The Colorimetry Method in Assessing Fire-Damaged Concrete

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Abstract

Fast and accurate assessment of fire-damaged concrete structures is of great significance for later maintenance and reuse. The traditional methods require large amount of experimental efforts, and some other new technologies are expensive and their applicability still needs further investigation. In view of this, a colorimetric method based on the optical analysis is proposed to evaluate the fire damage of the concrete in terms of the translation of the color coordinates in the chromaticity diagram. Fire damage experiment was first conducted on concrete cubes with two different strengths. Photos were then taken under the conditions of daylight vs. fluorescent light, and manual white balance vs. auto white balance. The chromaticity diagram is constructed to represent the relationship between the coordinates of the concrete colors and the maximum temperature that concrete was subject to. The conditions under the daylight and the manual white balance are recommended for taking photos to construct the chromaticity diagram, and a linear equation was obtained to estimate the heating duration and the maximum temperature that the concrete exposed to for the coordinates of the concrete color. The results of this study will advance the technology of non-destructively assessing the fire-damaged structures.

1. Introduction

Concrete is known to be the most widely used structural material that can exhibit quite excellent behaviors under different environmental conditions. Concrete can maintain considerable strength, even at high temperature. Many complex physical changes and chemical reactions occur in concrete when exposed to the increasing temperature. The properties of concrete exposed to fire largely depend on the decomposition temperature of different phases in concrete (Vejmelková et al. 2018; Zhang and Ye 2012). Firstly, the physically combined water starts to evaporate and the C-S-H begins to dehydrate at 100°C (Zhang and Ye 2012; Sabeur et al. 2016; Collier 2016). Then the C-S-H is gradually decomposed at 100°C - 300°C (Collier 2016). The portlandite starts to disintegrate at about 500°C (Schneider 1989). Finally, when the temperature rises to 600°C, the calcite begins to decompose (Zhang and Ye 2012; Collier 2016). These processes are accompanied by the deterioration of the concrete, such as the decay of the strength, the decline of the elastic modulus, the phenomena of cracking and spalling (Kim et al. 2013), and the color changes of the concrete. Some of the color changes are due to the chemical reactions that take place during the heating and may occur earlier than any noticeable loss of strength (Li et al. 2017).

Instead of rebuilding the structures, most fire-damaged concrete can still work perfectly after proper maintenance. Appropriate assessment can help find the damaged position and provide advices for the maintenance of the fire-damaged concrete. There have been several major assessment methods for fire-damaged concrete, such as the rebound method and the hammer method. The indicators of these assessments mainly focus on the strength decay of the fire-damaged concrete. Some other assessment methods like the ultrasonic method (Osumi et al. 2014; Yang 1993) and the impact method (Shin et al. 2013) detect the damage degree by wave velocity, which can be reduced by the internal damage in concrete. There are also some other methods like infrared thermal imaging (Du et al. 2002) and the drilling resistance method (Felicetti 2006; Colombo and Felicetti 2007). However, these methods have the same disadvantages of high cost, large error and demanding experimental effort. They are not suitable to be widely applied in practice.

The color of the concrete surface is likely to be a good indicator for fire damage assessment (Hager 2014). When light is irradiated on the concrete surface, part of the light will penetrate the concrete and the rest will be reflected. The selective reflection and absorption give materials specific colors. As is known, the concrete color will change to pink or red at the temperatures range from 300°C to 600°C, whitish grey at the temperatures range from 600°C to 900°C, and buff at the temperatures range from 900°C to 1000°C (Schneider 1989). These phenomena are mainly due to the fact that the color of the materials can be changed by micro cracks and chemical reactions (Ashby et al. 2009, 2013). Color changes caused by the temperature in the concrete are easy to be

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identified by visually comparing to that of the concrete unaffected by the high temperature (Bessey 1950). It is quite possible to detect the maximum fire temperature that the concrete experienced according to the changes of the color. Schneider (1989) showed that the hue of the concrete is greatly affected by the temperature, so it may be possible to estimate the temperature that the concrete has been exposed to by examining the discoloration of the concrete (Ingham 2009). In view of this, to assess the degree of the heating damage of the concrete by quantifying the color changes of the concrete surface, a new method is proposed in this study to assess the fire-damaged concrete by evaluating the color coordinates in the chromaticity diagram. In recent years, the colorimetry method has been used in the field of structural fire safety (Oestmo 2013; Felicetti 2013; Gómez-Robledo et al. 2013; Li et al. 2017). The instruments that were used to take photos of the materials include digital cameras (Carré et al. 2014; Colombo and Felicetti 2007), flatbed scanners (Annarel and Taerwe 2011) and spectrometers (Annarel and Taerwe 2009). However, previous studies only roughly estimated the fire temperature of the concrete by visually observing photos, or simply carried out colorimetric method on fewer samples. The research on the systematic application is lacking. By quantifying the color information of the concrete surface, this study systematically links the color coordinates with the heating temperature, the heating duration and the strength loss, and the best shooting conditions was also advised.

Two aspects were studied in this paper, as shown in Table 1. One is the residual strength of the heated concrete and the other is the analysis of the chromaticity diagram of the concrete. Fire damage experiment was first conducted on concrete cubes with two different strengths. They were heated under four different temperatures ranging from 200°C to 800°C for the duration of 1 hour and 3 hours. Photos of the concrete cubes after cooling were taken by a normal digital camera. The color messages of each photo were analyzed in the chromaticity diagram and three groups of linear relationship were found, including color vs. coordinate, coordinate vs. heating temperature and duration, heating temperature and duration vs. residual strength.

### 2. Materials and methods

#### 2.1 Materials

Ordinary portland cement (OPC) was used as cementitious material to make concrete samples. The chemical compositions in terms of oxide mass percentage are listed in Table 2. The coarse aggregate is limestone, and the fine aggregate is quartz sand. The parameters of the aggregate are shown in Table 3. Two types of the concretes (C30 and C60) were made into standard cubes with size of 100 mm × 100 mm × 100 mm. They were demolded at the age of 24 h after casting, and then cured in a sealed condition at the temperature of 20°C until the age of 28 days. The mixture proportions of these two concretes are shown in Table 4. The measured average compressive strength of the C30 concrete at the age of 28
days is 60.2 MPa, and the average compressive strength of the C60 concrete is 76.9 MPa. The concrete samples were then kept under the room temperature and ventilated conditions for 180 days until the heating test.

2.2 Tests

(1) Heating test
The heating instrument used in the fire simulation test is a QSH muffle furnace. The voltage and the power of the muffle furnace are 220 volts and 8 kilowatts, respectively. The cube specimens were heated from room temperature to the preset maximum temperatures of 200°C, 400°C, 600°C and 800°C, respectively, in the muffle furnace at a heating rate of 10°C per minute. Similar to actual fire, the initial environment (before heating) in the muffle furnace is under the atmospheric condition, which is an oxidizing environment. Five faces of the cube were directly heated at the same time in the furnace, except the interface between the sample and the inner wall of the furnace. The samples were heated at each maximum temperature for 1 hour and 3 hours, respectively. The longest heating duration of 3 hours was selected due to the fact that, in reality, about 98% of the fires normally do not last for 3 hours (Fire Department of Ministry of Public Security of China 2018). Three parallel samples were heated for each case. After heating, the samples were then naturally cooled down to room temperature in the furnace, which took about overnight. A T335 infrared thermal imager with an accuracy of 0.1°C was used to measure the temperature of the concrete to ensure that the concrete had cooled to the room temperature.

(2) Image acquisition
The color information of the concrete surface was collected by using the ordinary digital camera (Nikon-D7100). Photos were taken on the directly heated surface, and 3 photos were taken on each surface. There are two factors that affect the quality of the images. One is the environmental conditions related to the light source, and the other is the setting of the white balance of the camera. In this study, photos were taken under the conditions of two light sources (sunlight vs. fluorescent light) and two white balances (automatic vs. manual), respectively. The dust caused by the high temperature heating on the surface of the samples was wiped by using alcohol pad. Although the measurement can be affected by alcohol wiping, the effect is considered minor (Li et al. 2017).

When setting the automatic white balance of the camera, the function of “automatic white balance” is selected. When setting manual white balance of the camera, a special device called “gray card” should be placed under the light source, and shot by the “manual white balance” function of the camera. The information of the grey color can be extracted by the camera to facilitate the white balance setting. Samples should be shoot under the same light source to reduce the effect of environmental changes on the quality of photos.

(3) Residual strength test
Compressive strength test was conducted to measure the residual strength of concrete after heating. The samples were loaded uniformly at the rate of 0.5 - 0.8 MPa/s until failure. Three parallel samples were measured for each case, and the average value was used.

2.3 Color space selection
The color space is made up by all kinds of colors. The color spaces commonly used in the colorimetry method include the HSI color space (Short et al. 2001, 2002), the CIE XYZ color space (Colombo and Felicetti 2007), the RGB color space (Hager 2014) and the CIE L*a*b* color space (Annarel and Taerwe 2009). The RGB color space is the original color space, and the HSI and the L*a*b* color spaces are all transformed from it. The detection cost of HSI is too high to be widely used in practice. Moreover, in the process of converting RGB to HSI, the hue H could produce a singularity that cannot be eliminated (Chapron 1992), which would result in ignoring the low saturation pixels in the image analysis. L*a*b* color space is suitable for computer analysis and has been integrated into Adobe Photoshop and MATLAB software. Although the color distribution in the L*a*b* color space is uniform, it cannot contain all the colors. In view of the above situation, this paper adopts RGB and XYZ color spaces for the colorimetry analysis.

It is well known that the red, the green, and the blue are the three primary colors. All other colors can be composed by these three colors. In the RGB color spatial distribution diagram as shown in Fig. 1, the visible light with a wavelength of $\lambda$ can be obtained by combining the three colors with the fractions displayed in the coordinates, and this combination is unique. Because all the colors have unique RGB values in the RGB color space, the slight changes of the concrete colors can be detected according to the changes of the coordinate values.

Some research works have stated that the RGB color space is not really suitable in practice (Felicetti 2004). As shown in Fig. 1, some fractions in RGB space are nega-
The transformation process is shown by Cowan (1983) as: the XYZ color space as shown in base of the color space by linear transformation to obtain the XYZ color space can be converted to another color space by linear transformation. Fortunately, color space is a linear space, which means that each color space can be converted to another color space by linear transformation.

To meet the practical requirements and to eliminate some negative coordinates in the original RGB space, the International Commission on illumination transforms the base of the color space by linear transformation to obtain the XYZ color space as shown in Fig. 2. The linear transformation process is shown by Cowan (1983) as:

\[
\begin{align*}
X &= 0.41245 \cdot R + 0.35758 \cdot G + 0.18042 \cdot B \\
Y &= 0.21267 \cdot R + 0.71516 \cdot G + 0.07217 \cdot B \\
Z &= 0.01933 \cdot R + 0.11919 \cdot G + 0.95023 \cdot B
\end{align*}
\]

where \( R \), \( G \) and \( B \) represent the coordinate values of the color in the RGB space, respectively. \( X \), \( Y \) and \( Z \) represent the combination fractions of the color in the XYZ space.

Based on the XYZ spatial distribution diagram, all colors can be represented in the first quadrant, as shown in Fig. 3. However, it is still not convenient for judging the changes of the colors, there are several steps to simplify the image. First, there is a common feature for all the color systems that the intensity of the light affects the chromaticity diagram is constructed by normalizing and projecting through linear transformation from the RGB color space into the chromaticity diagram, as shown in Fig. 3. All colors have a unique corresponding point on the X-Y (Z=0) plane. All the corresponding points on the X-Y plane are distributed in a fixed area surrounded by a curve. This figure is called the chromaticity diagram, as shown in Fig. 4. So far, with a series of linear transformations, all colors in the color space can be uniquely represented by the XY coordinate values.

2.4 Image analysis

Accurate analysis of each photo is the key to the entire experiment. There are 24 million pixels in a picture and each pixel will have a corresponding RGB value to represent its color. Several zones selected randomly at the center and edges of each image were used to extract the RGB value by MATLAB or Photoshop. The average RGB values of the representative pixels can be calculated to represent the color of the entire photo. Then the chromaticity diagram is constructed by normalizing and projecting through linear transformation from the RGB system to the XYZ system.

To obtain the color information of the photos quantitatively, the following three steps are conducted to differentiate light intensities in the XYZ coordinate system. This is good news for the colorimetry method. The influence of the light intensity is exactly what should be eliminated. It is not possible to keep the light intensity constant during the photo shooting because the environmental conditions change continuously. Therefore, a normalization on the \( X+Y+Z=1 \) plane is carried out in colorimetry method to eliminate the effects of light intensity. In the normalization, any color will find its unique corresponding point on the \( X+Y+Z=1 \) plane. Finally, all the points on the \( X+Y+Z=1 \) plane are projected to the X-Y (Z=0) plane. The projection is just like the process from \( C' \) to \( C'' \) (shown in Fig. 3). All colors have a unique corresponding point in the X-Y (Z=0) plane. All the corresponding points on the X-Y plane are distributed in a fixed area surrounded by a curve. This figure is called the chromaticity diagram, as shown in Fig. 4. So far, with a series of linear transformations, all colors in the color space can be uniquely represented by the XY coordinate values.
termine the coordinates in the X-Y chromaticity diagram:
(a) Extracting the photo information: The fractions of the RGB values can be obtained from the chromophoto-
graphy by the following equation.

\[ R G B = [(R G B_{\text{raw}} / 255 + 0.055) / 1.055]^4 \]  \tag{2}  
(b) Linear transformation from the RGB to XYZ coor-
dinate system: Detailed methods have been described in
equation 1.
(c) Normalizing and projecting to the X-Y chromaticity
diagram: To reduce the influence of light intensity, all
colors are normalized on the X+Y+Z=1 plane, and then
projected to the X-Y (Z=0) plane. Their x and y coor-
dinates in the X-Y chromaticity diagram are calculated by:

\[ x = X / (X + Y + Z) \]
\[ y = Y / (X + Y + Z) \]  \tag{3}  

3. Results and discussion
3.1 Photo information
The core of colorimetry method is to characterize the color change. Before quantitative analysis, one can first observe the unprocessed photos visually, which will help to establish an intuitive judgment on the color changes of the concrete surface.

Because of few obvious difference of the color changes between the C30 and the C60 concrete, the photo processing of the C30 concrete are taken as an example. Photos of the C30 concrete heated for 1 h were shot under the conditions of daylight-auto white balance [Fig. 5(a)], daylight-manual white balance [Fig. 5(b)], fluorescent-auto white balance [Fig. 5(c)], and fluorescent-manual white balance [Fig. 5(d)] conditions, respectively. The surface color of the concrete varies with the increase of the heating temperature as shown in Fig. 5. The higher the heating temperature of the fire, the lighter is the color of the concrete surface.

Although the specimens are the same, their photos show different colors under different shooting conditions. The color of the photos shown in Figs. 5(a) and 5(b) is gray, and that in Figs. 5(c) and 5(d) is blue. This visual difference is due to the different light sources and the white balance. However, the trend of the color changes caused by the increase of the heating temperature is consistent. Therefore, the changes of the concrete color can be used as a base for evaluating the fire-damaged concrete in terms of the heating temperature that concrete was subjected to.

3.2 Chromaticity diagram
Through the steps mentioned above, the chromaticity diagram (Fig. 6) of the C30 concrete under the conditions of the daylight-auto white balance is obtained from the photos shown in Fig. 5(a). The data points in Fig. 6(a) are the average values of the surface color of the sample at different temperatures, and their colors are expressed by different coordinate values. When the color of the concrete changes, the movement of the data points in the chromaticity diagram can be observed. The movement of the data points reflects the changes of the maximum temperature and the heating duration that the concrete was subjected to.

According to the maximum temperature that the concrete is exposed to, all the data points in the chromaticity diagram can be divided into four groups (200°C, 400°C, 600°C, and 800°C). As can be seen from Figs. 6(b) and 6(c), the data points in the same group (exposed to the same maximum temperature) are located in a specific area in the chromaticity diagram. There is a clear boundary between different groups, indicating that the surface color of the concrete is different after exposure to different maximum temperatures, and this difference can be vividly shown in the chromaticity diagram.

According to Schneider (1989), the color of concrete changes regularly with increasing heating temperature. This change can also be observed in the chromaticity diagram as shown in Fig. 6(a). When the temperature rises from 200°C to 400°C, the average coordinate value in the chromaticity diagram moves from (0.326, 0.369) to (0.330, 0.367), which is towards to the bottom right and to the direction of the red color in the chromaticity diagram with coordinate of (0.639, 0.330), as shown in Fig. 6. It is judged from the movement that the color of the concrete surface changes to red when the temperature rises from 200°C to 400°C. This is consistent with the observation that the color of the concrete may develop to pink or red at 400°C (Schneider 1989). In Fig. 6(b), the translation of the coordinates to the red direction can also be observed for all the samples. So the red shift behavior

![Fig. 4 Chromaticity diagram - the zone surrounded by the dashed line in Fig. 3. All the colors can be expressed by the XY coordinates in this diagram [after Felicetti (2004)].](image-url)
in the chromaticity diagram can be used as a sign that the concrete temperature reaches 400°C.

The average coordinate values of concrete heated at 600°C and 800°C are (0.322, 0.360) and (0.318, 0.356), respectively, as shown in Figs. 6(a) and 6(c). The coordinate values in the chromaticity diagram show obvious phenomenon of white shift when the heating temperature rises from 400°C to 600°C and 800°C. The position of concrete color moves to the bottom left towards the white point with the coordinates of (0.307, 0.342) in the chromaticity diagram. This is consistent with the photographic results shown in Fig. 5(a), where the color of the concrete is close to gray or white. The phenomenon of white shift can be used as a sign of more severe damage in concrete.

3.3 Residual strength

Figure 7 shows the effect of the heating temperature on the residual strength of the concrete under different heating durations and for different concrete types. It showed that the residual strength of the C30 and C60 concrete has a linear relationship with the heating temperature, and the correlation coefficient of the curves is about 0.97, consistent with the conclusion from Lv (2002) and Chen (2003). Therefore, the damage degree of the concrete in terms of the residual strength is directly related to the heating temperature.

Figure 7(a) shows the relationship between the residual strength and the heating temperature for C30 and C60 concrete under the heating duration of 1 hour. Though the reduction rate of the residual strength between the C30 and the C60 concrete is different, the strength reduction for both concretes heated for 1 hour is similar at the maximum heating temperature of 800°C (reduction of 57.8% for C30 vs. reduction of 56.3% for C60). That indicates the effect of high heating temperature on the residual strength of the concretes is the same when the heating duration is short.

Figure 7(b) shows the relationship between the residual strength and the heating temperature for C30 and C60 concrete under the heating duration of 3 hours. The strength reduction of these two types of the concrete under the heating duration of 3 hours is similar to that of 1 hour. Compared with Fig. 7(a), the total strength reduction of the C30 concrete under the heating duration of 3 hours is more than that heated for 1 hour (reduction of

![Fig. 5 Photos taken under the conditions of (a) daylight-auto white balance, (b) daylight-manual white balance, (c) fluorescent-auto white balance and (d) fluorescent-manual white balance for the C30 concrete after heating for 1 hour.](image-url)
73.8% for 3 hours vs. reduction of 57.8% for 1 hour), but the strength reduction of C60 concrete under two heating duration is similar (reduction of 58.4% for 3 hours vs. reduction of 56.3% for 1 hour). It means that the strength reduction of the low-strength concrete is much more than that of the high-strength concrete under the condition of longer heating duration.

Table 5 lists the values of the residual strength of the concretes and the strength reduction compared to the strength at the age of 28 days. It found that the major temperature range responsible for the strength reduction is between 400°C to 800°C. The portlandite and the calcite decomposed successively within this temperature range and caused failure of the main components that provide strength for the concrete.

### 3.4 Effect of different factors on chromaticity diagram

#### (1) Effect of the white balance

The coordinates of the data points obtained under the condition of auto white balance [Fig. 6(a)] and the manual white balance [Fig. 8(a)] are different. Since the white balance only changes the color of the images instead of the true color of the concrete samples, the overall movement of the concrete color in the chromaticity diagram caused by the change of white balance can be explained by its linear transformation behavior in the color space. However, the sensitivity to the color changes under different conditions of white balance is maintained in the chromaticity diagram, all color changes can be clearly displayed in the chromaticity diagram even after the linear transformation of the shooting conditions.

Figures 8(b) and 8(c) show the color distribution of the concrete exposed to the temperature of 200°C - 400°C and 400°C - 800°C, respectively, under the condition of manual white balance. The characteristic of linear distribution of color is more significant under the conditions of manual white balance compared to that under the condition of auto white balance [Figs. 6(b) and 6(c)]. In Fig 8(b), the two straight lines are parallel,
indicating that the degree of the red shift obtained under the manual white balance is uniform. The same characteristics can be observed in Fig. 8(c). The linear equation fits all the color points by \( y = 0.919x + 0.06 \) \( (R^2 = 0.997) \), and the white point \((0.307, 0.342)\) in the chromaticity diagram is also on the straight line. This shows that under the condition of manual white balance, the color changes obey completely the law of the white shift.

The condition of manual white balance is perfect for constructing the chromaticity to distinguish the color of the concrete exposed to different temperature. Figs. 8(b) and 8(c) show clear boundaries between the four groups of the data points, and there is no overlapping among their coordinate. Therefore, the color changes of the concrete can be more accurately captured by the manual white balance to assess the fire damage compared to the auto white balance. The following analysis and discussion are based on the results under the condition of the manual white balance.

### Table 5 Residual strength of the heated concretes.

| Heating duration | Temperature (°C) | C30 Residual strength (Standard deviation) (MPa) | Reduction of the strength compared with 28 days strength (%) | C60 Residual strength (Standard deviation) (MPa) | Reduction of the strength compared with 28 days strength (%) |
|------------------|------------------|-----------------------------------------------|----------------------------------------------------------|-----------------------------------------------|----------------------------------------------------------|
| 1 hour           | 20               | 60.2 (1.08)                                   | 0.0                                                      | 20                                            | 76.9 (3.01)                                               | 0.0                                                      |
|                  | 200              | 53.4 (1.84)                                   | 11.3                                                     | 200                                           | 75.1 (3.13)                                               | 2.3                                                      |
|                  | 400              | 45.6 (2.97)                                   | 24.3                                                     | 400                                           | 68.0 (2.73)                                               | 11.6                                                     |
|                  | 600              | 34.5 (3.25)                                   | 42.7                                                     | 600                                           | 51.2 (3.21)                                               | 33.4                                                     |
|                  | 800              | 25.4 (2.52)                                   | 57.8                                                     | 800                                           | 33.6 (3.30)                                               | 56.3                                                     |
| 3 hours          | 20               | 60.2 (1.08)                                   | 0.0                                                      | 20                                            | 76.9 (3.01)                                               | 0.0                                                      |
|                  | 200              | 46.7 (2.06)                                   | 22.4                                                     | 200                                           | 72.1 (2.51)                                               | 6.2                                                      |
|                  | 400              | 41.1 (3.05)                                   | 31.7                                                     | 400                                           | 63.2 (2.50)                                               | 17.8                                                     |
|                  | 600              | 29.1 (2.96)                                   | 51.7                                                     | 600                                           | 41.3 (3.42)                                               | 46.3                                                     |
|                  | 800              | 15.8 (2.15)                                   | 73.8                                                     | 800                                           | 32.0 (2.80)                                               | 58.4                                                     |

(2) Effect of the light source

In addition to the white balance of the camera, the lighting condition is also an important factor affecting the chromaticity diagram of the concrete color. Figure 9 shows the chromaticity diagram of the C30 concrete at different heating temperatures under the condition of fluorescent-manual white balance. In Fig. 9(a), the phenomenon of the red shift and the white shift can also be observed. Compared to Fig. 8(a), the coordinates of the data points in the chromaticity diagram move left when the light source changes from daylight to fluorescent light. This means that, similar to the white balance, the changes of the light source will also lead to the linear transformation of the color information. This confirms the feasibility of the colorimetric method for fire damage assessment under different light sources.

However, the range of the error bars in Fig. 9(a) far exceeds those in Fig. 8(a), and there is a large overlapping area between the error bars of each temperature. In Figs. 9(b) and 9(c), the above phenomenon is manifested.

Fig. 8 Chromaticity diagram (a) of the C30 concrete with photos taken under the conditions of daylight-manual white balance, showing a tendency of shifting to the red point \((0.639, 0.330)\) and a tendency of shifting to the white point \((0.307, 0.342)\). (b) and (c) are the local diagrams and trend lines of the C30 concrete heated at 200°C - 400°C and 400°C - 800°C, respectively. M represents manual white balance.
by the fact that the color of the concrete surface is more
discrete in the chromaticity diagram under the condition
of fluorescent light. The data points between each group
is mixed, and a clear boundary cannot be obtained. The
coordinates of the color in the chromaticity diagram
constructed under the condition of fluorescent light
source cannot be used to estimate effectively the heating
duration and the heating temperature of the concrete.

Since the surface of the concrete is uneven and the
direction of the fluorescent light source is single, more
shadows appear on the concrete surface, and the discol-
oration of the concrete surface cannot be fully reflected.

On the other hand, since daylight is a directional light
source, a more continuous and well defined chromaticity
diagram can be obtained so that the heating temperature
and the degree of damage to the concrete can be deter-
mined more accurately. The following discussions are
based on results under the condition of daylight and
manual white balance.

(3) Effect of the heating duration
It is clear that the longer the heating duration, the greater
the damage of the concrete. Figure 10(a) shows the
chromaticity diagram of the concrete surface after heat-

Fig. 9 Chromaticity diagram (a) of the C30 concrete with photos taken under the conditions of fluorescent-manual white
balance, showing a tendency of shifting to the red point (0.639, 0.330) and a tendency of shifting to the white point (0.307,
0.342). (b) and (c) are the local diagrams of the C30 concrete heated at 200°C - 400°C and 400°C - 800°C, respectively.
Note: F represents fluorescent light.

Fig. 10 Chromaticity diagram (a) of the C30 concrete heated for 1 and 3 hours with photos taken under the condition of
daylight-manual white balance. The tendency of shifting to the white point (0.307, 0.342) occurs with the increase of the
heating duration. (b) and (c) are the local diagrams and trend lines of the C30 concrete heated at 200°C - 400°C and
400°C - 800°C, respectively.
ing at each temperature for 1 hour and 3 hours, respectively. The color of the concrete surface also shows red shift and white shift with the increase of the heating temperature under the heating duration of 3 h. It indicates that the colorimetry method is also applicable under different heating duration. More importantly, the increase of the heating duration is reflected by the white shift. This means that the heating duration of the concrete can be judged by the degree of the white shift, and it is applicable to any heating temperature.

Figures 10(b) and 10(c) show the color distribution of the concrete surface at each temperature for 3 hours. Although the slopes of the two straight lines shown in Fig. 10(b) are similar, the distance between them is shorter than that of Fig. 8(b), and some of the data points appear overlapping. In Fig. 10(c), the color of the concrete exhibits a perfect phenomenon of white shift at 400°C - 800°C, there is, however, an overlapping between the two sets of data points at 600°C and 800°C. The above phenomenon shows that the longer the heating duration, the closer the color differences of the concrete at adjacent temperatures.

(4) Effect of the type of the concrete

The C30 and C60 concrete were tested in the same way to identify the validity of the colorimetry method for different types of concrete. Figure 11(a) shows the chromaticity diagrams of the C30 and C60 concrete under the condition of daylight-manual white balance. The phenomenon of the red shift and the white shift of the C60 concrete can also be clearly found, which means that it is feasible to assess the heating temperature of different types of the concrete from the chromaticity diagram. The coordinates of the C60 concrete move to the bottom left compared to the coordinates of the C30 concrete, which is related to the material composition of the two concretes. Therefore, different coordinate values need to be specified in the chromaticity diagram for different types of the concrete.

Figures 11(b) and 11(c) show the color distribution of the surface of the C60 concrete with the heating duration of 1 hour. It is seen that the color coordinates also show linear distribution characteristics. However, the coordinates of the concrete colors overlap each other between 200°C and 400°C [Fig. 11(b)], indicating minor color changes under the heating temperature between 200°C and 400°C. This is consistent with the strength change shown in Fig. 7, which indicates that the residual strength of the C60 concrete also has little changes when the temperature rises from 200°C to 400°C. Therefore, certain relationship exists between the color of the concrete surface and the strength. The same phenomenon can be found in C30 concrete.

Moreover, in Fig. 11(c), there is a large gap between the color coordinates of the concretes heated at 400°C and 600°C, which represents the phenomenon of the white shift of the concrete color being greater under the heating temperature of 400°C - 600°C. It is also consistent with the strength reduction. In Fig. 7(a), the strength reduction under the heating temperature of 400°C - 600°C is 40% of the total reduction. Similar to Fig. 11(c), the color ordinates of C60 concrete under the heating temperature of 400°C - 800°C are also located on the same straight line and show significant characteristics of white shift. It shows that the colorimetry method is suitable for different types of the concrete. Due to the difference of the proportion of mixture, the colorimetry method is more accurate in assessing the C60 concrete under the heating temperature above 400°C.

![Fig. 11 Chromaticity diagram (a) of the C30 and C60 concrete heated for 1 hour with photos taken under the condition of daylight-manual white balance. (b) and (c) are the local diagrams and trend lines of the C60 concrete heated at 200°C - 400°C and 400°C - 800°C, respectively.](image-url)
4. Application and further study

The summary of the linear equation of the color of the concrete surface obtained from the chromaticity diagram under the condition of daylight-manual white balance is shown in Table 6. To infer the heating condition and the residual strength of a fire-damaged concrete, the following four steps can be conducted:

(a) Shooting the concrete surface by using an ordinary camera under the condition of daylight and manual white balance;

(b) Converting the color of the photo into (x, y) coordinates in the chromaticity diagram by using the method introduced in Section 2.4;

(c) Fitting these data points to obtain the coefficients of the linear equation;

(d) Comparing the coefficients \(a, b\) and the range of \(x\) with the parameters shown in Table 6.

The heating duration and the temperature of the unknown concrete can be judged by following the above steps.

However, this study is only a beginning, and further experiments are needed to enrich the table in the future, including more types of the concrete, more detailed heating duration and temperature setting.

5 Conclusion

In this study, a colorimetry method is proposed for non-destructively assessing the damage of the concrete after fires. The colorimetry method is based on the analysis of the photos taken on the surface of the heated concrete. The effect of the heating temperature and heating duration on the result of chromaticity diagram were analyzed, and the effect of different light sources and white balance conditions on the chromaticity diagram was compared. The major conclusions are:

(1) The maximum temperature that the concrete has experienced can be determined according to the locations and the coordinates of the concrete colors in the chromaticity diagram. There is a corresponding relationship between the coordinates of concrete colors and the maximum temperature in the chromaticity diagram. The heating damage of the concrete can be assessed by the translation of the color coordinate in the chromaticity diagram.

(2) The color coordinates of concrete exposed to the same heating temperature are distributed in a fixed area in the chromaticity diagram. There are obvious boundaries between the different temperature groups. When the maximum heating temperature rises from 200°C to 400°C, the concrete color in the chromaticity diagram would move towards the red point. When the maximum heating temperature rises from 400°C to 800°C, it would move towards the white point.

(3) The camera is not always accurate in recording the absolute color value, but it can maintain its sensitivity to the color variation under different shooting conditions (light source and white balance), and all the color variations caused by different light sources and white balance can be shown in the chromaticity diagram after linear transformation. The conditions under the daylight and the manual white balance are recommended for taking photos to construct the chromaticity diagram.

(4) Compared to the 1 hour heating duration, the color coordinates of the concrete heated for 3 hours are closer to the white point in chromaticity diagram when exposed to the same temperature. The color coordinates of the concrete that heated under the same maximum temperature are still located in a fixed area, though the heating duration is different. Therefore, the coordinates of concrete colors in the chromaticity diagram are mainly related to the maximum temperature. A table of the linear distribution coefficient of the color coordinates under different heating temperature and duration is developed and can be used to estimate the maximum heating temperature and the heating duration that the concrete was exposed to.

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References

Annarel, E. and Taerwe, L., (2009). “Revealing the temperature history in concrete after fire exposure by microscopic analysis.” Cement and Concrete Research, 39, 1239-1249.

Annarel, E. and Taerwe, L., (2011). “Methods to quantify the colour development of concrete exposed to fire.” Construction and Building Materials, 25, 3989-3997.

Ashby, M. F., Ferreira, P. J. and Schodek, D. L., (2009). “Nanomaterials, nanotechnologies and design: an introduction for engineers and architects.” London: Butterworth-Heinemann.

Ashby, M. F., Shercliff, H. and Cebon, D., (2013). “Materials: engineering, science, processing and design.” 3rd ed. London: Butterworth-Heinemann.

Bessey, G. E., (1950). “Investigations on building fires, part 2: the visible changes in concrete or mortar exposed to high temperatures.” In: National Building Studies Technical Paper 4. London: HMSO Publishing, 6-18.

Carré, H., Hager, I. and Perlot, C., (2014). “Contribution to the development of colorimetry as a method for the assessment of fire-damaged concrete.” European Journal of Environmental and Civil Engineering, 18(10), 1130-1144.

Chapron, M., (1992). “A new chromatic edge detector used for color image segmentation.” In: D. Haag Ed. Proc. 11th IAPR International Conference on Pattern Recognition, Vol. 3, Conference C: Image, Speech and Signal Analysis, Hague 30 August - 3 September 1992. Washington DC, USA: IEEE Computer Society Press, 311-314.

Chen, L., Li, B., Teng, T. J. and Chen, T. L., (2003). “The analysis about high temperature mechanical performance of concrete.” Concrete, 7, 26-28. (in Chinese)

Collier, N. C., (2016). “Transition and decomposition temperatures of cement phase - a collection of thermal analysis data points.” Journal Ceramics-Silikáty, 60(4), 338-343.

Colombo, M. and Felicetti, R., (2007). “New NDT techniques for the assessment of fire-damaged concrete structures.” Fire Safety Journal, 42(6-7), 461-472.

Cowan, W. B., (1983). “An inexpensive scheme for calibration of a colour monitor in terms of CIE standard coordinates.” ACM SIGGRAPH Computer Graphics, 17(3), 315-321.

Du, H. X., Zhang, X. and Han, J. H., (2002). “Testing and evaluating damage of concrete exposed to fire by infrared thermal image.” Journal of Tongji University, 9, 1078-1082.

Felicetti, R., (2004). “Digital camera colorimetry for the assessment of fire-damaged concrete.” In: P. G. Gambarova, R. Felicetti, A. Meda and P. Riva, Eds. Proc. International Workshop on Fire Design of Concrete Structures: What now? What next?, Milan 2-3 December 2004. Brescia, Italy: Starrylink Editrice, 211-220.

Felicetti, R., (2006). “The drilling resistance test for the assessment of fire damaged concrete.” Cement and Concrete Composites, 28(4), 321-329.

Felicetti, R., (2013). “Assessment methods of fire damages in concrete tunnel linings.” Fire Technology, 49, 509-529.

Fire Department of the Ministry of Public Security of China. (2018). “China fire services.” Yunnan, China: Yunnan People's Publishing House Press. (in Chinese)

Gómez-Robledo, L., López-Ruiz, N., Melgosa, M., Palma, A. J., Capitán-Valvle, L. F. and Sánchez-Marañón, M., (2013). “Using the mobile phone as Munsell soil-colour sensor: An experiment under controlled illumination conditions.” Computers and Electronics in Agriculture, 99, 200-208.

Hager, I., (2014). “Colour change in heated concrete.” Fire Technology, 50(4), 945-958.

Ingham, J. P., (2009). “Application of petrographic examination techniques to the assessment of fire-damaged concrete and masonry structures.” Materials Characterization, 60, 700-709.

Kim, K. Y., Yim, T. S. and Park, P. K., (2013). “Evaluation of pore structures and cracking in cement paste exposed to elevated temperatures by x-ray computed tomography.” Cement and Concrete Research, 50, 34-40.

Koenderink, J. J., (2010). “Color for the sciences.” Massachusetts, USA: The MIT Press.

Li, Z. H., Wong, L. N. Y. and Teh, C. I., (2017). “Low cost colorimetry for assessment of fire damage in rock.” Engineering Geology, 228, 50-60.

Lv, T. Q., Zhao, G. F., Lin, Z. S. and Yue, Q. R., (2002). “The experimental research on applying rebound and ultrasonic to assess compressive strength of concrete subjected to fire and considered standing time effect after fire.” Concrete, 8, (21-23), 32. (in Chinese)

Oestmol, S., (2013). “Digital imaging technology and experimental archeology: a methodological framework for the identification and interpretation of fire modified rock (FMR).” Journal of Archaeological Science, 40(12), 4429-4443.

Osumi, A., Enomoto, M. and Ito, Y., (2014). “Basic study of an estimation method for fire damage within concrete sample using high-intensity ultrasonic waves and optical equipment.” Japanese Journal of Applied Physics, 53(7S), 07KC16.

Raina, S. J., Vishwanathan, V. N. and Ghosh, S. N., (1978). “Instrumental techniques for investigation of damaged concrete.” Indian Concrete Journal, 52(5-6), 147-149.

Sabeur, H., Platret, G. and Vincent, G., (2016). “Composition and microstructural changes in an aged cement pastes upon two heating–cooling regimes, as studied by thermal analysis and x-ray diffraction.” Journal of Thermal Analysis and Calorimetry, 126, 1023-1043.

Schneider, U., (1989). “Reparability of fire damaged...
structures: CIB W14 report.” Fire Safety Journal (Special Issue), 16(4), 251-336.
Short, N. R., Purkiss, J. A. and Guise, S. E., (2001). “Assessment of fire damaged concrete using colour image analysis.” Construction and Building Materials, 15(1), 9-15.
Short, N. R., Purkiss, J. A. and Guise, S. E., (2002). “Assessment of fire-damaged concrete using crack density measurements.” Structural Concrete, 3(3), 137-143.
Shin, S. W., Kim, S. Y. and Kim, J. S., (2013). “Applicability of impact-echo method for assessment of residual strength of fire-damaged concrete.” Journal of the Korea Institute for Structural Maintenance and Inspection, 17(5), 105-112.
Vejmelková, E., Koňáková, D., Scheinherrová, L., Doleželová, M., Keppert, M. and Černý, R., (2018). “High temperature durability of fiber reinforced high alumina cement composites.” Construction and Building Materials, 162, 881-891.
Yang, Y., (1993). “Evaluating temperature distribution of the sections of fire damaged concrete elements by ultrasonic pulse method.” Journal of Southwest Jiaotong University, 4.
Zhang, Q. and Ye, G., (2012). “Dehydration kinetics of portland cement paste at high temperature.” Journal of Thermal Analysis and Calorimetry, 110(1), 153-158.