- Technical Paper -

EVALUATION OF CONCRETE CRACK MONITORING WITH MECHANOCROMIC SENSOR

Sujeong PYEON*1, Gyuyong KIM*2, Hamin EU*3 and Jeongsoo NAM*4

ABSTRACT
In this study, an experimental study was conducted on the development of crack monitoring technology for concrete materials with mechanochromic sensors attached. A method of analyzing the sensor color change image by photographing the color change image of the sensor according to the crack induction and progress of the concrete specimen was proposed. Equations are proposed to derive the crack width from the relationship between the analysis result and the crack width. Through this, the possibility of using a mechanochromic sensor for monitoring cracks in concrete materials was confirmed.
Keywords: mechanochromic sensor, strain, deformation, discoloration, concrete, crack

1. INTRODUCTION

Every year, damage due to deterioration of structures such as civil engineering and building structures occurs worldwide. In order to reduce such damage, maintenance and repair according to the age of use of the structure is required, and various structural health monitoring systems (SHM) such as electronic endoscopes, wireless sensors, and radio frequency identification devices are being developed. SHM is an emerging technology applicable to civil, mechanical and aeronautical engineering to detect structural damage. Structural health and measurement monitoring sensors installed to detect damage and cracks require sophistication in installation and operation, and require a lot of time, manpower, and economic costs for operation.

Typical monitoring systems use cables to transfer data records to data pools, resulting in high system cost and labor-intensive installation. For example, installing 10-15 sensors in a small system have high cost per channel. As the size of the structure increases, more sensors are required, and sensors with high resistance to the external environment are more expensive. In the case of large-scale structures or inaccessible or difficult structures, it is difficult to install and monitor sensors. A dense and high-precision sensor network is required for accurate detection of large-scale structures, which is the reason for the increase in construction costs. In addition, more labor is required to manage it, and it may be difficult to determine the degree of damage to the structure at the right time due to the increase in construction time [1].

Most monitoring systems require additional equipment in addition to sensors, and recent various sensor networking systems are developing at various stages [2,3]. As a way to utilize the structure itself as a sensing solution, it is possible to manufacture it at a reasonable cost by using a conductive material to create a uniform electrically conductive network inside the concrete, and continuously monitor damage by observing resistivity and the like. Metal powder, carbon nanofibers, graphene, and other electrically conductive materials (ECM) are generally used as materials that are mainly used [4].

On the other hand, Lee developed a mechanochromic sensor that causes discoloration when a physical force is applied, and this sensor is used for strain measurement of homogeneous materials such as steel in machinery and aviation fields. In addition, it is used as a hydrogel that expresses mechanical discoloration as elasticity in various fields such as curvature of body joints and elasticity of displays. The advantage of mechanochromic sensors is that they do not require power or power to operate. In the construction field, the current structure condition monitoring system monitors problems with aging management of structures that are difficult to access or detect through image processing techniques. However, due to factors such as discoloration occurring on the surface of cracks, damage evaluation of structures through image processing is only available for some cracks [2].

Therefore, in this study, in order to examine the possibility of using mechanochromic sensors in the construction field, it was identified whether the discoloration reaction of the mechanochromic sensor occurs smoothly according to the deformation of the concrete material. The color change of the mechanochromic sensor was used to evaluate the deformation of cracks and structural damage generated in concrete, and image analysis was performed by imaging the tensile deformation of the test specimen.
To examine the deformation and discoloration reaction

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of the mechanochromic sensor and verify the concrete crack width measurement method, a sensor was attached to the crack area of a large concrete beam member to measure the crack width using color change.

2. EXPERIMENTAL DESIGN

2.1 Fabrication of specimens

The test specimen manufactured to estimate the discoloration reactivity of the attached mechanochromic sensor according to the tensile strain of concrete is a fiber-reinforced cement composite at the level of F_{ck} 40 MPa, and the overall test specimen manufacturing process is shown in Fig. 1. Fiber-reinforced cement composites were used to prevent local fracture after cracking of the specimen and to observe the discoloration reaction as the crack progressed. As the material used, Portland cement was CEM Type 1 (SsangYong C&E) of ASTM C 150-85, and fine aggregate in standard condition according to ASTM C33/C33M-18 and fly ash of ASTM C618 class C type were used. The physical and chemical properties of the binders used are shown in Table 1. The fiber was a straight steel fiber with a length of 13 mm, a circular cross-sectional shape, and an aspect ratio of 60. The steel fiber used has a density of 7.85 g/cm^3 and a tensile strength of 2,700 MPa. The test specimen was manufactured as shown in Fig. 1, and Table 2 shows a mixture capable of inducing cracks of 1.0 mm through the ductile behavior of the cement composite.

The mechanochromic sensor used in this test is an angle-insensitive mechanical discoloration sensor using a Fabry-Perot (F-P) resonator structure composed of flat thin films, and details are shown in Fig. 2. The sensor is generally used to measure the strain of a homogeneous material such as steel, and is used to express mechanical discoloration in various fields, such as curvature of the body and elasticity of a display, as elasticity. The mechanochromic sensor attached to grasp the tensile deformation of concrete can detect even micro cracks, and continuous color change occurs according to the deformation of the attachment surface, and there is no dependence on the viewing angle. The sensor is composed of a thin upper metal layer and a thick lower metal layer, and specific wavelength interference occurs due to a phase difference of reflected light. At this time, if the resonance condition is changed as the thickness of the dielectric spacer (SBS layer) of the sensor is changed, the reflection spectrum of the sensor surface is changed and the color is changed. The occurrence of deformation of the test piece to which the mechanochromic sensor is attached can be identified by the color change of the sensor. According to the existing literature, it can be confirmed that the sensor coupled to the aluminum specimen visualizes and quantitatively measures the surface deformation of the specimen. In addition, it is possible to map the deformation of the surface field to which the sensor is attached through color extraction at high resolution [2,3]. Through this, it is possible to explain a phenomenon in which a color change gradually occurs from an initial color value when a structural deformation occurs due to stress such as tension being applied to the mechanochromic sensor.

Table 1 Mechanical properties of the used materials

Type		Density (g/cm^3)	Fineness (cm^2/g)
OPC(C)	Ordinary Portland cement	3.15	3,200
Fly ash (FA)	Class C	2.20	3,000
Silica sand(S)	Type 7	2.64	-

Table 2 Mix proportion specimens (kg/m^3)

F_{ck} (MPa)	W/B	W	C	FA	S	SF
40	0.4	400	850	150	350	78.5

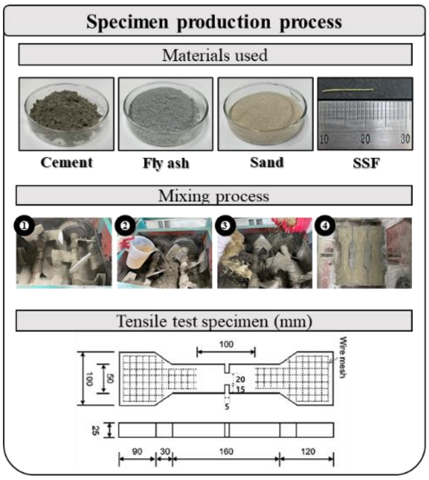


Fig.1 Details of the direct tensile test specimen manufacturing process and specimen

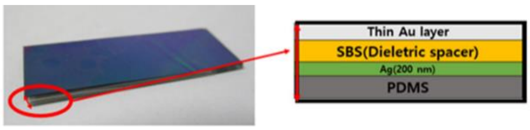


Fig.2 Structure of Mechanochromic sensor

2.2 Experimental Method

The overall deformation and discoloration environment of the concrete test specimen to which the mechanochromic sensor is attached is presented in Fig. 3. The sensor's attachment surface was measured by selecting a total of five levels: concrete finish, urethane finish, epoxy finish, water-based paint finish, and oil paint finish, which are common paint forms of the structure with Table 3. For the attachment of the mechanochromic sensor, an area of 10*7 (mm) was adhered to the concrete surface in the center direction at both ends of the sensor. The products used for adhesion were Henkel's Locktite SF 770 Primer and 406 Adhesive, and a mechanochromic sensor was attached at an interval of about 30 seconds after application of the adhesive.

To determine the time series of deformation, deformation of the test specimen was induced using a static direct tensile test device with a capacity of 250 kN with a stress loading rate of 3 mm/min on Fig. 4. A white chamber was installed to determine the discoloration of the surface of the mechanochromic sensor as the deformation appearing in the set environment increased. This blocks visual errors so that the sensor surface can drop a certain amount of light. Tensile deformation photography of the test piece and the sensor was measured at the same position from both the sensor surface. As for the tensile deformation that occurs, Mercury, HIDAKE Technologies (Brno, Czech Republic) was used through imaging, and a quantitative measurement method that satisfies the accuracy presented in ASTM E82-10a was used. In order to evaluate the tensile strain of the test specimen through imaging, two or more +-type points were selected on the surface of the test specimen, and tensile deformation was evaluated in the image through image mapping. The accuracy of image analysis was improved by selecting two or more distances as shown in Fig. 5 and entering them on the program, and the actual measured distance between each test specimen is shown in Table 4 [5].

In addition, as shown in Figure 5, the surface color of the sensor appearing in the discoloration process of the mechanochromic sensor of the tensile test piece imaged according to the type of finish surface was reviewed through RGB value extraction. Correlation analysis of only for R value among RGB values for each frame and elongation according to deformation was performed, and R^2 was derived accordingly. For correlation analysis, Statistical Package for Social Sciences version 26 (IBM SPSS Statistics 26, SPSS Inc., Chicago, IL) was used.

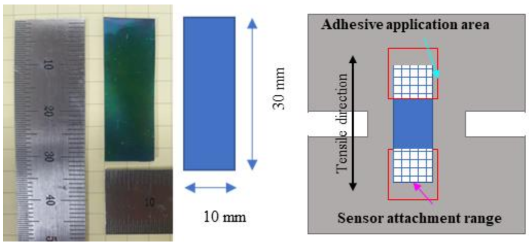


Fig.3 Environment and method for attaching mechanocromic sensor

Table 3 Finishing type of concrete specimen

Finishing Type				
Concrete	Urethane	Epoxy	Water-based paint	Oil paint

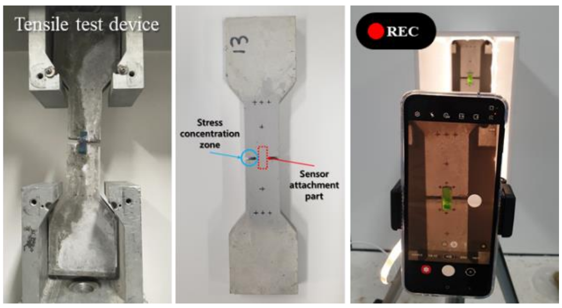


Fig.4 Stress concentration zone and setting for video recording

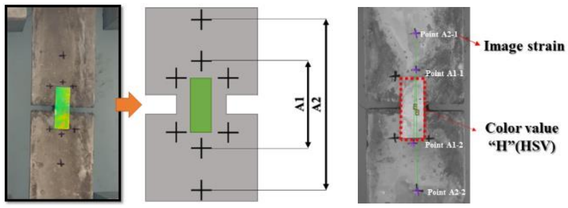


Fig.5 Analysis of deformation and discoloration extracted from images (left: Spacing of Cement Composites for Image Elongation Measurement, right: Deformation and discoloration analysis tool through image)

Table 4 The distance in mm between the + shaped points on the surface of the freeze-thaw specimen used in the image analysis technique (classified for each specimen)

Finishing Type	Section A (mm)	Section B (mm)
Concrete	40.32	101.66
Urethane	39.95	100.84
Epoxy	41.26	102.91
Water-based paint	40.19	100.08
Oil paint	40.62	101.49

3. RESPONSE RESULTS OF DISCOLORATION SENSOR ACCORDING TO FINISH SURFACE OF CONCRETE SPECIMENS

3.1 Concrete

As the strain increases, the surface reflectance of the concrete finish-attached mechanochromic sensor gradually decreases, resulting in discoloration as the sensor's layer interface becomes rough and the scattering of incident light increases. Up to 1,000 frames, RGB data was shown by recognizing the range of the sensor edge, and unlike the one shown in Fig. 6, the initial green data was not recognized. However, the corresponding RGB data was analyzed by recognizing the sensor tensile strain section after 1,000 frames. In the 2,100-to-2,500-frames section, the light reflection of the sensor surface caused by torsion of the test piece during the direct tensile test was measured. Through this, it is determined that light reflection correction of the sensor surface is necessary. The RGB Value and the tensile strain R^2 shown in Fig. 7 were measured to be irrelevant due to data noise caused by light reflection in the 2,100 frames to 2,500 frames sections.

Frame 1	Frame 1,000	Frame 2,000	Frame 3,000	Frame 3,800

Fig.6 Deformation and discoloration of sensors (concrete)

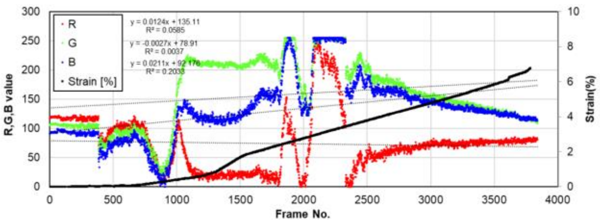
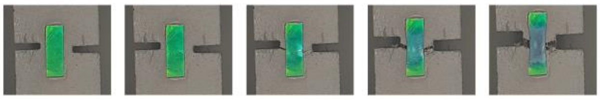


Fig.7 RGB values and strain (concrete)

3.2 Urethane

The sensor deformation and discoloration characteristics of the test specimen finished with the two-liquid urethane waterproof material are shown in Fig. 8. After the 1,000 frames in which the tensile strain of the test piece and the RGB Value of the sensor were changed on Fig. 9, the color of the deformation section was discolored from green to purple. It was found that R Value had the highest correlation among Value, and it was analyzed that the reflection spectrum of the surface was consistent with the discoloration from the existing literature to the simulated green-purple series [2,3].



Frame 1	Frame 1,000	Frame 2,000	Frame 3,000	Frame 3,700

Fig.8 Deformation and discoloration of the sensor (urethane)

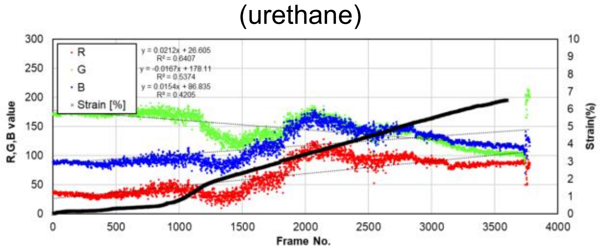
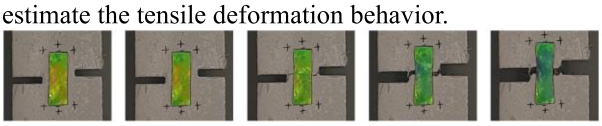


Fig.9 RGB values and strain (urethane)

3.3 Epoxy

Fig. 10 and Fig. 11 show the sensor discoloration according to tensile deformation of the direct tensile test piece finished with the upper epoxy-based paint. The initial color value of the sensor was found to be close to the yellow line. The yellow-green-purple discoloration process of sensors attached to the epoxy finish surface shows a wider color distribution than the Green-Purple series. It was analyzed that the yellow series appeared on the sensor due to the increase in d (thickness) during the sensor manufacturing process, and the color distribution was different. From the deformation start frame to the 1,000 frames, the tensile strain, R Value, and B Value of the test specimen showed linear behavior. In this case, it is shown that the R Value may be used as an index to estimate the tensile deformation behavior.



Frame 1	Frame 700	Frame 1,400	Frame 2,100	Frame 2,900

Fig.10 Deformation and discoloration of the sensor (epoxy)

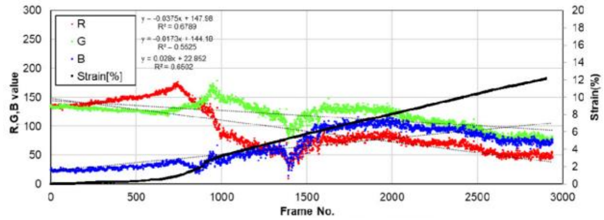


Fig.11 RGB values and strain (epoxy)

3.4 Water-based paint

Fig. 12 and Fig. 13 show the color change of the sensor according to tensile deformation of the specimen finished with water-based paint. It can be confirmed that after the change in G Value occurs in the range of 600 frames where the tensile strain of the test specimen occurs, a linear change in the tensile strain rate and the RGB Value appears. Although R Value was expected to act as an influencing factor for the tensile strain rate and the overall deformation when checked visually with R, RGB data analysis showed that G Value had a high correlation. This is judged to have affected R^2 because the linear behavior of the G Value and the tensile strain that appear after the 900 frames is more sensitive than the R Value.

Frame 1	Frame 1,000	Frame 2,000	Frame 3,000	Frame 3,600

Fig.12 Deformation and discoloration of the sensor (water-based paint)

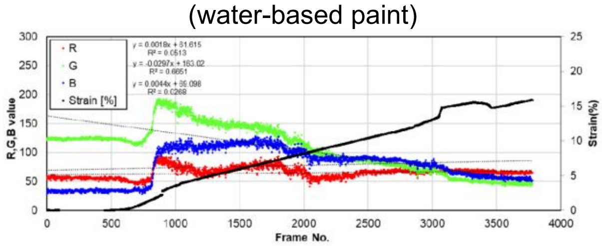
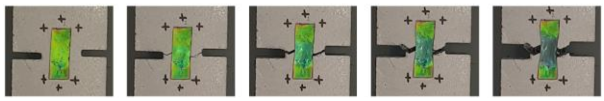


Fig.13 RGB values and strain (water-based paint)

3.5 Oil paint

Fig. 14 and Fig. 15 show the strain of the test piece using oil paint as a finishing material and the discoloration reaction of the attached sensor. The sensors in this specimen showed color changes in the early Light green-deep Green series, and after 800 frames, each RGB Value shows tensile strain and linear behavior.



Frame 1	Frame 900	Frame 1,800	Frame 2,700	Frame 3,400

Fig.14 Deformation and discoloration of the sensor (oil paint)

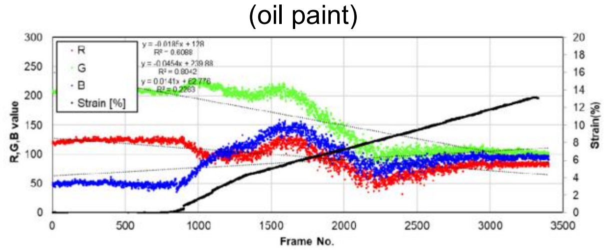


Fig.15 RGB values and strain (oil paint)

4. DERIVATION OF CRACK IDICATORS ACCORDING TO DEFORMATION AND DISCOLORATION EXTRACTION

After confirming the results of the tensile deformation and sensor discoloration reaction of the tensile test piece, additional deformation experiments were conducted to verify the deformation and discoloration effectiveness of the mechanochromic sensor using the concrete beam member. The overall change state of the color was confirmed by extracting it as an HSV value, and Python (Python Software Foundation) was used for color extraction. HSV color space is a color model similar to the human visual system, and image processing is possible in a way similar to that of human visual processing. In the case of mechanochromic sensors, it was confirmed that the values of H, S, and V components changed as the tensile strain of concrete specimens increased, and in particular, the relationship between H value and tensile strain was found to have a linear relationship in repeated experiments. In addition, H is an indicator of color, and a more linear relationship is derived because it is not affected by the color expression perceived differently according to changes in brightness and saturation.

However, since it is not easy to photograph only the deformation and discoloration of the mechanochromic sensor attached to the structure, it is difficult to specify the range of deformation and discoloration of the sensor, which may affect the derivation of quantitative crack width. In addition, in order to extract the color range of only the sensor area from the entire captured image of the mechanochromic sensor, the color analysis range of the captured image was determined and parts other than the sensor were removed. Among the HSV components of the surface of the mechanochromic sensor appearing during image capture, all H values exist in the range of 20 to 150, and S (Saturation) and V (Value) are distributed in the range of 50 or more. Therefore, after dividing the image into 100*300 pixel levels, the HSV component values extracted from the pixels of the deformed area are returned according to the range as shown in Table 5, removing the background other than the sensor and having only the color components of the sensor Simplified.

As shown in Fig. 16, in the image taken by the mechanochromic sensor, no discoloration reaction is expressed in all areas for all sensors, and in particular, no deformation or discoloration reaction itself appears in the adhesive part. Since the surface of the mechanochromic sensor in the part that does not undergo deformation maintains the initial color, the H value of this part is the same as the initial value, and the H value is the lowest among the sensor areas. Therefore, the H value of the surface color of the mechanochromic sensor when the deformation level is the highest is equal to the result of the largest deformation. In this way, the result formula was derived to grasp the deformation according to the discoloration reaction of the sensor. The lowest H value in the captured image of the mechanochromic sensor was defined as Hmin, and the highest H value was defined as Hmax, and dH, the ratio of the two values, was obtained as in Equation (1)[6].

$$dH=H\_max/H\_min \quad (1)$$

The equation representing the relationship between the calculated dH value and the strain was derived as in equation (2)[6], and using this, the discoloration and deformation characteristics of the mechanochromic sensor can be quantitatively derived.

$$Strain = 3.0523 \times dH-4.4955 \quad (2)$$

The H value and strain analysis performed in this study were all performed according to Eqs. (1) and (2), and based on the calculations, the index of discoloration and the derivation formula for crack width were proposed.

Table 5 Determining the scope of use of color elements

	Range	Return value
Step 1	H < 20, H > 150, S < 50, V <50	H,S,V = 0,0,0
Step 2	H > 20	H,S,V = H,255,255

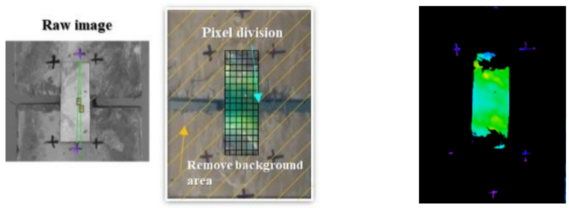


Fig.16 Results of background removal process for image analysis of the captured mechanochromic sensor (left: Image control for improved image accuracy, right: Control result of the image)

5. VALIDATION OF CRACK MONITORING TECHNIQUE USING MECHANOCROMIC SENSOR

5.1 Overview of Concrete Beam Member Crack Measurement Experiment

Previously, as a result of deformation and discoloration of the mechanochromic sensor due to tensile deformation of the concrete test specimen, a crack induction experiment of a large beam member was conducted to verify the method of measuring the crack width of concrete. This experiment identifies the shape of bending and shear cracks due to rebar arrangement inside the beam member. The cross-sectional size of the beam member is H600*B450 and the length is D3,600 mm. The maximum load displacement of the concrete beam was designed to be 18.55 and compressive strength was set to f_{ck} 35 MPa. In this study, as shown in Fig. 17, a sensor was attached at the initial time of crack occurrence to measure the width of the crack advancing according to the load. The mixing table for manufacturing concrete beams is shown in Table 6 below.

Table 6 Mix proportion of concrete beam (kg/m^3)

W/B (%)	S/a (%)	W	C	FA	Sand	Aggregate
41.1	45.0	167	142	61	1,381	955

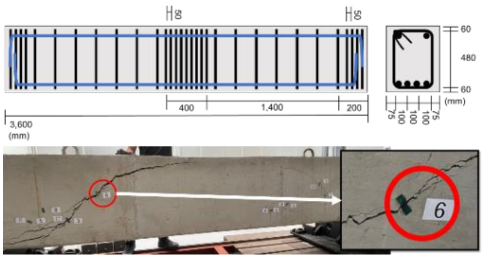


Fig.17 Design section of a concrete beam member and measurement site

5.2 Measuring result of crack width of concrete beam member using mechanochromic sensor

As shown in Table 7, the crack width measured at the crack scale and the crack width derived by the discoloration image crack of the mechanochromic sensor were compared according to the progress of the crack in the beam member. Cracks in the beam member were targeted at sensors whose discoloration range was clearly distinguished because the sensor did not progress in the direction of uniaxial tension due to sine-field cracks, and the crack width was derived from the analysis focusing on discoloration images in the crack range. As a result, the crack width of the concrete beam member was similar to the value measured by the actual crack scale.

As a result of measuring the crack width of the sensor using the structural member, it was considered that it is possible to measure the crack width through analysis of the sensor discoloration image, but it was confirmed that there is a limit to deriving reliable data due to sensor manufacturing, discoloration other than cracks, and irregular discoloration.

Table 7 Comparison results of crack width and image analysis through crack scale

Sensor position	Surface status		
Sensor image			
Crack width-scale	0.250	0.650	1.700
Crack width-color variation	0.334	1.041	2.094

6. CONCLUSIONS

(1) With the mechanochromic sensor attached to the specimen, it was confirmed that discoloration of the sensor occurred according to the deformation of the specimen, and it was possible to grasp the discoloration of the sensor in real time as the crack progressed.

(2) As the strain of the mechanochromic sensor of the test specimen increased according to the finishing type, R, G, and B values tended to converge to about 100 sections. This means that the tensile strain and discoloration reactivity of the mechanochromic sensor show linear behavior, so the convergence of each color value is likely to be used as an indicator to grasp the deformation and discoloration of the mechanochromic sensor.

(3) RGB and HSV color coordinate systems were used to quantitatively analyze the discoloration image of the dynamical discoloration sensor, and color quantification was found to be effective when using the HSV color coordinate system, and it was confirmed that the H value and concrete deformation were linearly increased. Only the H value of the sensor surface was extracted to quantify the degree of discoloration, and the crack width of concrete was estimated using the *dH* value that can derive the relationship with concrete deformation.

(4) As a result of monitoring the deformation of the concrete material using the mechanochromic sensor through this study, the degree of discoloration of the sensor developed at a similar level according to the degree of crack development through image analysis, but for more accurate monitoring It is judged that it is necessary to improve the reliability of the model and the basis of the experimental environment based on the data collected under various conditions such as the sensor attachment location and the effect on the attachment surface.

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