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FORENSIC EVALUATION OF TEMPERATURE HISTORY FOR FIRE-DAMAGED CONCRETE USING AN ORDINARY DIGITAL CAMERA: CASE STUDY OF THE BURNED PALMA HALL PAVILION II, UP DILIMAN

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ABSTRACT

Though generally-regarded for its resistance to fire, concrete's physico-chemical characteristics are also affected when subjected to elevated temperatures. This may pose issues on the integrity of a concrete structure. Changes in the concrete properties are manifested in color changes brought about by chemical reactions that take place in elevated temperatures. The aim of this study is to develop a method for color image analysis using an ordinarydigital camera, to enable an easy, quick-to-execute and inexpensive method of evaluating the integrity of a concrete structure exposed to fire without compromising the quality of analysis. The method was tested on samples taken from the burned Palma Hall Pavilion II, UP Diliman. Images were taken and processed for their relative hue values and referenced against existing RHV-temperature curves. It was found that the highly damaged columns sustained up to approximately 550°C and that slightly damaged columns sustained up to possibly 337°C.

Key words: *fire damage, concrete, thermal properties, forensic evaluation*

1. INTRODUCTION

One of the major reasons behind concrete's popularity as a building material is its inherent resistance to fire. It is non-combustible, and has a slow rate of heat transfer making it an effective barrier against fire. (The Concrete Centre, 2004)

Although concrete is known to have a high resistance to elevated temperatures, longperiods of exposure to it induces physico-chemical changes that lead to mechanical

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strength decay. (Piasta (1984), Alonso (2004), and Fernandez-Municio (2008), cited by Alonso (2009), and Arioz (2007))

According to Larbi & Nijland (2001), Hertz (2005), Georgali & Tsakiridis (2005) and Khoury et al. (2007), the following physico-chemical changes happen to concrete at elevated temperatures. Between 70-80°C, ettringite in the concrete dissociates leading to disappearance of small spines developed in air bubbles during hydration. Starting 100° C, physically-bound water in aggregates and cement paste evaporates. Chemically bound water dissociates from calcium silicate hydrate (CSH) starting 110°C. This results to an increase in capillary porosity and micro-cracking in the concrete matrix. Gypsum dissociates between 120-163°C causing its depletion in the cement paste. At 300°C, thermal expansion of the aggregates would have significant effect leading to increased internal stresses, resulting to significant increase in micro cracks. This leads to around 30-40% reduction in the concrete strength. The dissociation of calcium hydroxide [$Ca(OH)_2$] at 530°C results to shrinkage. At 600°C, CSH gel further dissociates. At this temperature, the concrete would have lost up to 80% of its strength. More minerals in the aggregate and cement phases, such as feldspar, become amorphous at 1150°C. Concrete components start to melt at 1200°C and at 1400°C, the concrete melts completely.

This strength decay can eventually lead to detriment in the overall safety of the structure (Alonso, 2009). Because of this, fire-damaged concrete structures must be evaluated and assessed. The goal of the assessment process is to be able to propose appropriate repair measures or to recommend an appropriate action for the structure (e.g. demolition, retrofitting), whichever is more suitable for the situation at hand. This can be achieved by a combination of visual inspection and hammer soundings, non-destructive testing, and sampling of materials and subsequent laboratory testing (Ingham, 2009b).

These methods include inspection of the average response of the concrete cover, point-by-point response of small samples, and special interpretation techniques. Colombo and Felicetti (2007) pointed out that majority of these methods are usually not practical for in situ applications as some methods are either fast but sketchy (e.g. Schimdt rebound hammer) or accurate but time consuming (e.g. point-by-point response of small samples). Other established methods include thermoluminscence (Jingxian et.al., 1997) and petrographic (Annerel & Taerwe, 2009) analyses.

Colorimetry, or color image analysis, is among the non-destructive techniques used in assessing fire-exposed concrete. It is based on the hues given off by the different elements, usually heavy metals, and their compounds comprising the tested material. This principle is also used in a wide variety of applications such as spectrophotometric determination of heavy metal concentrations in water, remote sensing and atmospheric pollution monitoring .

The color of concrete is expected to change from normal to pink or red at 290-590°C, whitish grey at 590-950°C, and buff at 950-1000°C (Colombo, 2007). These color changes can be attributed to the chemical reactions taking place in the concrete upon exposure to elevated temperatures. Ettringite in the cement matrix oxidizes at around 300°C causing a reddish hue. At approximately 600°C, the calcium silicate hydrate (CSH) matrix and the portlandite dissociates and becomes dehydrated leading to a whitish gray appearance of the concrete. Further dehydration at 950°C causes the color to turn yellowish or buff. A summary of these color changes along with its corresponding temperature and other physical effects is shown in Table 1.

Table 1. Physical and Color Change Effects of Elevated Temperatures on Concrete (Yuzer, et al., (2004) cited by Gosain, et al., (2008))

Temperature	Color Change	Changes in Physical Appearance and Benchmark Temperatures	Concrete Condition
0 °C to 290 °C	None	Unaffected	Unaffected
290 °C to 590 °C	Pink to Red	Surface crazing: 300 °C; Deep cracking: 550 °C; Popouts over chert or quartz aggregate: 575 °C	Sound but strength significantly reduced
590 °C to 950 °C	Whitish Grey	Spalling, exposing not more than 25% of reinforcing bar surface: 800 °C; Powdered, light colored, dehydrated paste: 575 °C	Weak and Friable
950+ °C	Buff	Extensive Spalling	Weak and Friable

The assessment of fire-exposed structural concrete using color image analysis (colorimetry) can be done in a number of ways using different techniques, methods of analysis, and equipment. Color image analysis can be done by visual inspection or on a microscopic level using a scanning electron microscope (SEM) or a polarizing and fluorescent microscope (PFM) (Annerel and Taerwe, 2009). In another study by the same authors (2011), they presented two additional, faster methods for quantifying color changes in concrete: (1) the use of a spectrophotometer, and (2) using a calibrated flatbed scanner. The results of the latter study indicated that the spectrophotometer and the flatbed scanner proved to be an effective tool in quantifying color changes in heated concrete; however, these methods require special equipment and can be quite costly.

This research addresses that concern through the use of an ordinary digital camera and correspondingly analyzing the images using the relationship between the relative hue value and the temperature.

The objectives of this research are the following:

1. Develop a practical and efficient color image analysis technique using an ordinary digital camera.
2. Perform the developed color image analysis technique in an actual fire-exposed concrete column.
3. Estimate the maximum temperature experienced by the concrete based on the color image analysis.

The use of color image analysis on fire-exposed concrete structures may provide a rapid and accurate assessment of the structure's remaining bearing capacity. The question of whether to demolish or to repair fire-exposed building can be addressed practically and efficiently by this method (e.g. Annerel & Taerwe, 2011). This analysis can also be done using a number of alternative methodologies. Subjective visual assessment can be done (e.g. Chew, 1993 and Yuzer et al, 2004); however, an expert's judgment is needed in identifying the color properties of the samples. Other methods include the use of a polarizing microscope (Short, 2001) and a spectrophotometer (Lee, Choi, & Hong, 2009). The latter color image analysis techniques provide accurate results but require the use of sophisticated and expensive equipment. Recent studies have developed practical methods for color image analysis including the use of a calibrated flatbed scanner (Hager, 2010 & 2013).

In this research, a color image analysis procedure with the use of an ordinary camera is developed. Images taken are then processed through the use of a computer program which eliminates the inconsistencies and human errors in visual assessment. The method also addresses the issues of cost, ease and speed of execution and the high level of required technical skills necessary to implement the sophisticated assessment methods. At the same time, it offers a more reliable and accurate methodology than the current rapid assessment methods.

2. METHODOLOGY

For the case study, Palma Hall Pavilion II in the University of the Philippines Diliman was analyzed. A fifth-alarm fire hit the building last June 9, 2010 at around 11:00 PM. Palma Hall Pavilion II housed the UP Institute of Chemistry where the organic and biochemistry laboratories are maintained. According to news reports, firefighters had a hard time entering the building due to chemical fumes that triggered flashovers. The firefighters resorted to using chemical foam instead of water to put out the fire. The UP College of Science Secretary back in 2010, Evangeline Amor, noted that it was the first time that a fire hit the building. Based on eyewitness accounts, the building's second floor sustained heavy damage (Jimeno, 2010).

Three types of columns in the building were analyzed: undamaged (UD), slightly damaged (SD) and highly damaged (HD), classified based on visual inspection and on the columns' proximity to the origin of the fire. Concrete cores were taken for the purpose evaluating the extent of damage. Due to the restrictions in the area and in order to preserve the structural soundness of the burned area, only two cores were taken for each category. Photographs of the cross section were taken under controlled conditions. Because of the high variability in the aggregate color, whether locally or internationally, only the cement paste portion, and not the aggregate phase, were analyzed for their relative hue values (RHV).

Hue value is the primary color parameter investigated because the discoloration of fire-damaged concrete is closely related to this parameter (Short, 2001 cited by Lee, et al, 2009). Because of this, L*C*h color space of the Commission Internationale de l' éclairage was used instead of the RGB color space. RHV was used in the analysis to address the possible initial differences concrete color.

RHV versus temperature calibration scales were developed based on the data by Lee, Choi, and Hong (2009) from Korea and Hager (2013) from Poland. For the latter, scales were imaged, read into MATLAB and converted from RGB to L*C*h color space. From these calibration scales, the estimated temperature sustained by the concrete was computed.

3. CALIBRATION SCALE DEVELOPMENT

In a study by Lee, Choi, and Hong (2009) entitled, "Color and Material Property Changes in Concrete exposed to High Temperatures", concrete samples with varying water-to-cement ratio were heated to target temperatures in an electric oven wherein color changes, as well as other physical and mechanical properties were investigated. Japan Minolta's Spectrophotometer (CM-2500D) was used to take images. Type I Portland Cement produced in Korea was used in this research. The chemical composition of the cement used is shown in Table 2. Concrete samples were prepared with water-to-cement ratios of 0.45 and 0.55. Details of the concrete mix proportions are shown in Table 3.

Table 2. Composition of Type I Portland Cement (Lee et.al., 2009) [Korea]

Property	**%**
Silicon Dioxide (SiO_2)	22.18
Ferric Trioxide (Fe_2O_3)	3.16
Aluminum Trioxide (Al_2O_3)	5.50
Calcium Oxide (CaO)	62.62
Magnesium Oxide (MgO)	2.33
Potassium Oxide (K_2O)	0.93
Sulfur Trioxide (SO_3)	1.75
Sodium Oxide (Na_2O)	0.07
Loss on Ignition	0.90

Table 3. Concrete Mix Proportions Design (Lee et. al., 2009) [Korea]
(G: Large Aggregate, S: Fine Aggregate, C: Cement, FA: Fly Ash)

w/c	**S/a (%)**	**Binder (kg/m3)**	**Water (kg/m3)**	**Mix Proportions (kg/m3)**			
				G	**S**	**C**	**FA**
0.45	48.5	338	152	939	878	304	34
0.55	48.5	338	186	893	856	304	34

Concrete samples were exposed to temperatures ranging from 100°C to 700°C, in increments of 100°C. The RHV was taken with respect to a sample exposed to a temperature of 20° C. Figures 1 and 2 illustrate the effect of elevated temperature on concrete color, expressed in L*c*h color space, for w/c = 0.45 and w/c = 0.55 respectively. The average to correspond to w/ c=0.5. The calibration scale derived from this study is shown graphically in Figure 3.

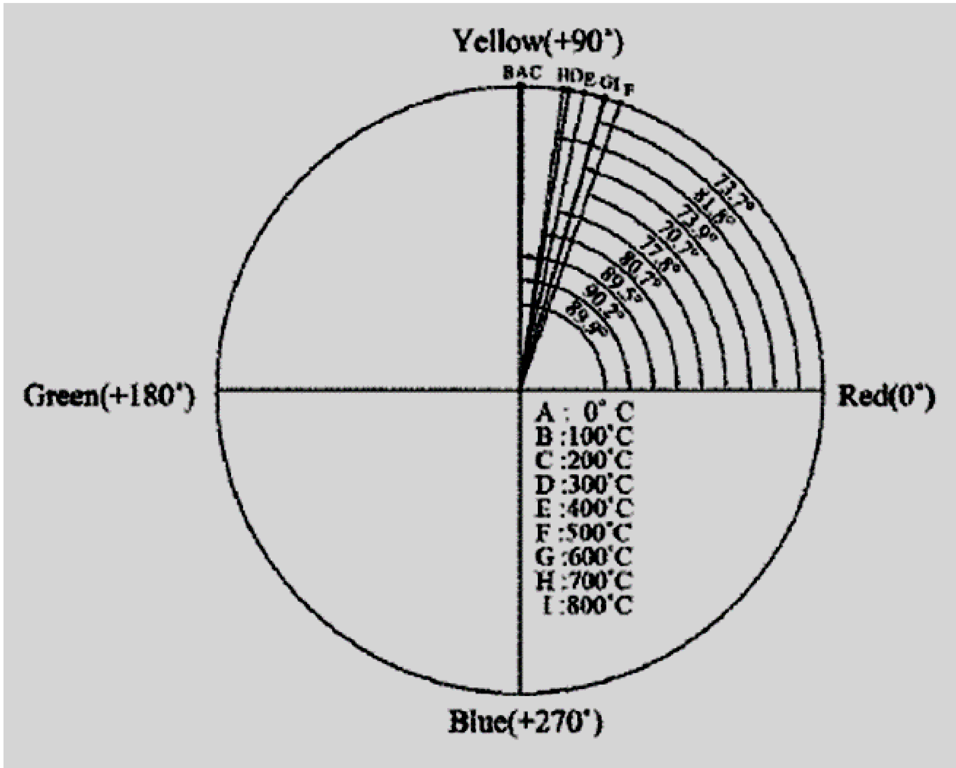


Figure 1. Hue Angle Changes by Temperature expressed in L*C*h (w/c = 0.45) (Lee, Choi, and Hong, 2009) [Korea]

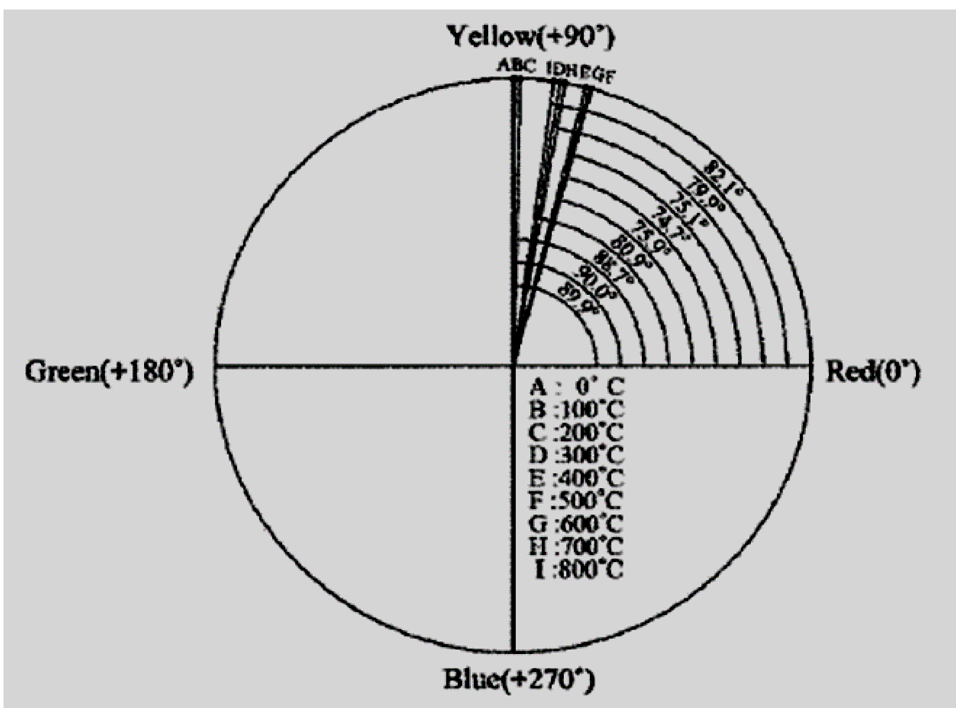


Figure 2. Hue Angle Changes by Temperature expressed in L*C*h (w/c = 0.55) (Lee, Choi, and Hong, 2009) [Korea]

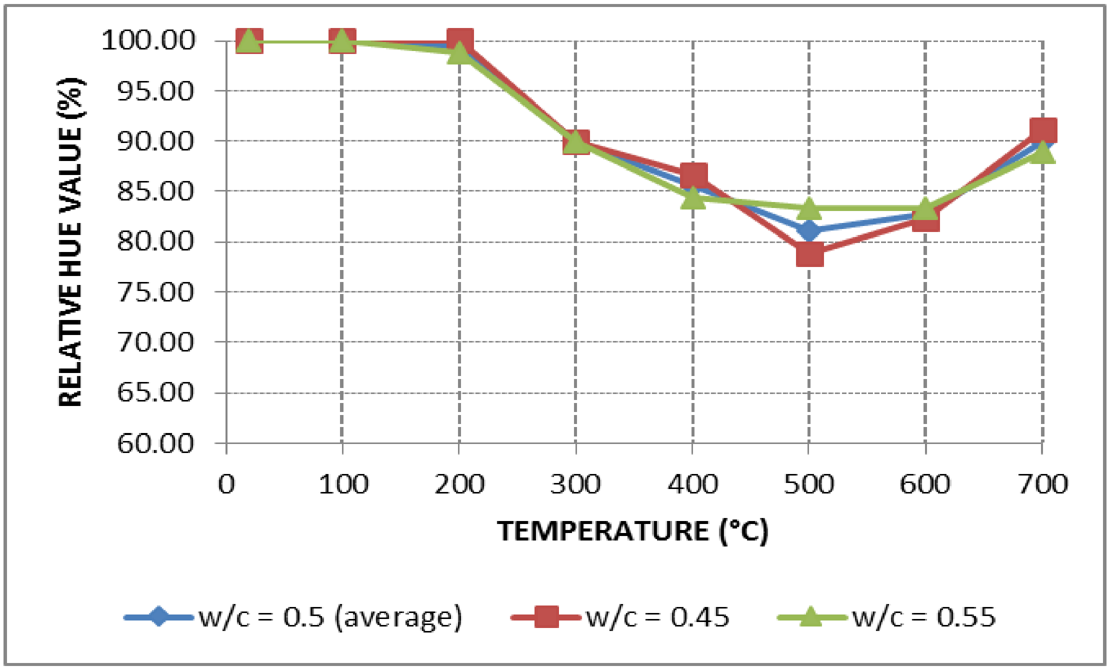


Figure 3. Relative Hue Value (%) vs. Temperature
(Lee et.al., 2009) [Korea Calibration Scale]

A similar study by Hager (2013) entitled, "Colour Change in Heated Concrete", color changes in concrete under the influence of heat were investigated using a general-purpose flatbed scanner (HP Scanjet G2410). Ordinary concrete (OC) and High-Performance concrete (HPC) were subjected to different temperatures. Changes in the color and mechanical properties were investigated.

CEM II/A-V 42.5R cement type produced in Poland, consisting of 80-94% Portland cement clinker, 6-20% fly ash and 0-5% minor components, was used in the research. The concrete mix proportions used in the research are as follows:

Table 4. Concrete Mix Proportions Design (Hager, 2013) (Poland)

Constituent	Unit	OC	HPC
Cement (CEM II/A – V 42.5R	kg/m3	322	478
Water	dm3/m3	193	129
w/c	-	0.6	0.27
Sand (0-2 mm)	kg/m3	623	
Gravel (2-8 mm)	kg/m3	660	
Gravel (8-16 mm)	kg/m3	550	

Concrete samples were heated at temperatures ranging from 100°C to 1000°C, in increments of 100°C. RHV were taken relative to a sample exposed to 20°C. Images of the results for the ordinary concrete in were shared by Hager via electronic mail in .TIF format as follows: 20° C (OC0.tif), 100°C (OC1.tif), 200°C (OC2.tif), 300°C (OC3.tif), 400°C (OC4.tif), 500°C (OC5.tif), 600°C (OC6.tif), 700°C (OC7.tif), 800°C (OC8.tif), 900°C (OC9.tif), and 1000°C (OC10.tif).

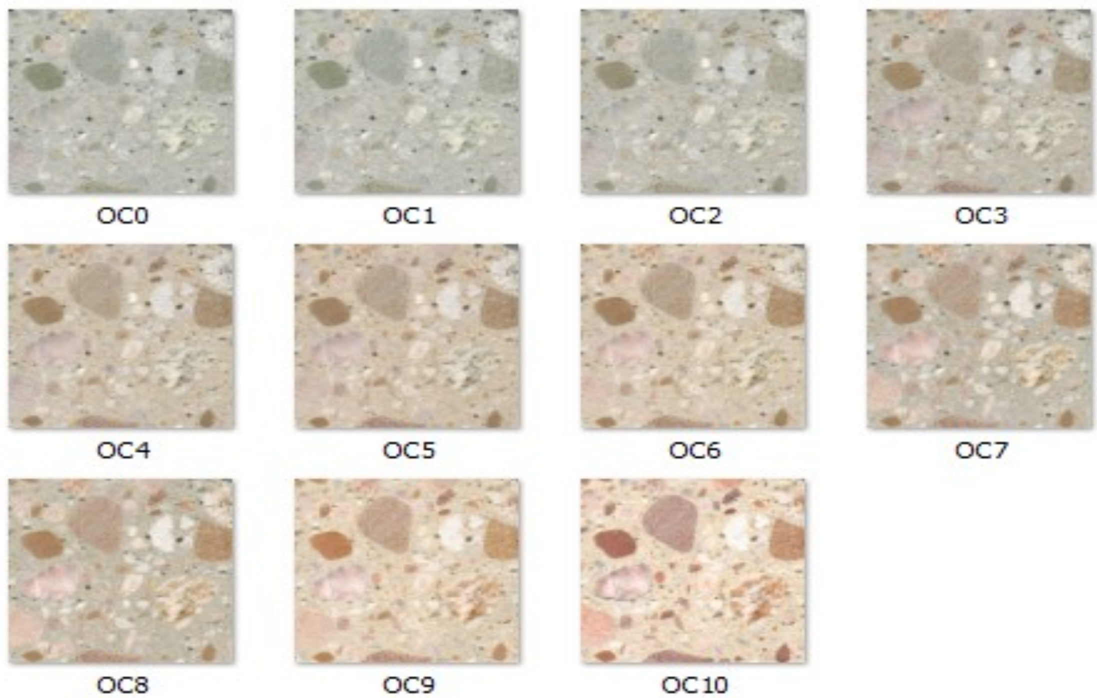


Figure 4. Images of ordinary concrete exposed to various temperatures (Hager, 2013)

The images were read in MATLAB for their hue values. These values were then normalized with that of OC0, which is the concrete sample at 20°C, to get the relative hue values. Results are shown in Table 4.

Table 5. Relative Hue Value versus Temperature for w/c = 0.6 (Hager, 2013)

Temp (°C)	Hue Value (%)	RHV (%)
20	107.70	100.00
100	106.92	99.27
200	99.55	92.43
300	86.71	80.51
400	77.59	72.04
500	72.67	67.47
600	73.84	68.56
700	79.01	73.36

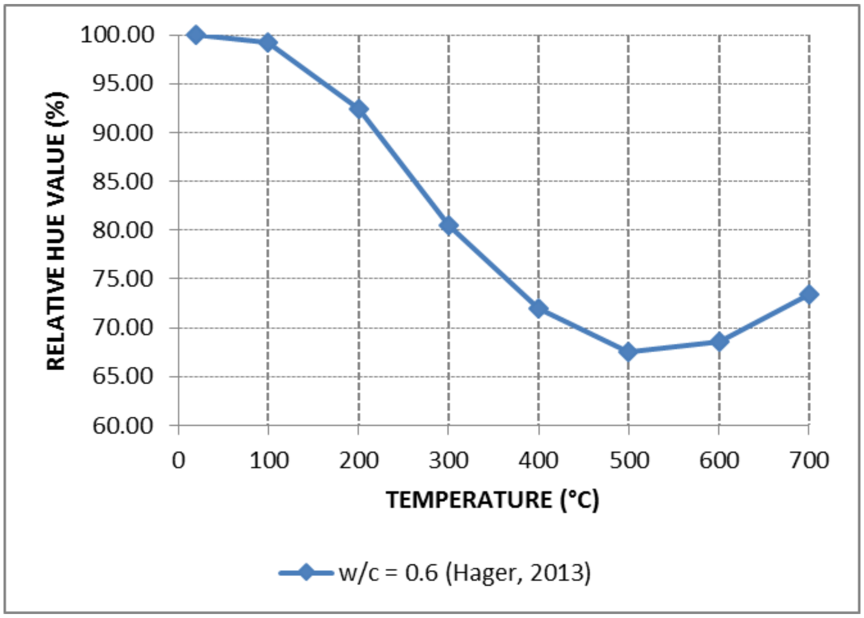


Figure 5. Relative Hue Value (%) versus Temperature Calibration Scale from Hager, 2013 [Poland]

The two calibration curves were superimposed as shown in Figure 6. The curve derived from Hager's work is significantly lower than that from Lee's.

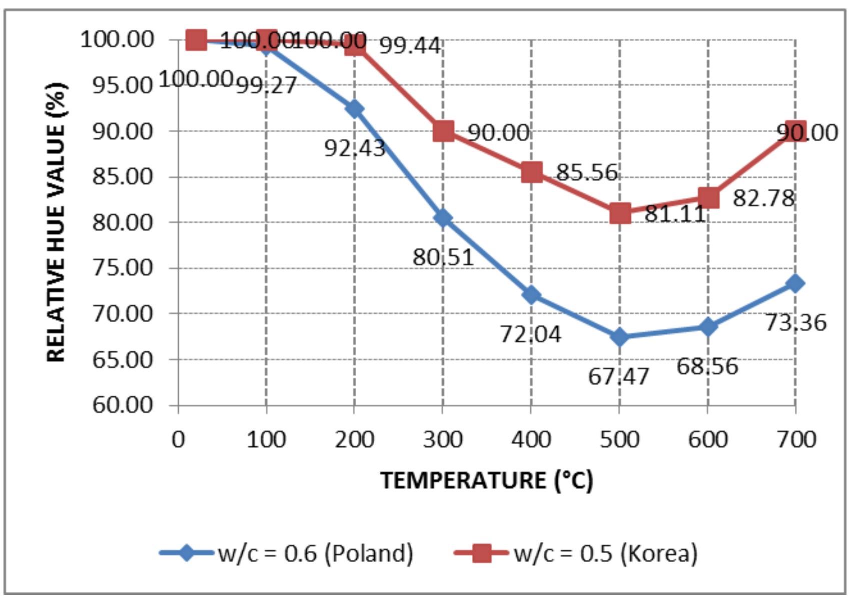


Figure 6. Superimposed calibration curves from Lee's (Korea) and Hager's (Poland) studies

Portland cement type 1, which is the most commonly used cement in general construction, was used in the study of Lee. On the other hand, CEM II/A-V 42.5R, consisting of 80-94%

Portland cement clinker and mixed with fly ash, was used in Hager's study. Fly ash refers to the residues produced during the combustion of coal that rise with the flue gases. This material predominantly consists of silicon dioxide (SiO_2) with some other compounds found in ordinary Portland cement. It is assumed that the fly ash component does not significantly affect the color change in the concrete. Further, relative hue values are taken in lieu of the absolute hue values, to normalize and take into account the difference in the amounts of the compounds that respond to temperature change.

In terms of the concrete composition, the variation in the water-to-cement ratio could have caused differences in the color change in response to the rise in temperature.

Other factors that could have affected the color of the concrete with elevated temperature include the inherent color and presence of reactive metals in both the fine and the coarse aggregates. To minimize the influence of these factors in the results, only the cement phase part of the images were analyzed.

4. COLOR IMAGE ANALYSIS OF PHILIPPINE CONCRETE

Philippine concrete in ordinary construction typically has Portland cement type 1, which is similar to that used in the study by Lee et. al. The water-to-cement ratio, however, varies depending on the required strength of the concrete. For normal strength concrete, it typically ranges from 0.4 to 0.6. As such, the reaction of Philippine concrete to elevated temperatures may also be similar to the response of concrete in Korea and Poland in the two studies. These calibration curves were used to test the methodology in Philippine concrete.

Undamaged (UD), slightly damaged (SD) and heavily damaged (HD) concrete from the building selected. The depths of damage caused by fire were measured reckoned from the concrete cover. Results are shown in Table 2. It can be noted that even in highly damaged columns, the depth of damage does not go beyond 45mm. Considering the minimum concrete cover requirement set by the National Structural Code of the Philippines, fire would have just started to affect the steel reinforcement which is typically at a depth of 40mm or greater.

Table 6. Measured Depth of Damage in cores by Visual Observation

Core Designation	Measured Depth of Damage (mm)
Slightly Damaged 1 (SD1)	20-25
Slightly Damaged 2 (SD2)	25-30
Highly Damaged 1 (HD1)	40-45
Highly Damaged 2 (HD2)	35-40

Sections of the core were then photographed with five samples each, scanned and processed for hue values and referenced against the undamaged columns, for which the temperature experienced was assumed to be 20°C. From this, the RHVs were derived and compared against the calibration curves from Hager's and Lee's studies. The results are shown in Tables 6 through 9.

Table 7. L*C*h, RHV, and Temperature Values for Slightly Damaged Core 1(core SD1)

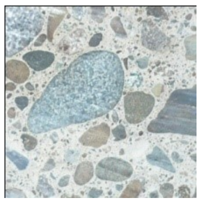
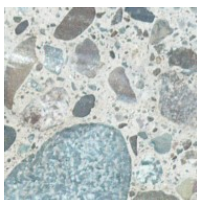
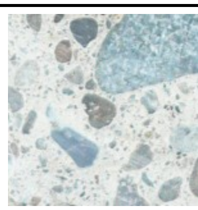
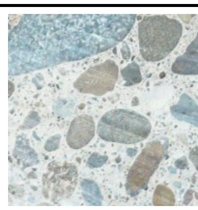
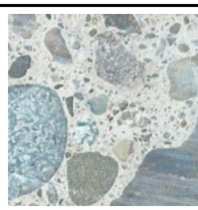
	Image	L*C*h Value	RHV (%)	Temp (°C) (Hager - Poland)	Temp (°C) (Lee - Korea)
Undamaged Cross Section		L: 76.0381 C: 5.2117 H: 175.9932	100%	20°C	20°C
Damaged Cross Section 1		L: 77.7137 C: 5.2775 H: 171.0682	97.20%	130°C	224°C
Damaged Cross Section 2		L: 77.0175 C: 5.2022 H: 163.3285	92.80%	195°C	270°C
Damaged Cross Section 3		L: 83.0407 C: 4.9719 H: 173.9804	98.86%	106°C	206°C
Damaged Cross Section 4		L: 79.0178 C: 5..2233 H: 169.2682	96.18%	145°C	235°C
Damaged Cross Section 5		L: 75.8347 C: 5.1702 H: 173.4359	98.55%	111°C	209°C

Table 8. L*C*h, RHV, and Temperature Values for Slightly Damaged Core 2 (core SD2)

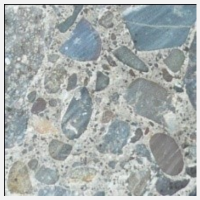
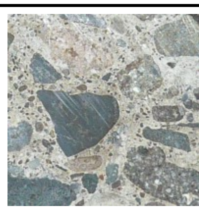
	Image	L*C*h Value	RHV (%)	Temp (°C) (Hager - Poland)	Temp (°C) (Lee - Korea)
Undamaged Cross Section		L: 69.8884 C: 5.2664 H: 176.0620	100%	20°C	20°C
Damaged Cross Section 1		L: 65.4928 C: 5.3824 H: 153.8558	87.39%	242°C	359°C / 664°C
Damaged Cross Section 2		L: 63.8131 C: 5.4015 H: 145.9631	82.90%	280°C	460°C / 602°C
Damaged Cross Section 3		L: 67.2204 C: 5.2811 H: 148.1897	84.17%	269°C	431°C / 619°C
Damaged Cross Section 4		L: 65.9092 C: 5.4787 H: 155.5508	88.35%	234°C	337°C / 677°C
Damaged Cross Section 5		L: 75.8347 C: 5.1702 H: 173.4359	90.19%	219°C	298°C

Table 9. L*C*h, RHV, and Temperature Values for Highly Damaged Core 1 (core HD1)

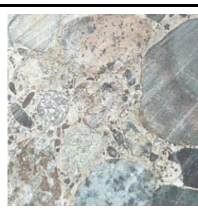
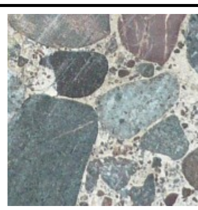
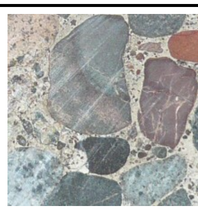
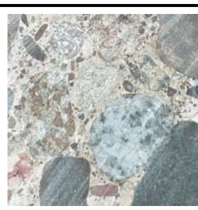
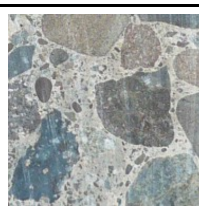
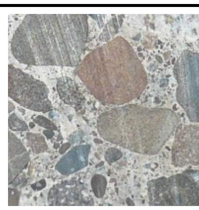
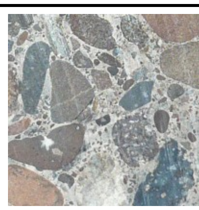
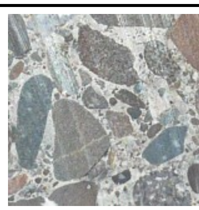
	Image	L*C*h Value	RHV (%)	Temp (°C) (Hager - Poland)	Temp (°C) (Lee - Korea)
Undamaged Cross Section		L: 65.2707 C: 6.4647 H: 189.4472	100%	20°C	20°C
Damaged Cross Section 1		L: 65.3564 C: 5.4946 H: 154.8352	81.73%	290°C	486°C / 537°C
Damaged Cross Section 2		L: 73.2762 C: 5.1259 H: 142.4039	75.17%	363°C	N/A~ 500°C
Damaged Cross Section 3		L: 61.7680 C: 5.4328 H: 170.4315	89.96%	221°C	301°C / 699°C
Damaged Cross Section 4		L: 65.0355 C: 5.8586 H: 152.3427	80.41%	301°C	N/A~ 500°C
Damaged Cross Section 5		L: 71.7104 C: 5.3870 H: 153.6698	81.11%	295°C	500°C

Table 10. L*C*h, RHV, and Temperature Values for Highly Damaged Core 2 (core HD2)

	Image	L*C*h Value	RHV (%)	Temp (°C) (Hager - Poland)	Temp (°C) (Lee - Korea)
Undamaged Cross Section		L: 72.3408 C: 5.4408 H: 185.3984	100%	20°C	20°C
Damaged Cross Section 1		L: 65.9408 C: 4.9752 H: 149.9926	80.90%	297°C	N/A~ 500° C
Damaged Cross Section 2		L: 64.4541 C: 4.9779 H: 158.8540	85.68%	257°C	397°C / 640°C
Damaged Cross Section 3		L: 66.6209 C: 4.5718 H: 137.2392	74.02%	377°C	N/A~ 500° C
Damaged Cross Section 4		L: 65.7906 C: 5.0298 H: 147.6483	79.64%	310°C	N/A~ 500° C
Damaged Cross Section 5		L: 66.3800 C: 4.2247 H: 156.7846	84.57%	266°C	422°C / 625°C

In Tables 9 and 10, the RHV is seen to reach values lower than the minimum value on the Korean calibration scale. In such cases, it was assumed that the sustained temperature was 500°C, the lowest point in the calibration scale. It can also be noted that there are instances where two temperature values correspond to the computed RHV; for instance, damaged cross sections 1 and 3 of core HD1 and sections 2 and 5 of core HD2 (Table 10). For these instances, additional analysis need be done to determine the actual temperature sustained by concrete. Other factors that could be taken into consideration include the temperature sustained by adjacent samples, or the proximity from the origin of fire.

For the slightly damaged columns, the two cores yielded average relative hue values of 96.72% and 86.60% respectively. This, when compared against the Korean and Polish generated calibration curves, translates to a maximum sustained temperature in the range of 138°C to 229°C and 249°C to 377°C. For the highly damaged columns, the maximum sustained temperature is in the range of 294°C to 553°C

Table 11. Average Hue Value, RHV, and Estimated Temperature Values for cores SD1, SD2, HD1, and HD2.

Core	Parameter	Damaged
SD1	Average Hue Value	170.2162
	Relative Hue Value	96.72%
	Maximum Temp (Korea calibration curve)	229°C
	Maximum Temp (Poland calibration curve)	138°C
SD2	Average Hue Value	152.4707
	Relative Hue Value	86.60%
	Maximum Temp (Korea calibration curve)	377°C
	Maximum Temp (Poland calibration curve)	249°C
HD1	Average Hue Value	154.7366
	Relative Hue Value	81.68%
	Maximum Temp (Korea calibration curve)	548°C
	Maximum Temp (Poland calibration curve)	294°C
HD2	Average Hue Value	150.1037
	Relative Hue Value	80.96%
	Maximum Temp (Korea calibration curve)	553°C
	Maximum Temp (Poland calibration curve)	302°C

5. CONCLUSION AND RECOMMENDATIONS

Based on the results of the study, color image analysis using an ordinary digital camera can be used to determine the experienced temperature of fire-damaged concrete. This method is grounded on the chemical changes occurring in concrete, particularly in the cement phase, leading to color changes when subjected to elevated temperatures. In this method, no special preparation of concrete is required before photographing and analyzing the images.

The method that was developed, using concrete's relative hue value with respect to its undamaged state, proved to be an effective method in determining temperature values experienced by concrete. Based on the developed calibration scales, the RHV of concrete decreases as temperature increases up to 500°C after which RHV increases again with increasing temperature. This is probably one indicator of Lucioni, Figueroa, and Danesi's (2003) findings cited by Arioz (2007) that changes experienced by concrete at the temperature level of 500°C are considered irreversible.

This method also addressed the disadvantage presented by Annerel and Taerwe (2011) in using a digital camera for color image analysis. In this method, the hue values obtained from the images captured by the digital camera was not used as an absolute reference but rather, served as a reference point or base line for computing relative hue values for other images. Also, the issue of lighting being less controlled is addressed by simulating a dark room set-up using an ordinary box and using the built-in flash of the camera as the illuminant.

The maximum temperature obtained in the slightly damaged columns is between 249°C and 377°C, and for the highly damaged column, between 302°C and 553°C depending on the original water-cement ratio of the concrete used in preparing the concrete. From the result in this case study, we can conclude that the said columns need to be repaired in order to restore the original capacity but are still in sound condition.

It is recommended that RHV-temperature calibration curves be developed for Philippine concrete because there may be characteristic differences in concrete in Korea and Poland from the local concrete mix. This must also be developed for the spectrum of water-cement ratios used in practice in the country. This can similarly be done for mortar and cement pastes.

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