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Assessment of Concrete Degradation with Hyper-spectral Remote Sensing

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ABSTRACT: This study investigates a hyper-spectral remote sensing method to assess degradation of concrete in artificial structures such as tunnels, bridges or buildings. Three different degradation processes caused by carbon dioxide (carbonation), sodium chloride (salt injury), and sulfuric acid (sulfate degradation) were examined by hyper-spectral measurement of concrete surface. The normal concrete and the degraded concrete showed clear difference in their spectra, and regression analysis also showed high correlation between the spectral signatures at specific wavelengths and the degradation characteristics including degradation depth or period.

1. INTRODUCTION

Concrete degradation has become serious social problems in urban areas since tips of concretes fell off in tunnels and bridges in Japan Railway (JR) lines. The Sanyo Shinkansen, Japanese bullet train, had serious damages by the fallen concrete blocks several times in these two years. Now monitoring of concrete degradation and its maintenance has been urgent tasks in order to keep urban infrastructure sound. So far, the monitoring and maintenance of concrete structures has been done only by visual inspection and hammering. But usually it is very time consuming and labor consuming. Therefore development of non-destructive inspection methods is strongly needed.

This study investigates a hyper-spectral remote sensing method to assess degradation of concrete in artificial structures such as tunnels, bridges or buildings. Hyper-spectral remote sensing enables to measure continuous spectrum of an object in the range between 400-2500 nm in less than 10nm width, and it has an advantage to measure physical, chemical or biological parameters without touching the object (W. L. Smith and Y. Yasuoka eds, 2000). In this study, a hyper-spectral remote sensing method was applied to measure three different concrete degradation processes caused by carbon dioxide, sodium chloride, and sulfuric acid.

It was shown that the spectrum of degraded concrete was strongly affected by generated chemical materials after degradation, and also the spectral characteristics at specific wavelengths had high correlation with the degradation characteristics such as degradation depth or degradation period depending on the degradation process. Degradation depth of concrete was successfully evaluated with the regression models between the spectral characteristics at specific wavelengths and the degradation characteristics.

2. MECHANISM OF CONCRETE DEGRADATION

Three major processes for concrete degradation were investigated in this study. These are caused by external carbon dioxide, sodium chloride, and sulfuric acid, and chemical formulas for each degradation process listed below.

$$Ca(OH)_2 + H_2CO_3 \rightarrow CaCO_3 + 2H_2O \qquad \text{(Carbonation)} \qquad (1)$$

$$Ca(OH)_2 + 2Cl^- \rightarrow CaCl_2 + 2OH^- \qquad \text{(Salt injury)} \qquad (2)$$

$$Ca(OH)_2 + SO_4^{2-} + 2H_2O \rightarrow CaSO_4{\bullet}2H_2O + 2OH^- \qquad \text{(Sulfate degradation)} \qquad (3)$$

When these chemical reactions reach the reinforcing bar, corrosion happens and it makes crack to the concrete’s surface. Then, tips of concrete begin to fall down. The spectrum of concrete surface after degradation and the pure chemicals which may have relationships to the degradation are measured by hyper-spectral remote sensing together with degradation characteristics such as degradation depth and degradation period.

3. HYPER-SPECTRAL CHARACTERISTIC OF CONCRETE

The spectrum of the normal concrete and the artificially degraded concretes after chemical reactions were measured with a spectrometer (GER-2600) with a spectral range from 400nm to 2500nm and with a spectral resolution of 2nm. Next, the spectra of generated chemicals such as calcium carbonate, sodium chloride, and calcium sulfide were measured. Figure 1-4 shows the examples of spectrum for the degraded concretes due to carbonation. Figure 1 and 2 shows the spectrum of $Ca(OH)_2$ and $CaCO_3$ which are chemicals relevant to the concrete carbonation.

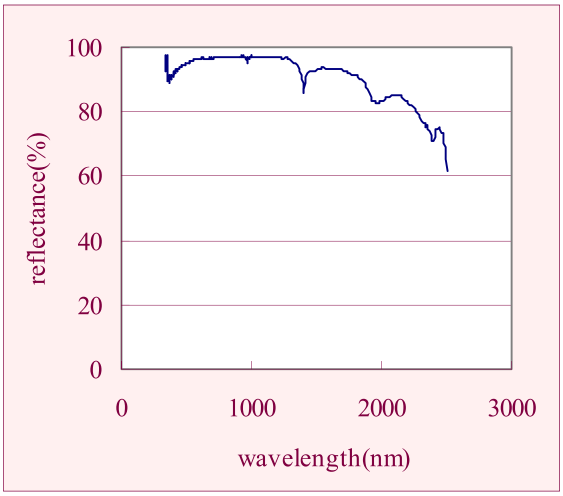

Fig. 1 Spectrum of $Ca(OH)_2$

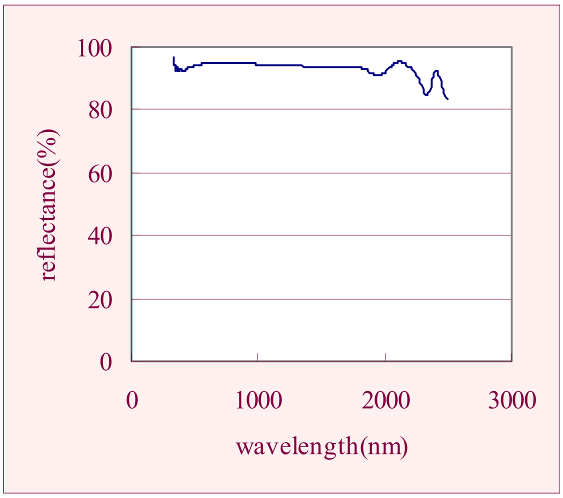

Fig. 2 Spectrum of $CaCO_3$

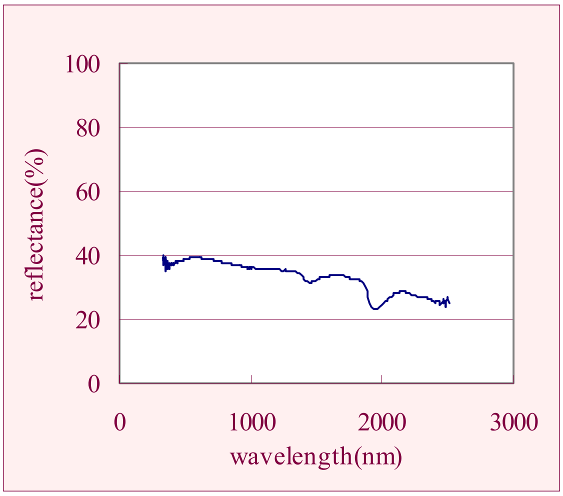

Fig. 3 Spectrum of normal concrete

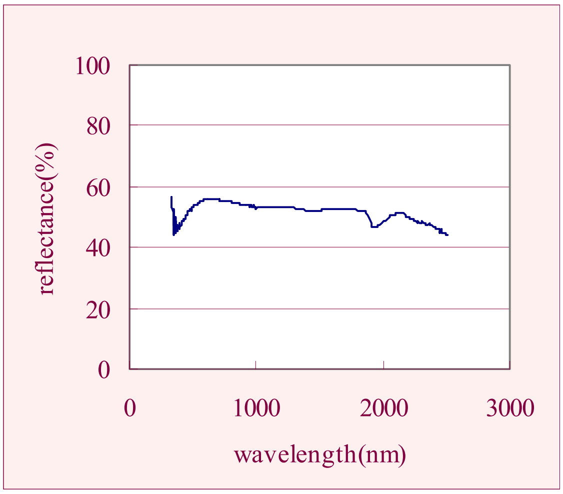

Fig. 4 Spectrum of degraded concrete by CO_2

Normal concretes (Fig. 3) contain 25% of calcium hydroxide (Fig. 1). Concretes damaged by carbon dioxide (Fig. 4) generates calcium dioxide (Fig. 2) in its process. Absorption peak observed around 1450nm in normal concrete is hardly observed in degraded concretes. The tendency of decline of reflectance in normal concrete is turned into flat in degraded concrete, too. These characteristics indicate that the spectrum of concretes damaged by carbon dioxide is strongly affected by the spectrum of calcium dioxide that is generated in its degradation process.

4. ESTIMATION OF DEGRADATION DEPTH WITH SPECTRAL CHARACTERISTICS

In order to investigate the specific wavelengths of spectrum for degradation estimation, concretes were artificially degraded and its spectrums were measured periodically. Standard concretes whose water-cement ratio is 55% were prepared as samples. For three months, concretes were exposed in 10% carbon dioxide and 10% solution of salt. Measurements were done every week for 12 weeks.

Then, using medicine such as phenolphthalein and a solution of silver nitrate, degradation depth by carbon dioxide (Hc: carbonation depth) and by sodium chloride (Hs: salt injury depth) were measured. Next, using the spectral reflectance at specific wavelengths and the degradation depth, regression model was formulated to estimate the degradation depth from the reflectance. Fig. 5 shows the temporal change of the measured degradation depth by carbon dioxide, Hc.

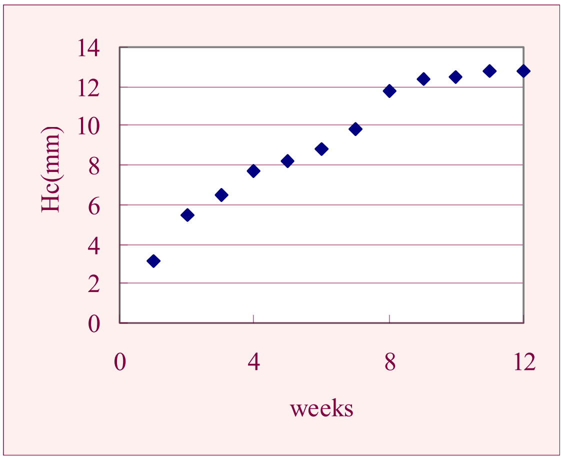

Fig.5 Temporal change of concrete degradation depth by CO_2 (Hc)

4.1 Correlation between the spectral characteristics (first order derivative) and the degradation depth

For 12 weeks, reflectance values themselves vary around 20% at each wavelength, and the spectral reflectance at each wavelength does not have a high correlation with degradation depth. In this study, therefore, first order derivative of the spectral reflectance was introduced as the spectral characteristics (Fig. 6) to calculate correlation with the degradation depth. The first order derivative represents the change at each wavelength and it reflects the shapes of spectrums.

Fig. 6 The first order derivative of the spectrum of concrete surface for different degradation period

At the wavelengths where the first order derivative changes from minus value to plus such as around 1450nm and 1950nm, the spectrum has absorption peaks. From Fig. 6 it is shown that the spectral characteristics around these absorption peaks change depending on the degradation period (degradation depth). Figure 7 shows the correlation coefficient between the first order derivative of the spectral reflectance and degradation depth. The spectral characteristics around 440nm, 1393nm, 1930nm, 2127nm,and 2340nm have high correlation with degradation depth and are shown to be effective specific wavelengths to evaluate the degradation depth.

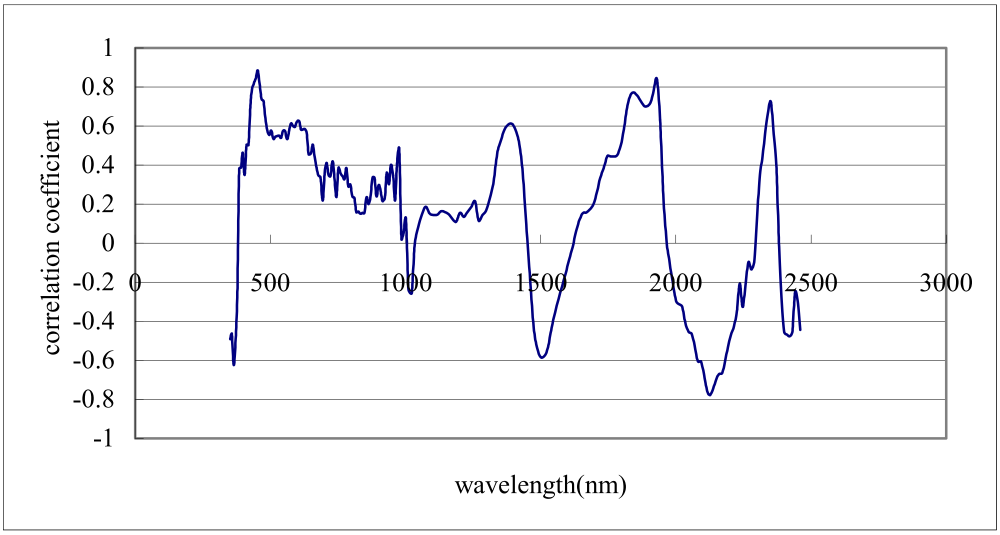

Fig. 7 Correlation coefficients between the first order derivative and the degradation depth

4.2 Estimation of degradation depth

Multivariate statistical analysis was applied to a set of the first order derivative and degradation depth. The following Eq. (4) was selected for the estimation model of the degradation depth.

$$Hce = 275.3X_{440} + 531.0X_{1500} + 506.9X_{2341} + 4.4 \quad (4)$$

$$(R^2 = 0.807)$$

where Hce is the estimated degradation depth and $X_{\lambda i}$ is the first order derivative at the wavelengths λi.

Figure 8 illustrates the relation between the estimated degradation depth (Hce) and the measured one (Hc). It shows a good correlation between them, and also it indicates degradation depth of concrete was successfully assessed from hyper-spectral data.

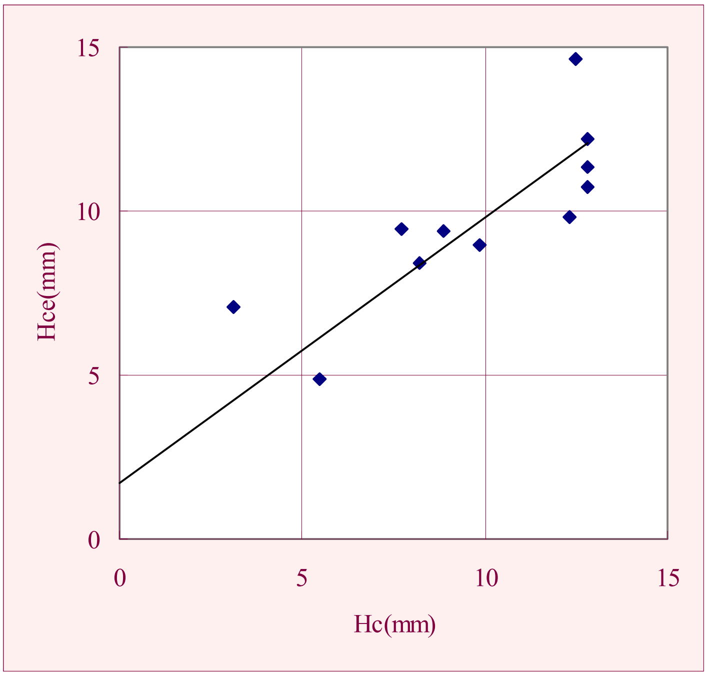

Fig. 8 Comparison between the estimated degradation depth (Hce) and the measured degradation depth (Hc)

5. CONCLUSIONS

In this study, using hyper-spectral remote sensing, the relationships between the spectrum of degraded concretes and that of chemicals generated after degradation were examined. Then, an estimation model for the concrete degradation depth was formulated from the spectrum of concrete. The result indicates concrete degradation may be evaluated from the measurement of spectral signatures of concrete surface.

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