{kg}/\text{m}^3$ )
- $\gamma_{cl}$  : Safety coefficient
- $C_0$  : Chloride ion concentration on the surface ( $\text{kg}/\text{m}^3$ )
- $\operatorname{erf}$  : Error function
- $x$  : Cover (cm)
- $D_{ap}$  : Diffusion coefficient ( $\text{cm}^2/\text{y}$ )
- $t$  : Years in service (y)

**Figure 13** shows the estimation results of chloride ion concentration inside the concrete of bridge B **(-a)** and bridge C **(-b)**). As shown in **Fig. 14**, the value corresponding to the surface is obtained by analyzing the powder scraped off from the surface with a grinder and collected by a cyclone vacuum. A value corresponding to the interior was obtained by analyzing sample concrete that was sliced and crushed. The resultant values were used to calculate a diffusion coefficient by curve fitting with Equation (1). The curve according to the spectroscopic analysis was drawn by assigning the measured value to  $C_0$  and applying the diffusion coefficient derived from the analysis of the surface powder and sample. The value predicted by the spectroscopic analysis proved larger than the analytical value obtained from the actual sample.



**Fig. 14** Sampling powder from concrete surface



**Fig. 13** Estimated chloride ion concentration versus depth of concrete

According to the above method, it is possible to estimate the diffusion status inside concrete based on the chloride ion concentration on the surface of concrete measured by spectroscopic analysis. Determination of reinforcement corrosion is made by comparing the chloride ion concentration at the depth where reinforcing bars are situated with the defined value (normally  $1.2 \text{ kg}/\text{m}^3$ ).

## 6. Conclusion

The findings of this paper are summarized as follows:

- (1) It has become possible to indicate deterioration factors on concrete surfaces by means of non-destructive inspection by creating a contour map. The chloride ion concentration can be shown for each of the bridge units, sites, and measured positions. Therefore, it is possible to guess which spot is most deteriorated and by what factor.
- (2) Chloride ion concentration inside concrete can be estimated by an equation and the value of concentration on the surface, which is useful for selecting an appropriate repair method according to the degree and type of deterioration.
- (3) Two-dimensional assessment can be performed in order to diagnose the impact of various factors on each bridge from different perspectives, such as the surrounding environment and bridge structure.
- (4) The current measuring speed is  $200 \text{ m}^2/\text{d}$ . Efficient measurement can further enhance the capacity.

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