Assessment of Concrete Efflorescence based on Hyper-spectral Imaging

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ABSTRACT

Efflorescence is a phenomenon mostly made by carbonation process of concrete structures. It is one of the internal damages seriously considered in evaluating the durability of concrete bridges. In Korea, the guideline for the bridge safety inspection requests to assess crack, efflorescence, spalling and reinforcement exposure in prior for the slabs and girders of concrete bridges. Currently, the assessment is performed based on the visual inspection of expertized engineers, which may result in subjective inspection result. In this study, a novel method to assess concrete efflorescence is proposed based on hyper-spectral imaging (HSI) device. The HSI acquires the light intensity for a number of continuous spectral bands of light for each pixel in an image, which makes the HSI provides more detailed information than a normal color camera that collects intensity for only three bands corresponding to the colors, RGB (red, green, and blue). A stepwise assessment algorithm is developed based on the spectral features developed to decompose efflorescence area from the inspected concrete area. The algorithm is verified in the laboratory testing using concrete specimens with the efflorescence, which shows high accuracy of the proposed HSI-based assessment.

1. INTRODUCTION

Efflorescence is one of the important aspects of concrete degradation such as crack, creep and spalling. Although efflorescence does not severely harm structural safety in the short term, it may cause severe damage on structural resistance in the long term. While efflorescence is developing on concrete's surface, concrete losses its alkalinity that mostly causes corrosion of the reinforcement inside the concrete structure. Despite the importance of efflorescence management in structural health monitoring, assessment of efflorescence is mostly based on the visual inspection, which may lead to mistakes and omissions due to the expertise and subjective decision of the inspectors. But few research has been reported on the assessment technique of the concrete efflorescence.

Under this background, hyper-spectral imaging (HSI), widely used in agriculture, environment, mineralogy, etc., can be a good alternative to the visual inspection as an effective non-destructive and non-contact sensing technique. HSI technique was reported as a reliable and rapid alternative to traditional colorimeter, standard pH electrodes and universal testing machines for measuring color, pH and tenderness of beef, respectively (ElMasry *et al.* 2012). Also, it was suggested for predicting tropical tree growth rates in single-species stands resulting that a single image can predict landscape variation in growth rates across 20 species (Caughlin *et al.*, 2016).

Application in structural health monitoring and other civil engineering areas is still limited despite effectiveness of the HSI technique. An experimental research was carried out to develop a quantitative measurement technique of concrete's strength using hyperspectral remote sensing, whose result was quite satisfactory (Lee *et al.*, 2012). The HSI was evaluated practical for detecting chemical leaching of concrete structure (Vaghefi *et al.*, 2011). The HSI technique was also used to detect contamination on a building's wall in the field of building management (Baseley *et al.*, 2016).

In this study, a novel approach device has been proposed for the objective and quantitative assessment of the concrete efflorescence using the HSI. This approach was focused on finding distinctive features between the spectral profiles of efflorescence and concrete, and developing distribution map of efflorescence on concrete surface. The HSI device used in this research acquires scattering profiles for all 419 wavebands in 420nm-950nm with spectral resolution of 1.31nm. Owing to the enough amount of information acquired by the HSI system, the technique is useful in identifying key features for efflorescence assessment. Specific objectives of this research are to:

(a) Acquire hyperspectral images from efflorescence and non-degraded concrete surface over the visible and near infra-red (VNIR) region between 420 and 950nm;

(b) Propose an empirical algorithm to assess the concrete efflorescence against normal concrete based on the features found from the spectral profiles, and

(c) Verify the developed algorithm in the experiment on concrete specimens, one of which is with efflorescence and the other without any contamination or degradation.

2. HYPERSPECTRAL IMAGING

HSI, like other spectral imaging, collects and processes information from across the electromagnetic spectrum of light. The goal of HSI is to obtain the spectrum from each pixel in the image of a scene to find objects identifying materials or to detect processes. In hyperspectral imaging, the recorded spectra have fine wavelength resolution and cover a wide range of wavelengths. Engineers build hyperspectral sensors and processing systems for applications in astronomy, agriculture, biomedical imaging, geosciences, physics, and surveillance. Hyperspectral sensors look at objects using a vast portion of the electromagnetic spectrum. Certain objects leave unique 'fingerprints' in the electromagnetic spectrum. Known as spectral signatures, these 'fingerprints' enable identification of the materials that make up a scanned object (Chang, 2003; Grahn and Geladi, 2007; Lu and Fei, 2014).

3. ASSESSMENT OF CONCRETE EFFLORESCENCE USING HYPER-SPECTRAL IMAGING

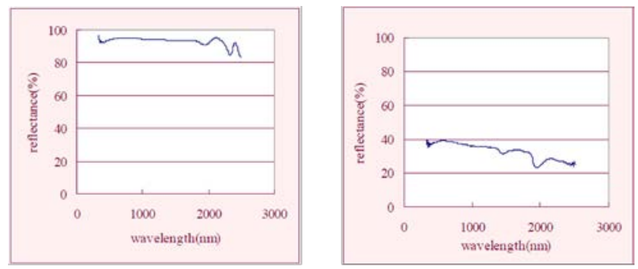
3.1. Concrete Efflorescence

Efflorescence is a crystalline deposit salts (carbonates, sulfates, chlorides), usually white, that forms on or near the surface of concrete products. Efflorescence usually consists of carbonates of calcium, sodium and potassium originating from the cement, but can also consist of salts from the surrounding environment. Concrete structure loses its alkalinity during formation of efflorescence (Michael *et al.*, 2007).

3.2. Hyper-spectral Characteristics of Normal Concrete and Efflorescence

Different intensity of reflectance is one of the most distinguishable features of hyperspectral characteristics between normal concrete and efflorescence. In our experiment, normal concrete's reflectance has shown usually under 35% of intensity of light which is exposed on its surface, while efflorescence has a wide range of reflectance varying from 40% to 70%. A previous research also reported a similar result that normal concrete has reflectance about 40 percent while chemical components of concrete efflorescence (e.g., $CaCO_3$) show very high reflectance intensity (Arita *et al.*, 2001).

But reflectance cannot be used as a sole threshold to detect the efflorescence, since some of concrete has bright grey surface with highly-reflectance similar to efflorescence. Thus, slope angle of the hyperspectral profile was considered as a complementary threshold. In the literatures showing hyperspectral characteristics of chemical components composing normal concrete and efflorescence, the spectrum of $CaCO_3$ and $Ca(OH)_2$ is bent around 550nm and have a gradual descent from 450nm to 550nm where concrete's spectra have a steep slope angle. In our experiment, the spectral profiles of efflorescence and normal concrete shows similar bending tendency around 550nm, which showed the adequateness of the slope angle as a complementary threshold.



(a) (b)

Figure 1. Spectra of (a) $CaCO_3$ and (b) normal concrete

3.3. Proposed Algorithm for concrete efflorescence assessment

An empirical algorithm to assess the efflorescence against the concrete is proposed using the threshold using reflectance and slope angle. Each threshold suggested in 3.2 was applied to this algorithm in the stepwise manner. The whole steps of building efflorescence distribution map are depicted as a flowchart in Figure 2.

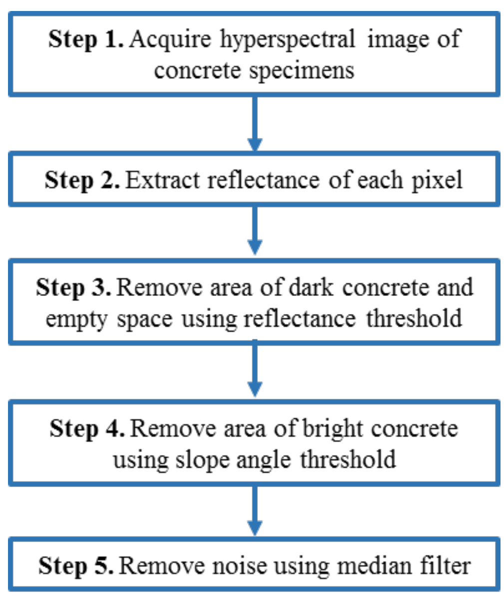


Figure 2. Flowchart of proposed empirical algorithm.

4. LABORATORY TEST

4.1. Test Setup

To validate our proposed algorithm, a laboratory test was performed using two cubic concrete specimens. Their sizes are 48 mm x 48 mm x 48 mm. The first specimen is apparently dark grey colored and has efflorescence on one side of its surfaces. The second specimen is comparatively bright colored without efflorescence. The bright concrete has similar brightness to the efflorescence, and thus, the bright concrete specimen is expected to show the validity of the slope angle of spectra as a threshold to assess the efflorescence.

As shown in the Figure 3, the system consists of a hyper-spectral camera along with a focusing lens (PS-VNIR, Specim, Spectral Imaging Ltd., Finland). The camera is located 80 cm distant from the specimens, and the image was captured by a PC with data acquisition and analysis program, ENVI (Harris Corporation, FL, USA). As a light source, two 650W halogen lamps were fixed in front of the samples. A 99% barium sulfate reflector was placed next to the specimens to calibrate the light source condition.

Figure 3. Experimental setup for HSI of concrete specimens.

4.2. Experimental Spectra.

After hyperspectral images were acquired for the specimens, the hyperspectral profiles were randomly extracted at 5 pixels of specimens with different characteristics (thick-layered efflorescence, thin-layered efflorescence, bright and dark concretes) as shown in the Figure 4. Reflectance of efflorescence is varying from 0.3 to 0.75 depending on its density (*i.e.*, thickness). It was observed that the denser efflorescence is, the brighter its reflectance is. Although reflectance of efflorescence is relatively higher than that of concrete, bright grey colored concrete also have high reflectance ranging from 0.4 to 0.6 like the efflorescence. However, the slope angles of concrete parts show remarkable change around 550nm compared to those of thick and thin layered efflorescence parts. Thus, the combinational usage of reflectance and slope angle change around 550nm will provide robust assessment of the efflorescence regardless of existence of the bright objects nearby.

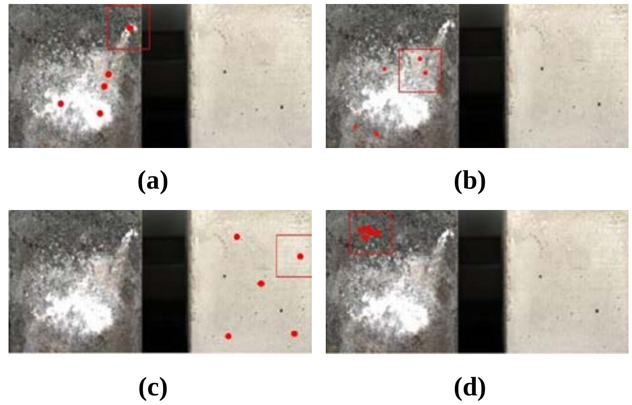


Figure 4. Pixel locations where hyperspectral profiles were extracted: (a) thick-layered efflorescence, (b) thin-layered efflorescence, (c) bright concrete, and (d) dark concrete.

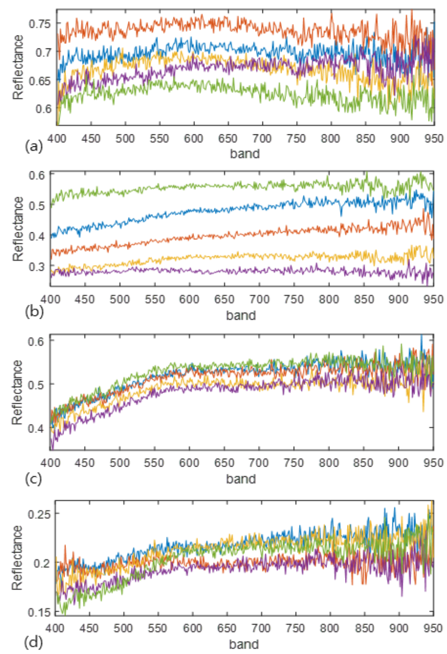
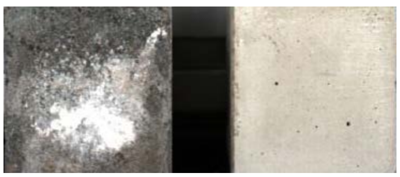


Figure **5**. Hyperspectral profile extracted from each portion of concrete specimen from: (a) thick-layered efflorescence, b) thin-layered efflorescence, (c) bright concrete, and (d) dark concrete.

4.3. Assessment of Efflorescence by Proposed Algorithm

The proposed empirical algorithm was applied to the obtained hyperspectral image of the specimens. Firstly, the dark part of concrete and empty space between two concrete specimens were erased first using a low level of brightness threshold (Step 3 of Figure 2). Then, bright concrete was removed by applying the slope angle threshold (Step 4 of Figure 2). Finally, the small pixels in the detected efflorescence was considered as noise, which was subsequently removed by a median filter.

The final distribution map of efflorescence was obtained as Figure 6. Compared to the original (RGB) image in Figure 6(a), the efflorescence part in the dark concrete specimen seem to be successfully obtained. To quantitatively estimate the accuracy of the proposed algorithm, the assessment result was compared with visually-observed efflorescence. In the original image, the pixels whose brightness is larger than 120 on the dark concrete specimen was considered as efflorescence, and its area was found to be 20.54% of the whole image. Area of efflorescence detected by proposed algorithm were 19.45% of the whole image. As compared in Figures 6(b) and 6(c), the assessed efflorescence by the proposed algorithm shows big similarity to the visually-observed efflorescence obtained from the original image within the error of 2%. The result shows that suggested algorithm can be good alternative to the visual inspection.



(a) Original image

(b) Efflorescence from original image

(c) Assessment image by proposed algorithm

Figure 6. Assessment result by proposed algorithm compared to original image.

5. CONCLUDING REMARKS

The assessment of concrete efflorescence using HSI was investigated in this paper. From the hyperspectral profiles of the efflorescence and normal concrete obtained from literature review and our experiment, two features (brightness and slope angle) were determined to find the efflorescence against normal concrete. Based on the two features, an empirical algorithm was proposed for the assessment of efflorescence. The validation test of the proposed algorithm was carried out using two concrete specimens. The result can be summarized as:

(1) The brightness cannot be used as a sole threshold to detect the efflorescence if there are object nearby with high brightness. The slope angle around 550 nm provides good complementary threshold for the assessment of efflorescence against the concrete. This agrees well with the literature.

(2) The proposed algorithm resulted in accurate assessment of efflorescence area compared to visually-observed one (within 2% error).

(3) Considering that the guideline for the bridge safety inspection of Korea requests to report efflorescence area rate, it is expected that hyperspectral imaging can be a useful method to meet demands of inspection standard and enhance accuracy and quality of inspection.

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ACKNOWLEDGEMENT

This research was supported by a grant (16SCIP-C116873-01) from construction technology research Program funded by Ministry of Land, Infrastructure and Transport of Korean government.

BIOGRAPHIES

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Soojin Cho is an assistant professor at the University of Seoul in South Korea. He received his PhD and MS environmental engineering from KAIST, Korea (2011 and 2005, respectively). After working as a postdoctoral researcher at the University of Illinois at Urbana-Champaign in the US and UNIST (Ulsan National Institute of Science and Technology) in Korea, he joined at the University of Seoul as a tenure-track faculty member in 2016. His major research area is structural health monitoring, structural dynamics, smart sensors, wireless sensors, and NDT technologies for civil structures.