Color and Material Property Changes in Concrete Exposed to High Temperatures

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Abstract
When a concrete structure is exposed to heat such as a fire, its material properties, such as weight, compressive strength and elasticity, are degraded. The exposure also accompanies cracking, spalling and color changes. Therefore, a structure's quantitative damage assessment is very critical in determining whether to dismantle or strengthen the structure after a fire. The purpose of this study is to consider the color change of heat exposed concrete as a major parameter in conjunction with material property changes, such as weight loss and compressive strength degradation, for the purpose of identifying the relationship between concrete color change and material property changes at high exposure temperatures.

For this purpose we manufactured concrete samples with varying water-to-cement ratios and heated them to target temperatures of 100, 200, 300, 400, 500, 600, 700 and 800°C in an electric oven, whereupon their color changes, weight losses and residual compressive strengths were measured for analysis. Experiment results show that the color change into red in concrete samples exposed to higher temperatures has a consistent relationship with weight loss rate and residual compressive strength. This result indicates that measuring the hue value in a concrete material can enable assessment of its material property changes.

Keywords: high temperature; concrete; color changes; compressive strength; weight loss

1. Introduction
When reinforced concrete structures are exposed to fire, their material properties such as compressive strength, elasticity coefficient and rebar yield strength, are degraded and color change is accompanied. Therefore, the structure's damage assessment is essential in determining whether to dismantle or augment the structure after a fire. For this purpose, it is important that material changes such as cracking pattern, deformation and discoloration, are observed visually and non-destructive tests and core tests are performed to quantitatively assess the concrete's deterioration level such as strength reduction and neutralization. (J. R. Santos et al., 2002; Matteo Colombo et al., 2007; Ufuk Dilek, 2005)

It has been known that concrete exposed to high temperature experiences change in its hue depending on the exposed temperature level. In general, at temperatures of 300°C to 600°C concrete hue changes to pink or red, in the range from 600°C to 900°C, to whitish grey and from 900°C to 1000°C, to buff color. Since concrete's hue value changes as temperature increases, we can estimate the level of compressive strength degradation by observing the hue change. (N. R. Short et al., 2001; B. Georgali et al., 2005)

Also, Deng-Fong Lin (2004) captured images of heated mortar test samples using a digital camera, conducted photo analysis of the images to determine magnitudes of color elements in each coordinate, and thereby identified the relationship between the hue change and temperature of mortar test samples exposed to various temperature levels.

Behavior of a concrete structure exposed to high temperature shows no loss in concrete strength at temperature less than 100°C. However, at this level the moisture within internal pores begins to evaporate. At 200°C the residual compressive strength is reduced to 80~90% of the original level. At 300°C decomposition of silicate hydrates begins and the residual compressive strength falls to about 70% of the initial level. At 500°C or above, dehydration of silicate hydrates occurs and the residual compressive strength falls to 30~40%. (J. R. Santos et al., 2002; G. A. Khoury, 1992)

At 110°C and above decomposition of chemically bound water in calcium silicate hydrate (CSH) occurs as an important change. Decomposition of CSH and thermal expansion of aggregates increase internal stress so that fine fractures are created in the concrete structure at 300°C or higher. Calcium hydroxide (Ca(OH)_2), which is the most important element in...
cement paste, is decomposed at about 530°C and causes dry shrinkage of concrete structure. (Omer Arioz, 2007; Nabi Yüzer, 2004)

Eurocode 2 (2004) presents concrete weight loss in a quantitative formula in terms of density change, which occurs from temperature increase. According to this formula there is no weight loss at 100°C, whereas 2~5% weight loss occurs in 200°C~400°C and 5.9~8.5% in 500°C~800°C or higher temperatures.

The purpose of this study is to identify the relationship between color change and material property change in concrete structures exposed to high temperatures due to fires by investigating their color change as a major variable in conjunction with material property changes including weight loss and compressive strength reduction.

2. Basic Theory of Color Analysis

2.1 Color expression method (N. R. Short et al., 2001)

Color changes are expressed and quantified in color space coordinates using respective factors. Methods of color description are numerous but are largely classified into two categories: One is to express as a combination of red, green and blue (RGB), and the other describes colors from the viewpoint of hue, saturation and intensity (HSI).

Since the RGB coordinate system is simple and easy to express an image, it is widely used for cameras and monitor screens. Colors, which are combined from individual signals of red, green and blue, are defined as percentages of red, green and blue. However, the disadvantage of this system is that humans cannot identify colors combined from red, green and blue colors.

Saturation represents the degree of mixture between a pure color and the white color. That is, a bright and deep red color, which is not mixed with white color, indicates high saturation. As white color is added, the color changes to bright red, pink, and then white. In the HSI coordinate system, the circumference indicates 100% saturation while the center 0% saturation.

Lightness represents the degree of a material reflecting the light. Therefore, it represents relative brightness or darkness. In a bright light red color has high lightness, whereas, the darker the light, the less the lightness.

In the HSI coordinate system lightness is indicated on the vertical axis on the circular plane. The entire HSI coordinate system is expressed in the form of a dual cone shape, where a specific color is defined in terms of hue, saturation and lightness on the cone.

2.2 Color order systems (Konica Minolta, 1998)

To express a color on an object, it is necessary for us to classify colors based on a rule for humans to distinguish. Such a system of representing colors is called 'color order system.'

Existing color order systems include CIE XYZ system; L*a*b, L*C*h and Hunter Lab, which are expressed as coordinate transformations from the CIE XYZ system.

L*a*b color order system was adopted as the international standard in 1976 at International Commission of Illumination (ICI) and is most widely used for representing colors on objects as a nearly uniform color space for visual perception.

As shown in Fig.2., in the L*a*b color order system, lightness is indicated as L*, hue and saturation as a* and b*, respectively; a* and b* indicate color directions where a* is towards red, -a* towards green, b* towards yellow and -b* towards blue. As the number increases in each direction, hue increases, whereas, as we move towards the center, color approaches to no saturation color.

As shown in Fig.2., L*C*h color order system is based on the L*a*b system, where L* indicates lightness and C* saturation. As C* value increases, the color is situated in the outer area of the color

![Fig.1. HSI Color Space](image1)

![Fig.2. L*a*b/L*C*h Color Space](image2)
order system circle with increasing chroma, whereas decreasing chroma places a color closer towards the center of the circle, where no saturation occurs.

Also, \( h \) indicates the hue angle, where a color hue is determined by an angle in counterclockwise direction from 0 degree in a* red color direction.

Lightness index \( L^* \) is the same as in \( L^*a^*b^* \) color order system. Saturation \( C^* \) and hue angle \( h \) are computed from Eq. (1) and Eq. (2), as follows.

\[
C^* = \sqrt{(a^*)^2 + (b^*)^2} \quad (1)
\]
\[
h = \tan^{-1}(b^*/a^*)(\text{degree}) \quad (2)
\]

2.3 Color measurement method (Konica Minolta, 1998)

Human eyes are excellent in comparing colors. However, humans have difficulty remembering colors and the ability differs significantly from one person to another. Therefore, an objective color tone standard and measurement systems are necessary to accurately represent and analyze colors or color shades.

Methods of color measurement include visual perception and the use of a color measurement device. In general, spectral color meter is used to control colors in dye industry, painting and construction interior works. In our study we use such a device to quantize color measurements and apply the result to each color order system for analysis.

The principle of color measurement device is the same as the process a human perceives colors. A color is represented by three stimuli of \( X, Y \) and \( Z \), which are sums of stimuli, received at angular visual sensors with human eye characteristics from the spectral power distribution of the light source, that is, the reflection pattern of light from an object.

Since visible light in the wavelength range from 380nm to 780nm from a light source is either selectively reflected or penetrates through the surface of an object due to the chemical materials comprising the surface of the object and thus changes the spectral power distribution from the original wavelength of the light, we humans feel the colors as a light, which is different from the original light source, arrives at the human retina and generates stimuli, which are then transmitted to our cerebrum via the visual nerve system.

As shown in Fig.3., if the distribution curve is higher on the longer wavelength side of the color spectrum, the light is of a red color, whereas if the curve is higher on the shorter wavelength side, it is a blue color light.

In our study we used Japan Minolta's Spectrophotometer (CM-2500D) of Fig.4. for color analysis and Spectraworks software as the color analyzer program.

The main screen of the color analyzer software is as shown in Fig.5. For a measured test sample, its spectrum value, hue difference value, and parameters of \( L^*a^*b^* \) and \( L^*C^*h \) coordinate systems are quantitatively displayed.

3. Experiment Plan

3.1 Concrete mixing and test sample production

The cement we used for our experiment was regular Type I Portland cement produced in Korea having the chemical properties of Table 1. For large aggregates crushed granite with maximum dimension of 20–25mm was used. For fine aggregates washed sand with fineness modulus of 2.8 and absorption rate of 0.6 was used. For admixture fly ash was used to yield substitution rate of 10% for water-cement ratios of 0.45 and 0.55. Here, the substitution ratio is the ratio of the admixture used in place of cement.

Concrete mixing of test samples was planned with the water-cement ratios of 0.45 and 0.55. The target slump value of all mixes was set as 15cm and the target
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air volume 5.0% (tolerance 1.5%). These parameters are summarized in Table 2. and Table 3.

Production of test samples followed the 'Method of producing test samples for concrete compression strength testing' (KS F 2403, 1990). The test sample dimensions are commonly $\Phi 100 \times 200$. For internal temperature measurements, Type K thermocouples were inserted into sample middle areas at points 3cm, 6cm, 9cm, 12cm and 15cm from the surface. Based on KS F 2403 samples were capped after 24 hours, detached from the mold after another 24 hours and then cured in water for 28 hours in a constant temperature water tub of 20°C.

3.2 Test method

In our experiment we produced concrete test samples of $\Phi 100 \times 200$ with variable water-cement, heated them to various target temperatures in an electric oven, measured their color hue values, weight losses and compressive strengths, and analyzed the measurements in comparison to normal samples to identify the relationship between the color change, weight loss and the residual compressive strength in terms of the exposure temperature level.

For heating the test samples we manufactured an electric oven of 87cm × 80cm × 150cm and installed a control box to control the heating temperature and the heating rate. The target internal temperature inside the oven was set as 100°C~800°C and heating was done at the rate of 13.33°C/min. Once a target temperature is reached, the level was held constant for one hour to ensure that the entire sample body reaches the target water tub uniformly.

4. Experiment Result and Analysis

4.1 cracking and discoloration

The crack and discoloration patterns, noted on test samples after heating them in the electric oven at temperatures of 100°C~800°C and letting them cool, were as shown in photographs of Table 4. At temperatures of 100°C~200°C no cracks or discoloration were found from visual inspection as compared to unheated samples of normal temperatures.

However, discoloration started from 300°C, where the cement paste hue changed to red and the discoloration progressed more notably as the temperature increased to 600°C. At 600°C the aggregate color was changed to red color. At temperatures of 700°C or above, the overall color of sample was changed to whitish color.

As for crack occurrence, no cracks were observed visually at heating temperatures of 100°C~500°C. However, cracks started from 600°C and progressed more notably as temperature increased. For water-cement ratio of 0.45, the crack width was 0.2mm~1.0mm, and for the ratio of 0.55, the width was 0.2mm~0.8mm, showing more severe cracks in samples with water-cement ratio of 0.45.

Concrete exposed to high temperatures experiences moisture evaporation, whereupon shrinkage and thermal expansion occur simultaneously. Consequently,
the difference in thermal expansion characteristics between the cement paste and the aggregates causes cracks in the structure. Furthermore, it is known that high level pore pressure caused by moisture evaporation results in significant cracks in dense structures such as high strength concrete. (Omer Arioz, 2007; C. H. Oh et al., 1987)

4.2 Hue value change

It is known that discoloration of concrete exposed to high temperatures is more closely related to hue value from among the three elements of color coordinate system, lightness, saturation and hue. (N. R. Short, 2001) In our study we analyze the experiment results based on the hue value and identify its relationship with material properties.

The change in hue value in test samples in terms of exposure temperatures is graphed in Fig. 6. and Fig. 7. Hue values were measured at five spots on the top surface of two samples each with different water-cement ratio at each temperature level. Values with greater than 5% variation from the average were eliminated.

From the figures we note that hue values of samples show overall similar changes for both water-cement ratios of 0.45 and 0.55. There is no noticeable difference with unheated samples below 200°C. In the temperature range of 300°C–600°C we note progressive hue value changes. At temperatures of 700°C or above, measurement variations become larger and do not show any consistent pattern.

Hue value changes expressed in the L*C*h coordinate system for different water-cement ratios are as shown in Fig. 8. and Fig. 9.

In the figures, for water-cement ratio of 0.45, there is no difference in hue values between unheated sample (Point A) and heated samples at temperature levels of 100°C–200°C (Points B & C). From 300°C and above, the hue value changes to 80.7 degree (Point D), rapidly approaching the red color axis (Red, 0°).

As temperature rises to 600°C, the hue value change is accelerated (Points E, F and G). We note that as the hue values approach the red color axis, the surface color rapidly changes to red. In case of water-cement ratio 0.55 the pattern is similar to the case of 0.45 so that, in the temperature range of 300°C–600°C, the hue values change to 80.9–75.1 degree (Points D, E, F & G), approaching the red color axis (Red, 0°).

The reason for concrete hue changing to pink to red color when exposed to the temperature range of 300°C–600°C is because of the iron component in the small aggregates or large aggregates. In this temperature range hydrate decomposition and iron oxidation occur. (Matteo Colombo et al., 2007)

Relative hue values, expressed as hue ratio of heated sample against unheated sample by water-cement ratio and by exposure temperature, are shown in Fig.10.
occurs rapidly from 88% to 77% in case of water-cement ratio 0.45, and from 91% to 83% for water-cement ratio of 0.55.

Furthermore, the sample hue changes to whitish color at 700°C and above, showing increasing relative hue ratio.

4.3 Change in residual compressive strength

The compressive strengths of unheated concrete samples show an average of 59MPa for water-cement ratio of 0.45 and 40MPa for the ratio of 0.55. Residual compressive strengths by exposure temperature are as shown in Fig.11., where residual compressive strength refers to the ratio of compressive strength of heated samples against unheated samples.

In the figure we observe that, for both cement-water ratios, as the temperature rises, residual compressive strength tends to decrease. In the temperature range of 100°C~300°C residual compressive strength of 88%~80% is shown, whereas at 300°C and above residual compressive strength rapidly decreases to less than 10% at 800°C.

Current Eurocode 2 (2004) presents residual compressive strength ratio of normal strength concrete by aggregate type and the same for high strength concrete categorized into three strength levels. The strength reduction tends to increase as we move from normal concrete to high strength concrete.

When comparing the experiment results of our study with the residual compressive strength ratio pertaining to Class 3 in Eurocode, we note that our experiment values fall in the range of residual compressive strength ratio between the normal strength and the high strength concrete.

4.4 Relationship between weight loss rate and compressive strength

The change of weight loss rate due to exposed temperature in concrete samples is as in Fig.12. In the figure we note that the weight loss rate increases as temperature increases. In the temperature range of 100°C~800°C, the weight loss rate changes from about 0.5% to 7%. In particular, at 100°C when moisture evaporation begins to occur, rapid weight loss occurs. At 300°C the weight loss shows moderate reduction and increases again at 700°C and above. As for the water-cement ratio difference, there is no effect in the temperature range of 100°C~600°C. However, for 600°C and higher the larger water-cement ratio of 0.55, which contains more water, shows at most 12% greater weight loss rate.

4.4 Relationship between weight loss rate and compressive strength

Weight loss in heated concrete is related to moisture evaporation from temperature change. In general, at temperatures of 20°C~105°C gel water within concrete pores is completely discharged, while in the temperature range of 105°C~850°C, chemically bound water within cement hydrates is discharged into pores and evaporate, thus affecting concrete weight loss. (Y. Ichikawa et al., 2004)

Reduction of compressive strength in terms of weight loss change is expressed in Fig.13. In the figure we note that the reduction of compressive strength is less than 20% where weight loss rate is less than 3.5% and temperature of 300°C or less. However, when weight loss rate is 3.5% or greater, the compressive strength reduction occurs rapidly so that it reaches 90% or higher at weight loss rate of 6% or higher. Thus, the weight loss rate of heat-exposed concrete has a consistent relationship with the reduction of compressive strength and we can predict the compressive strength reduction by measuring the weight loss rate.

4.5 Relationship between relative hue change and material property change

The change in relative hue in terms of weight loss rate is expressed in Fig.14. As shown in the figure, the relative hue change is insignificant where weight loss rate is 2.5% or less.
However, at temperature of 300°C or higher where the weight loss rate exceeds 3%, relative hue change becomes pronounced, then subsides at about 5%. Therefore, in the temperature range from 100°C to 600°C there is a consistent relationship between weight loss rate and the relative hue change. Thus, we can predict the weight loss rate of concrete by measuring hue changes in samples.

Residual compressive strength ratio with respect to relative hue change in terms of exposed temperature is expressed in Fig.15. and Fig.16.

For both water-cement ratios, in the temperature range from 100°C to 600°C the higher the temperature, the greater the relative hue change and the less the resulting residual compressive strength in a consistent manner. Relative hue change reduces rapidly from 300°C to 600°C, whereas residual compressive strength is reduced drastically at temperature exceeding 300°C.

Thus, in the temperature range from 300°C to 600°C, the relative hue value change and the residual compressive strength change are consistent so that we can assess the exposed temperature and the level of compressive strength reduction by observing the hue change in concrete structures exposed to high temperatures such as fires.

5. Conclusions

For the purpose of clarifying the relationship between hue change and material property change in terms of concrete exposure temperatures, we conducted visual observations, hue analysis, and measured weight loss rate and residual compressive strength of test samples heated to target temperatures; compared the measurements against unheated samples and obtained the following conclusions.

1) Based on our visual observation of test samples exposed to high temperatures, color change to red begins at temperature above 300°C to 600°C. The color changes to whitish color at 700°C and higher. Cracks in test samples occur from 600°C and the crack width widens from 800°C.

2) Hue analysis shows that as temperature increases the hue change is more pronounced so that in the range of 300°C~600°C the color change to red is very significant.

3) Weight of test samples is reduced rapidly from 100°C due to moisture evaporation within the concrete, followed by a moderate reduction, then the weight loss rapidly increases at 700°C and higher.

4) Residual compressive strength tends to decrease as temperature increases. Residual compressive strength decreases rapidly at 400°C to 60% and falls below 10% at 800°C.

5) Although water-cement ratio does not impact the color change or compressive strength reduction as temperature increases, the weight loss rate is larger for greater water-cement ratio.

6) Weight loss and compressive strength loss both increase as temperature increases. Therefore we can assess residual compressive strength by measuring the weight loss rate.
7) Color change and residual compressive strength both show consistent reduction as temperature changes in the range of 100°C–600°C so that, we can predict reduction of exposed temperature and compressive strength reduction by measuring hue change of concrete structures exposed to high temperatures.

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