Image analysis on disintegrated concrete at the post-heating stage

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ABSTRACT

The relation between crack growth and reduction in the compressive strength after high temperature exposure and after air re-curing was investigated in this study. Concrete specimens were heated to 1000 ºC and they were subjected to air re-curing for 28 days. During re-curing period, their heated surfaces were monitored by using a digital single-lens reflex camera and the images were analyzed by using image analysis software. After cooling, the maximum reduction in the compressive strength of concrete was 49.5% and that of air re-cured concrete was 66.8%. Image analyses showed high correlations between crack growth and reduction in the compressive strength. This non-destructive method has the potential to represent the extent of damage in concrete after high temperature exposure.

Keywords: high temperature; fiber reinforced concrete; deterioration; crack development; black pixel analysis.

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Análisis de imagen sobre hormigón desintegrado en la etapa de post-calentamiento

RESUMEN

En este estudio se investigó la relación entre el crecimiento de grietas y la reducción de la resistencia a la compresión después de la exposición a altas temperaturas y después del curado con aire. Las muestras de hormigón se calentaron a 1000 ℃ y se sometieron a curado por aire durante 28 días. Durante el período de curado, sus superficies calentadas fueron monitoreadas usando una cámara réflex digital de lente única y las imágenes fueron analizadas usando un software de análisis de imágenes. Después del enfriamiento, la reducción máxima en la resistencia a la compresión del concreto fue del 49.5% y la del concreto curado al aire fue del 66.8%. Los análisis de imagen mostraron altas correlaciones entre el crecimiento de grietas y la reducción de la resistencia a la compresión. Este método no destructivo tiene el potencial de representar el alcance del daño en el concreto después de la exposición a altas temperaturas.

Palabras clave: alta temperatura; hormigón reforzado con fibra; deterioro; desarrollo de grietas; Análisis de píxeles negros.

Análise de imagem em concreto desintegrado na fase de pós-aquecimento

RESUMO

A relação entre o crescimento de fissuras e a redução da resistência à compressão após exposição a altas temperaturas seguida de resfriamento lento e ao ar foi investigada neste estudo. As amostras de concreto foram aquecidas a 1000 ℃ e, após submetidas ao resfriamento lento foram, na sequência sazonadas ao ar por 28 dias. Durante o período de resfriamento, sua superfície foi monitorada usando uma câmera reflex digital de lente única e as imagens foram analisadas usando o software de análise de imagens. Logo após o resfriamento, a redução máxima na resistência à compressão do concreto foi de 49,5% e a do concreto sazonado ao ar, após 28 dias, foi de 66,8%. As análises de imagem mostraram altas correlações entre o crescimento da fissura e a redução da resistência à compressão. Este método não destrutivo tem o potencial de representar a extensão dos danos no concreto após a exposição a altas temperaturas.

Palavras-chave: temperatura alta; concreto reforçado com fibra; deterioração; desenvolvimento de fissuras; análise de pixel preto.

1. INTRODUCTION

Thermal gradients, evaporation of free water and chemical changes in concrete are the main reasons of deteriorations such as crazing, surface delamination, cracking and spalling (Poon et al. 2001; Akca and Özyurt, 2013) Moreover, deterioration in concrete may continue in the subsequent days of cooling due to continuing changes occurred in microstructure of concrete. For example, rehydration of CaO results in $Ca(OH)_2$ with a 44% volume expansion and this reaction may cause cracking of concrete especially at the heated surface level (Lin et al. 1996; Alonso and Fernandez, 2004; Mendes et al. 2011).

The changes on the heated surfaces of concrete can be used to evaluate the residual properties of concrete after heat exposure. For example, color changes on heated or fire exposed concrete surfaces give information about maximum temperature experienced and amount of deterioration of concrete (Yüzer et al. 2004; Ingham, 2009). Pink to red coloration occurs due to oxidation of iron compounds in sand particles after 300 ℃ and whitish color concrete surface means that temperature

Akca, A. H., Özyurt, N.

of concrete exceeded 700 ºC at which decarbonation of carbonates takes place. Thus, reduction in strength can be predicted roughly without applying destructive tests on concrete in some cases. Similarly, cracks on the heated surfaces can be evaluated to predict residual concrete strength after cooling. Therefore, concrete specimens were subjected to air re-curing process after heating up to 1000°C. In this project, one face heating condition was applied to the specimens since it can be considered more realistic and applicable. Then, heated surfaces of concrete specimens were monitored by using a DSLR camera after cooling and the images were evaluated to understand the relation between crack width and crack growth rate on the heated surfaces and the reduction in compressive strength after heating.

2. EXPERIMENTAL STUDY

2.1 Materials and specimens
CEM I type Portland cement (PC) was used in concrete groups and total amount of cement in 1 m3 of concrete was 450 kg and all concrete groups had a water to cement ratio of 0.45. Table 1 shows mix proportions of concrete groups. As chemical admixtures, oil alcohol and ammonium salt-based air entraining admixture (AEA) and modified polycarboxylate based superplasticizer were used in concrete mixes. AEA content was the same and 0.3 kg (0.7 % of total weight of cement.) in all concrete groups. Super plasticizer amount was varied in order to obtain slump levels in S4 limits given in EN 206-1. Steel fibers were used as high melting point fibers and PP fibers were used as low melting point fibers to reinforce concrete groups. In PP fiber reinforced groups PP fibers were used 0.2 % of volume of concrete and in steel fiber reinforced groups steel fibers were used 0.5 % of volume of concrete. PP fibers and steel fibers were added at contents of 0.1 % and 0.25 % per volume in hybrid fiber reinforced concrete groups, respectively. River sand and siliceous gravel were used in all concrete groups as aggregates. Depending on fiber types and also presence of air entraining agent, 8 different concrete groups were designed as can be seen in Table 1.

11 cubic specimens with dimensions of 15x15x15 cm were produced for each concrete group. One day after production, specimens were demolded and placed in curing water for 27 days. Then they were conditioned in laboratory environment for additional 2 months before tests (Poon et al. 2001; Chang et al. 2006). Three cubic specimens were used to determine initial properties of concrete before heating. Remaining 8 cubic specimens were heated to 1000 °C. Two of them were used to monitor temperatures in concrete cubes during heating, 3 of them were tested to determine properties after cooling and remaining 3 cubic specimens were subjected to air re-curing. Therefore, in tables and graphs 0, X, and Z represent tests before heating, after cooling and after air re-curing, respectively.

Table 1. Mix proportions.

Series	W/C	Cement	Water	Crushed Stone	Crushed Sand	Sand	SP[a]	AEA	PP Fibers	Steel Fibers
					(kg/m^3)				(dm^3/m^3)	
C00	0.45	450	202.5	968	565	225	5.7	-	-	-
C0S	0.45	450	202.5	968	565	225	6.0	-	-	5
C0P	0.45	450	202.5	968	565	225	6.3	-	2	-
C0H	0.45	450	202.5	968	565	225	6.6	-	1	2.5
CA0	0.45	450	202.5	968	565	225	5.3	0.3	-	-
CAS	0.45	450	202.5	968	565	225	5.7	0.3	-	5
CAP	0.45	450	202.5	968	565	225	6.0	0.3	2	-
CAH	0.45	450	202.5	968	565	225	6.6	0.3	1	2.5

[a] SP stands for superplasticizer

Image analysis on disintegrated concrete at the post heating stage

Akca, A. H., Özyurt, N.

2.2 Heating procedure
An electrical furnace which has a 1250 °C maximum operation temperature was used in this study. Two stages of heating were determined and during the first stage, specimens were heated to 1000 °C and during the second stage specimens were kept at this temperature until the end of the total heating time (200 minutes). Figure 1 represents the heating procedure. Electrical furnace was operated at full power and temperature inside the furnace reached 1000 °C in approximately 120 minutes. Since furnace heating capacity was limited, heating rate was 20°C/min at the beginning but the rate decreased to 5 °C/min at the end of the first stage of heating. After the second stage completed, hot concrete specimens were not taken out until the furnace cooled down to 100 °C.
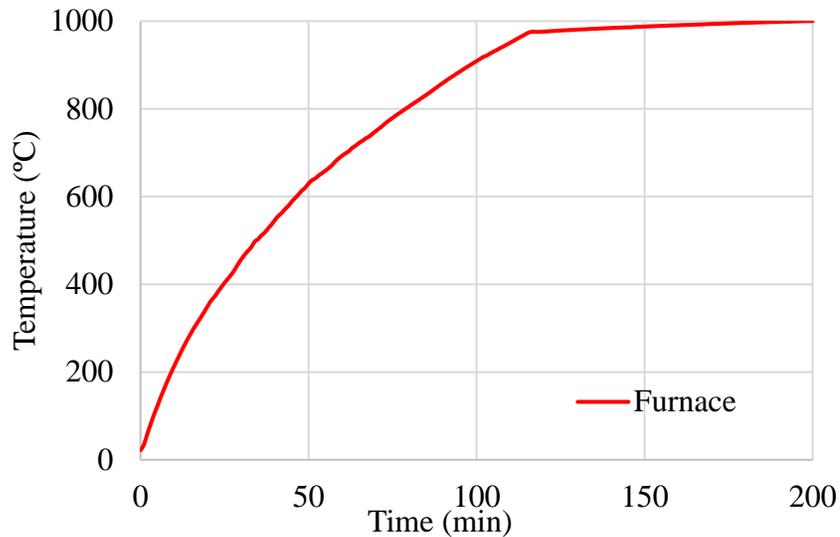

Figure 1. Heating procedure.

Four concrete cubes were placed together in the electrical furnace and in order to simulate one face heating conditions they were insulated with aerated concrete blocks as shown in Figure 2. For temperature monitoring K-Type thermocouples were placed inside a concrete specimen during heating.
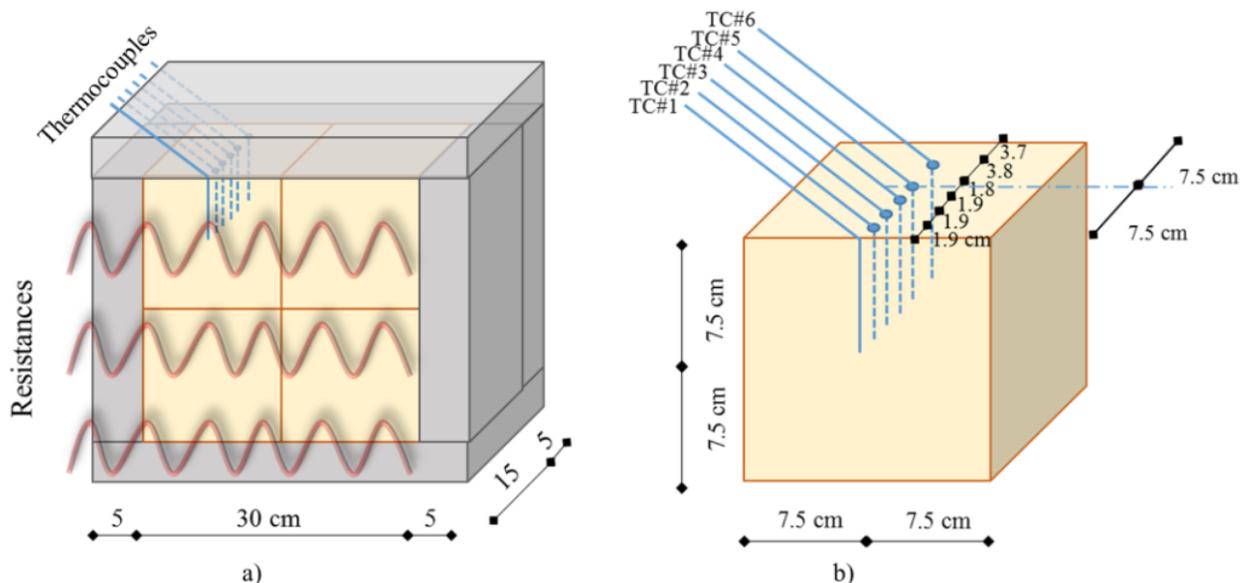

Figure 2. a) Heat insulation of concrete specimens in electrical furnace, b) positions of the K-type thermocouples used to monitor temperature change.

Image analysis on disintegrated concrete at the post heating stage
Akca, A. H., Özyurt, N.

2.3. Re-curing process

After heating and cooling processes 3 specimens were subjected to air re-curing for 28 days. Specimens were kept in laboratory environment which has a relative humidity of 65±10% and temperature of 20±2°C during re-curing period.

2.4. Crack width measurements

Visual changes on heated or fire exposed concrete give information about maximum temperature experienced and amount of deterioration of concrete (Yüzer et al. 2004; Ingham, 2009). Therefore, photograph of the heated face of a survived specimen from each concrete group was taken by using a DSLR camera. These pictures were analyzed via software called Image J as can be seen in Figure 3. During an analysis the whole picture area was divided into 9 subareas and maximum crack widths of each subarea were measured and then mean crack widths were obtained.

2.5. Black pixel analyses

Development of cracks during air re-curing was monitored by taking photos of heated surfaces at every hour for a week. A high resolution DSLR camera and a 100 mm macro lens were used in order to obtain detailed images. As can be seen in Figure 4, these images were converted to 8-bit black and white images by using Image J and black pixel analyses (BPA) were conducted on them. Black pixels represent cracks, air voids, surface delamination and shadow (due to positions of spotlights) on the heated surfaces of specimens. Total areas of black pixels were calculated for all images separately. Then these calculated values were divided to black pixel area of first image in order to obtain normalized area values. Finally, normalized area-time graphs were drawn for all concrete groups except the groups experienced spalling during heating and trend lines were fitted on the graphs as shown in Figure 5. These curves were used to monitor deterioration of concrete for a week. The slopes of fitted trend lines were called BPA rates and they were compared to compressive strength reduction ratios of air re-cured concrete groups.
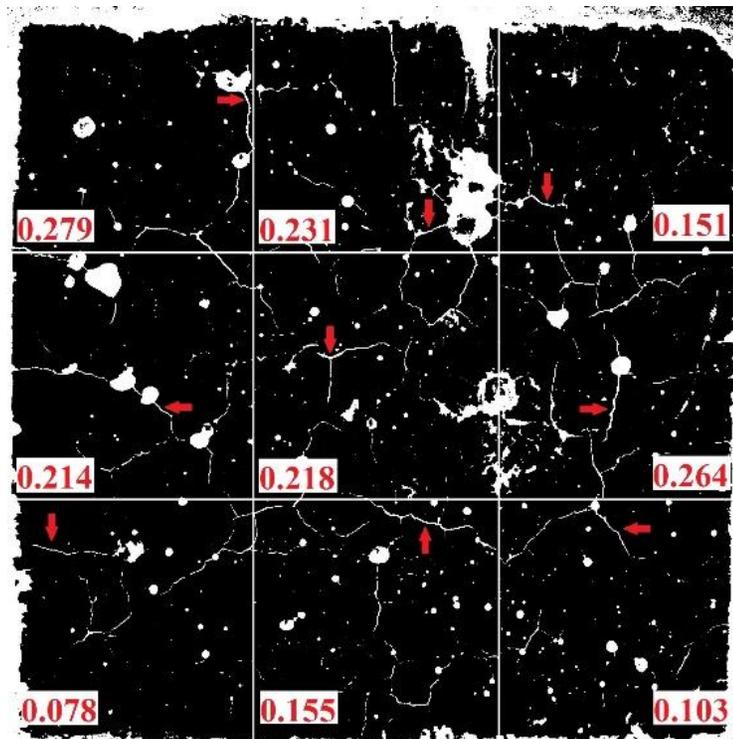

Figure 3. Crack width measurements on a C00X specimen (surface just after cooling).
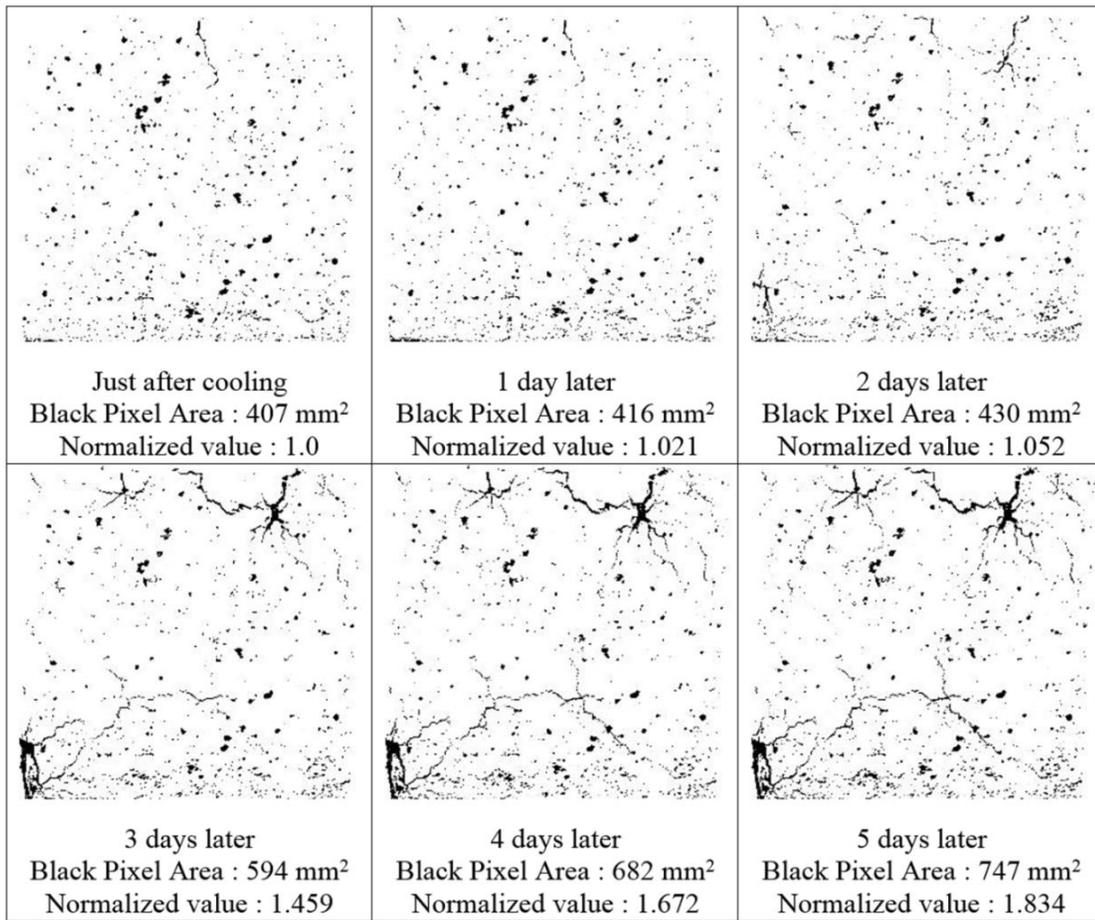
Figure 4. Crack growth monitoring on black and white images captured from C0PZ specimen during air re-curing.
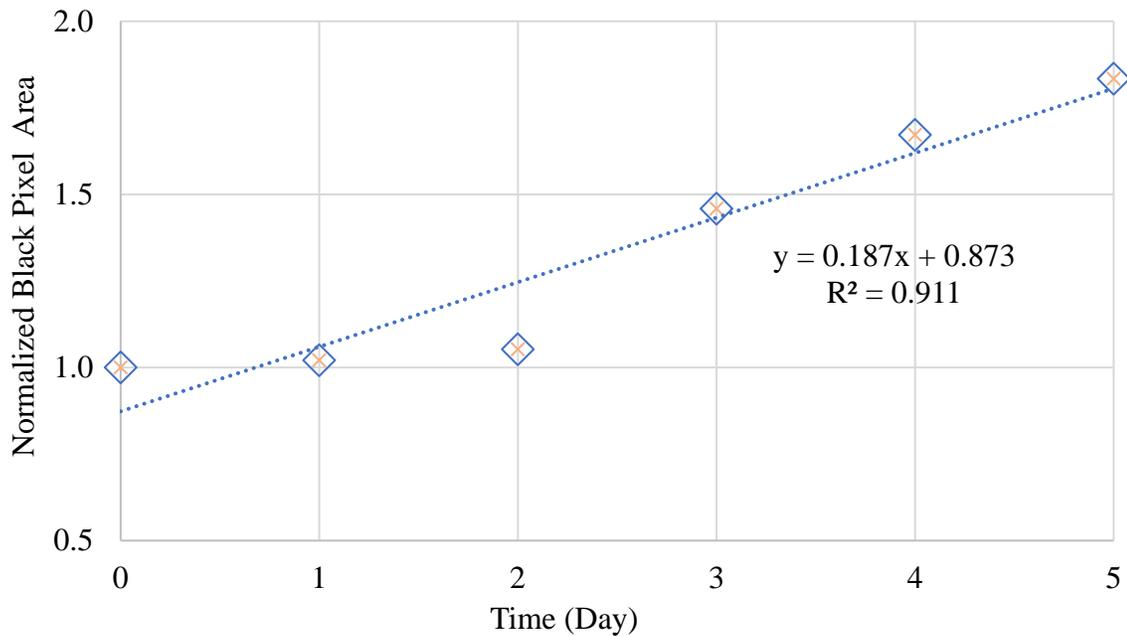

Figure 5. Black pixel analysis value of C0PZ specimen.

3. RESULTS

3.1. Temperature monitoring

Temperatures of heated surface and inner parts of concrete cubes were monitored during heating and temperature monitoring continued further during cooling of the furnace (150 minutes more). In cooling period, although heating of furnace was stopped, temperatures in concrete continued to increase. Thermocouple data was very close when they were compared in terms of cementitious material types. Therefore, all concrete groups were gathered under two categories depending on use of AEA in them. Table 2 shows average maximum temperatures monitored in concrete categories with and without air entrainment during total temperature monitoring (200+150 minutes). Results showed that, temperatures experienced in air entrained concrete were less than that of concrete without air entrainment. When the whole heating and cooling period is considered it can be seen that concrete groups experienced at least 583 °C of temperature which may result in severe strength losses (Poon et al. 2001; Akca and Özyurt, 2013).

Table 2. Average maximum temperature values at predefined depths from the surface during total heating and cooling processes (at the end of 350 minutes).

Thermocouple No	TC#1	TC#2	TC#3	TC#4	TC#5	TC#6
Depth (mm)	0	19	38	57	75	113
Without AEA[1] (°C)	1000	805	691	657	636	608
With AEA[2] (°C)	1000	784	662	627	608	583
Difference (°C)	0	21	29	30	28	25

Without AEA[1] stands for all concrete groups without air entrainment.
With AEA[2] stands for all concrete groups with air entrainment.

3.2. Compression tests

Cubic concrete specimens were loaded before heating, after cooling and after air re-curing (for 28 days) and compressive strength values of concrete groups were determined at every stage. Compressive strength values of all concrete groups decreased after heating and further reduction in residual strength was observed after air re-curing period. Reduction ratios in compressive strength of all concrete groups after cooling and after air re-curing can be seen in Table 3.

Table 3. Reduction in compressive strength with respect to before heating strength.

Reduction in compressive strength	C00	C0S	C0P	C0H	CA0	CAS	CAP	CAH
After cooling (%)	31.9	25.8	36.7	33.9	35.2	36.5	49.5	45.5
After air re-curing (%)	64.1	44.9	66.8	49.2	56.3	49.6	58.7	56.5

3.3. Crack width measurement (after cooling specimens)

Photographs of the heated face of a survived specimen from each concrete group were taken by using a DSLR camera. These pictures were analyzed via software called Image J, then mean crack widths were obtained. Average crack widths of concrete groups after cooling were given in Table 4. According to the results it can be concluded that there were cracks on the heated faces of the specimens around 0.20 mm after heating. Also cracking tendency of PP fiber reinforced concrete can be considered higher and that of steel fiber reinforced concrete can be considered lower with respect to plain concrete groups after cooling. On the other hand, larger cracks were observed on the air entrained concrete groups than concrete groups without air entrainment.

Akca, A. H., Özyurt, N.

Table 4. Average crack widths on the heated faces of concrete groups after cooling.

Crack width	C00X	C0SX	C0PX	C0HX	CA0X	CASX	CAPX	CAHX
Mean (mm)	0.188	0.175	0.196	0.181	0.195	0.182	0.206	0.204
Standard deviation (mm)	0.07	0.05	0.03	0.03	0.03	0.04	0.03	0.04

Calculated average crack widths were compared to reduction in compressive strength of specimens after cooling as can be seen in Figure 6. Results showed that increase in average crack width of specimens caused increase in reduction in compressive strength. This relation can be used to predict the extent of the deterioration in residual mechanical properties of concrete elements without applying destructive tests on them after an event of a fire.
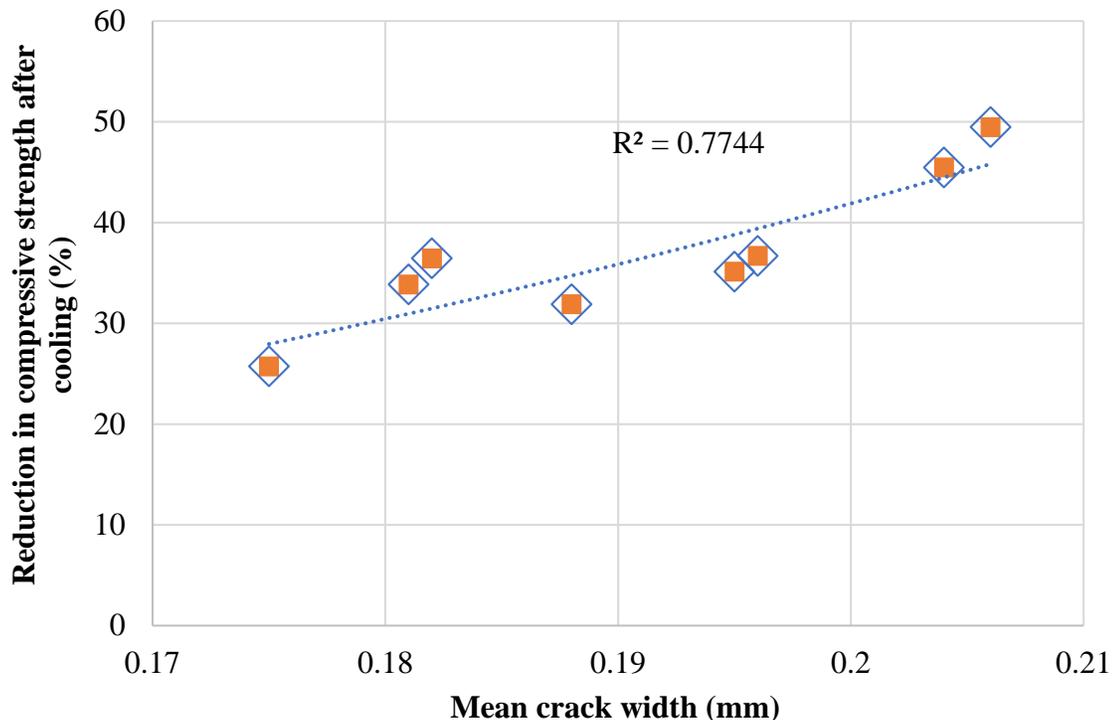

Figure 6. Relation between reduction in compressive strength and mean crack width after cooling.

3.4. Black Pixel Analysis (BPA) (for air re-curing period)
After cooling, sizes and numbers of cracks increased on the heated surfaces of concrete specimens probably due to expansive CaO rehydration. Therefore, surface pictures of specimens were captured during the first week of air re-curing and these pictures were evaluated in image analysis software in order to evaluate the relation between crack development rate and reduction in compressive strength during air re-curing period. Accordingly, BPA rates of air re-cured concrete specimens were calculated (as explained in Section 2.5) to monitor damage development and these values were compared to differences in compressive strength values after air re-curing period as shown in Table 5.

Table 5. Residual compressive strength and BPA values.

Group	X-Group[1] (MPa)	Z-Individual[2] (MPa)	(Z-X)/X (%)	BPA Rate (Day^{-1})
C00	Spalling was observed. BPA was not examined.			
C0S	Spalling was observed. BPA was not examined.			
C0P	36.9	20.1	- 45.5	0.187
C0H	36.7	24.6	- 32.8	0.056
CA0	35.5	22.2	- 37.5	0.087
CAS	34.9	25.6	- 26.9	0.087
CAP	25.3	21.2	- 16.1	0.007
CAH	27.2	24.3	- 10.5	0.019

X-Group[1] Represents average residual strength value of 3 specimens after cooling
Z-Individual[2] Represents individual residual strength value of monitored specimen after air re-curing

Individual compressive strength value of monitored specimen (air re-cured for 28 days following cooling period and tested at the end of this 28-day period) and average compressive strength value of 3 specimens tested after cooling (as an initial strength value before air re-curing period) were used to calculate the change in compressive strength during air re-curing period.

After comparison a scatter gram was obtained as shown in Figure 7 and it showed that there was a logarithmic relation between changes in compressive strength and BPA rates. Calculated R^2 value for all set of data was 0.77. This rate can be increased by using advanced photographing techniques, by analyzing in specific software, by increasing sample size etc. For example, air voids on the surface of the specimens influence the total amount of black pixels. If the effect of air voids is somehow eliminated more accurate BPA rates can be obtained.
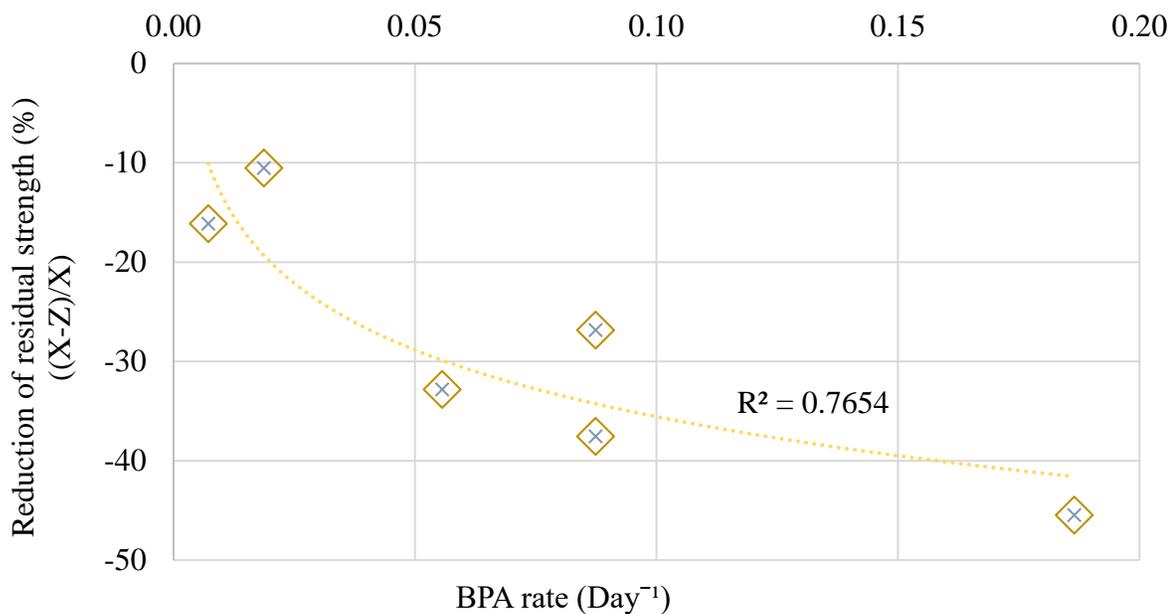

Figure 7. Black pixel analyses results.

4. CONCLUSIONS

In this study, disintegration of various kinds of concrete under air re-curing regime was investigated. BPAs were conducted on air re-cured specimens and the relation between crack development and reduction in compressive strength were evaluated. And the conclusions given below can be drawn regarding to the obtained results limited to the specimen geometry (cubic shape 15by15by15 cm)

1. Due to excessive temperature increase in concrete, compressive strength of concrete groups decreased approximately 35% after heating. Moreover, continuous cracking of concrete following to cooling caused further reduction in compressive strength.

2. Relation between cracks on heated surfaces and reduction in compressive strength was evaluated after cooling. The results showed that average crack width on the heated surface of concrete can give information about the decrease in compressive strength of concrete.

3. An image analysis technique was developed during this study which is called black pixel analysis (BPA) in order to understand the relation between the crack growth during air re-curing and compressive strength reduction after air re-curing. This method gave good results for high and it can be improved to better represent the extent of damage in concrete after high temperature exposure.

5. ACKNOWLEDGEMENTS

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