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Image-processing technique to detect carbonation regions of concrete sprayed with a phenolphthalein solution

Jeong-Il Choi [a], Yun Lee [b], Yun Yong Kim [c], Bang Yeon Lee [a,*]

[a] School of Architecture, Chonnam National University, 77 Yongbong-ro, Buk-gu, Gwangju 61186, Republic of Korea
[b] Department of Civil Engineering, Daejeon University, 62 Daehak-ro, Dong-gu, Daejeon 34520, Republic of Korea
[c] Department of Civil Engineering, Chungnam National University, 99 Daehak-ro, Yuseong-gu, Daejeon 34134, Republic of Korea

HIGHLIGHTS

- Image-processing technique to detect carbonation regions of concrete is developed.
- The proposed algorithm consists of primary and secondary detection processes.
- The proposed algorithm is capable of the accurate detection of carbonated regions.

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ABSTRACT

The carbonation of concrete is one of the factors influencing the durability of reinforced concrete members or structures. Manual measurements can reportedly induce low reproducibility when measuring carbonation depths. This study presents a new image-processing algorithm for the automatic detection of carbonated regions of concrete sprayed with a phenolphthalein solution. The proposed image-processing algorithm consists of a primary detection process based on binarization and a morphology analysis and a secondary detection process based on a convex hull. A series of tests of images of carbonated concrete sprayed with the phenolphthalein solution is conducted to assess the validity of the proposed image-processing algorithm. The validation test results showed that the proposed image-processing algorithm is capable of the accurate detection of carbonated concrete regions compared to direct visual inspections.

1. Introduction

Recent news reports have highlighted the growing numbers of aged and deteriorated structures made of reinforced concrete in developed countries [1]. Therefore, the repair or rehabilitation market for these structures is also growing. The first step in the repair or rehabilitation of such structures is an exact assessment of their load-bearing capacity, durability, and serviceability. Among these performance metrics, durability is the most important when attempting to predict the lifetime of a structure [2,3]. The carbonation of concrete is one of the factors influencing the durability of reinforced concrete, as it increases the corrosion potential of the steel embedded in the concrete. It is well known that the carbonation of concrete is a chemical reaction between calcium hydroxide in the concrete and carbon dioxide in the air. Carbonation induces the neutralization of concrete [4,5]; therefore, the degree and speed of the carbonation of concrete in reinforced concrete members or structures are important factors when assessing or predicting the lifetimes of structures.

In many standards, a phenolphthalein solution is used to determine the carbonation depth in concrete as an indicator. The color of a phenolphthalein solution when applied to the surface of non-carbonated concrete is close to purple. On the other hand, phenolphthalein solution when applied to the surface of carbonated concrete remains colorless [6–9]. The pH threshold of carbonation corresponds approximately to the pH at which the steel is depassivated in pore solution environments [10]. Therefore, using it as a measure of the depth of neutralization is feasible. The phenolphthalein-based method is the simplest way to determine the carbonation depth. It is common to use vernier calipers to assess the maximum depth, minimum depth, and average depth. However, manual measurements can lead to low reproducibility in measurements of the carbonation depth according to those who conduct such measurements.

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* Corresponding author.
E-mail address: bylee@jnu.ac.kr (B.Y. Lee).

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The image-processing technique enables an analysis of the characteristics of images quantitatively and allows the user to obtain significant information about images through proper image processing. Image-processing techniques have been developed and applied in relation to concrete. Many researchers have proposed image-processing techniques to detect surface cracks in concrete and to measure or identify the characteristics of cracks, such as their width, length, orientation, and patterns, to reduce the measurement time and labor and to avoid subjectivity in the measurements by those who actually conduct the process [11–14]. Image-processing techniques have also been successfully used to evaluate quantitatively the dispersion and orientation of fiber in fiber-reinforced concrete [15–17].

Adopting an image-processing technique for the measurement of the carbonation of concrete may enable faster, more efficient, and more accurate measurements of the carbonation depth in concrete. Segura et al. (2010) developed an image-processing algorithm which combines several operations to calibrate and align the images so as to eliminate the background and carry out further thresholding to segment the images to measure the degraded depths in cementitious materials [18]. Although the correlation expressed as the adjusted-R^2 of the linear fit between the automatically measured and the visually measured degraded depths was 0.96, the user must select the thresholding method according to the images when using this algorithm, which, therefore, means that it is not fully automatic. Herrera et al. (2015) proposed a digital image analysis method which is based on the difference between the intensities of red, green, and blue pixels [19]. They determined the carbonation depth by graphing the difference between the blue intensity and the red intensity to minimize the effects of the illumination and color density. They used four types of pH indicators, aqueous ethanol, phenolphthalein, thymolphthalein, and alizarine yellow R, and compared the carbonation depths according to both an image analysis and FTIR (Fourier-transform infrared spectroscopy). The correlations (R^2) between the image analysis results and the FTIR outcomes ranged from 0.69 to 0.88. They concluded that the measurement of the carbonation depth depends on the types of pH indicator used.

Although it was demonstrated that an image analysis is useful and efficient when used to determine the carbonation depth, literature on fully automatic image-processing suitable for measuring carbonated regions in concrete remains limited and validation studies of the proposed algorithm with a range of concrete images is also limited. In this study, it was assumed that the phenolphthalein solution can effectively distinguish between carbonated regions and non-carbonated regions of concrete. Based on this assumption, the purpose of this study is to present an automatic image-processing algorithm to detect carbonated regions in concrete sprayed with a phenolphthalein solution and to assess the validity of the proposed image-processing algorithm using various concrete images.

2. Characteristics of carbonated concrete images

2.1. Color and grayscale images

Fig. 1 shows a typical sectional image of a concrete surface sprayed with a phenolphthalein solution. The gray color, i.e., the original color of concrete, represents the carbonated region and the purple color represents the non-carbonated region. Therefore, the carbonation depth can be determined by measuring the length from the surface of concrete exposed to air to the closest boundary between the purple region and the gray region. However, this method is not feasible for determining this boundary based on a certain color value because the hue, saturation and brightness of purple can be influenced by the amount of phenolphthalein solution sprayed onto the concrete surface, the conditions of the image acquisition process, and the condition of the concrete.

Eq. (1) expresses the conversion formula of the color image with reference to the grayscale image by devising the weighted sum of each color component [20].

$$GR(i,j) = 0.2989 \times R(i,j) + 0.5870 \times G(i,j) + 0.1140 \times B(i,j) \qquad (1)$$

where $GR(i,j)$ is the intensity value of the (i,j) pixel and $R(i,j)$, $G(i,j)$, and $B(i,j)$ are the corresponding intensity values of the red, green, and blue colors. The color image includes the hue, saturation, and luminance information. In contrast, the grayscale image includes only intensity information pertaining to each pixel of the image. Although the grayscale image has less information than the color image, the grayscale image is often used for the detection of objects due to the relatively easy processing associated with these images. Fig. 2 shows a grayscale image of the image in Fig. 1.

The object can be segmented from the background in the grayscale image based on thresholding techniques, after which features such as the shape and size of the object can be extracted for further analysis [12]. A pixel in a grayscale image is replaced by a black pixel (with an intensity value of 0) if the intensity value of the pixel is lower than a threshold value. Otherwise the pixel is replaced by a white pixel (with an intensity value of 1). Therefore, the most important process during object detection using an image-processing technique is to determine the threshold value. Although many researchers have proposed thresholding methods, including methods based on the histogram shape, clustering, entropy, object attributes, and spatial characteristics [21], there is no robust method which can be applied to any image because the conditions and quality levels differ from image to image. Fig. 3 shows a binary image created from a grayscale image of the image in Fig. 2 after applying Otsu's thresholding method [22]. As shown in Fig. 3, it is impossible to detect accurately the carbonated concrete region when applying only simple image-processing based on a thresholding method. Therefore, a more robust method is necessary to distinguish between carbonated regions and non-carbonated regions.

2.2. Complementary color image

Complementary colors are pairs of colors which produce white or black when two colors are combined [23]. The color magenta, which is defined as a light purplish red or reddish purple, and is close to the color of non-carbonated concrete sprayed with a phenolphthalein solution, is expressed by red at 255, green at 0, and blue at 255. Therefore, the color complementary to magenta is green. In this study, the complementary characteristic between magenta and green was used to discriminate between carbonated concrete regions and non-carbonated concrete regions. Fig. 4 shows intensity images of the red, green, and blue colors of the image in Fig. 1. As shown in Fig. 4, the green intensity image shows a relatively clear boundary between the carbonated area and the non-carbonated area compared to the red and blue intensity images. This is attributed to the fact that the color complementary color to magenta is green.

3. Proposed image-processing method for detecting carbonation regions of concrete

Fig. 5 shows a flowchart of the image-processing algorithm proposed in this study for the automatic detection of carbonation regions of concrete. As described in Section 2, the colors of non-carbonated regions and carbonated regions of concrete are purple and gray (the original color of concrete), respectively, when the