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Chloride Intrusion Into Thermally Damaged Self-Compacting Concrete

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The post-heating resistance of limestone SCC against chloride intrusion is investigated considering key parameters such as water-to-cement ratio (0.4, 0.45, and 0.5), relative humidity and elevated temperature (300 and 400°). SCC mixtures were proportions to confirm to universal specification with regard to different workability requirements. Chloride profiles were determined for post-heated and companion prismatic (100x100x250mm) specimens, kept at room temperature. Consequently, diffusion coefficients were determined upon Fick's steady state formula. Post-heating damage was quantified, as well, using various techniques such as ultrasonic pulse velocity waves, resonant frequency, compression test measurements. The results indicated significant reductions in compressive strength and estimated dynamic modulus ranging from (20 to 60%) and (10 to 40%), respectively, with a corresponding increase in chloride diffusion coefficient reaching 80%. Both temperature and relative humidity levels had tangible impact on post-heating damage of SCC, hence percentage increase in chloride diffusion coefficient. The empirical models developed in this work showed excellent correlation between various damage indices and the percentage increase in diffusion coefficient. Furthermore, the electrical charge passing through SCC compared very well with the percentage increase in diffusion coefficient.

Keywords: Corrosion, Chloride, Self-compacting concrete, Diffusion, Thermal-damage.

Introduction

Corrosion of reinforcing steel in concrete is the most significant deterioration process affecting reinforced concrete structures. The two most important causes of corrosion of the reinforcing steel are carbonation and chloride contamination of the concrete. The ingress of chloride into concretes depends upon many factors; the most important of which is the cracking status of the concrete structures. Cracking in concrete structures may be inherent or as result of structural design faults, construction deficiencies, fire attack and/or lack of long term durability (Saetta 2005). Corrosion is accompanied by a loss of rebar cross-section and a build-up of corrosion products, which occupy a larger volume than the original metal from which they were derived. This generates tensile stresses causing cracking and spalling of the cover, which may results in significant deterioration in structural elements in a short of period of time.

Research works, concerned with the effect of load induced cracks on the chloride profile in concrete, showed that chloride ingress in concrete is dependent upon the size and depth of generated cracks (Rodriguez 2001; Gowripalan et al. 2005). The research findings indicated that relatively high pre-loading stresses are needed to affect significantly the ingress of chloride into concrete. Those investigated the effect of moisture content and freezing and thawing on the chloride profile revealed that relatively high number of freezing and thawing cycles would be needed to create internal damaged; that is high

enough to permit easy access of chloride ions into the vicinity of reinforcing steel embedded in air-entrained concrete (Iqbal and Ishida 2001; Ababneh 2002).

SSC has been increasingly used in the construction of highway roads, bridges, seashore structures, and chemical plants because of the ease by which SCC can be placed in forms, and finished without segregation (Ouchi et al. 2003). Compared to vibrated concrete, SCC possesses denser pore system because of its high binder content. Therefore, it is recommended for the construction of concrete structures located in harsh environments where it is exposed to severe physical and chemical attacks (Feng et al. 2010). Consequently, serviceability is improved, and service life is extended for such structures with their repair cost reduced (Wasim and Hussain 2015). Those compensate for the additional cost paid for using relatively high binder and admixtures contents in SCC (Okamura and Ozawa 1995; ACI Committee 318 2005). Unfortunately, the resistance of SCC to elevated temperatures was stipulated to be lower than that of conventional concrete because of SCC finer pore structure. The resulting damage is demonstrated by severe cracking and spalling of concrete; especially at reinforcing steel location (Persson 2004; Reinhardt and Stegmaier 2006; Schutter et al. 2007; Boström and Jansson 2008; Haddad et al. 2013). Structures that are most susceptible to heat or fire damage are nuclear and chemical plants, not to rule out concrete bridges, where an oil carriers may overturn and go inflame above or underneath, as reported in more than one occasion (Garlock et al. 2012).

Exposure of structural elements with SCC to temperatures of 400°C and less for a period of less than 3 hours would have a limited impact on their load carrying capacity without the need for repair. Nevertheless, resulting cracking would most probably allow easy intrusion of chloride ions into the vicinity of reinforcing steel rather undistorted by this level of heating (Haddad et al. 2013). Of course, chloride diffusivity in structural elements with heat-damaged SCC may worsen under vibration by dynamic loads; quantification of which is complicated and requires further research. The source of chloride ions may be deicing agents, spread in winter over major concrete bridges, seawater, atmosphere of humid climates, or chemically disposed compounds. The most recent work paper by Car'e (2008) concluded that heating cement pastes of varying strengths to temperatures slightly below 105°C had resulted in macroscopic cracking network and modification of their pore size distributions; and hence their transport properties, as expressed by apparent diffusion coefficient of chloride, were increased substantially.

Research Significance

Numerous literatures were dedicated to study the key parameters that control reinforcing steel corrosion in concrete structures to determine the proper methods that would prevent or reduce the ingress of chlorides into concrete, and consequently extend service their service life. Cracking of self-compacting concrete (SCC) by a direct fire or heating is expected to decrease its resistance against chloride intrusion. The present literature lack relevant data needed to develop empirical models that relate chloride diffusion coefficient in SCC to heat-damage indices.

Scope of present work

To achieve the study objective, cylindrical (150x300 mm) and prismatic (70x70x250 mm) specimens were cast using SCC mixtures at w/c ratios of (0.4, 45, and 0.5) with limestone aggregates, then cured for 28 days, conditioned for four different levels of humidity (30-100%) and later exposed to elevated temperatures in the range of (300-400°C) for 2 hours. The latter conditions simulate those predominate during a short-period fire or affect structural elements, located a way from the center of a major fire. The first part of study related to post-heating behavior of SCC was published by Haddad et al. (2013). In this paper, post-heated SCC prisms were saturated in water for 24 hours and then subjected to a chloride sodium solution at concentration of 3% for a period of 35 days. The chloride profile was determined across the depth using powder samples drilled from three different holes and for each specimen. Accordingly, the chloride diffusion coefficient was determined for various specimens then related to the amount of damage received using statistical modeling. Table 1 summarizes the parameters studied and corresponding type and number of specimens used.

Experimental Program

Materials Properties

Ordinary Portland cement (Type I) with limestone aggregate, having a maximum size of 19 mm was used in preparing different SCC mixtures. The physical properties for coarse and fine aggregates are reported in Table 2. Limestone powder of particles smaller than #100 was used as filler to maintain stability for SCC mixtures. It had an absorption of

13.8%, and a unit weight of 1920kg/m³. A superplasticizer, having a specific gravity of 1.11 without any chloride content, was used to produce flowing and a cohesive SCC along with a retarder from same Company: the retarder had a specific gravity 1.17.

Mix Proportioning

SCC mixtures were designed according to rational mix design method – Okamura and Ozawa (1995). The principle of the mix design method is that the content of coarse and fine aggregate is fixed and that the self-compactability of the fresh concrete can be achieved by adjusting only the water/binder ratio and superplasticizer. Several mixes were tried to obtain the best proportion so that filling, passing and segregation for SCC abilities are achieved. Three plain SCC mixtures at w/c ratios (0.4, 0.45 and 0.5) with limestone aggregate were prepared. The dosages of the superplasticizer and the retarding admixtures were adjusted in each mix to achieve workability requirements for SCC without segregation. The mix proportions of different concrete mixtures are listed in Table 3.

Mixing, Casting, Curing, conditioning, and heat treatment.

The mixing process was performed using a tilting drum mixer of 0.15m³ following the test method ASTM-C192 (ASTM 2005). The workability of SCC was evaluated using slump-flow, V-funnel, and U-Box tests according to specifications EFNARC (2002): results are summarized in Table 4. As can be noticed from Table 4, the workability parameters are in agreement with the upper and lower workability limits set for SCC by EFNARC (2002) and EU specifications (2010).

All specimens were cured for 28 days in water before certain groups were either dried in an oven, left in laboratory air, maintained in moist room, or immersed water to achieve varying levels of internal humidity. This was experimentally measured using a Humitest complete system, as described by Haddad et al. (2013). Finally, both cylinder and prism specimens, pertaining to various SCC mixtures, were subjected to thermal treatment at temperatures of 300, and 400 for two hours by means of an electrical furnace, and then left to cool at laboratory air.

Destructive and Nondestructive Testing of SCC

Post-heated and control SCC cylinders were capped with a sulfur compound to obtain a horizontal smooth surface then tested for load versus deformation response according to ASTM test method, C 469-05 (ASTM 20005). Acquired data were later analyzed for stress-strain diagram and its corresponding characteristics namely, ultimate strength, elasticity modulus, strain at failure, and toughness. At the same time, SCC prisms were tested non-destructively using resonance frequency, and ultrasonic pulse velocity, according to ASTM specifications C215, and C597, respectively. The resonance frequency and density of SCC were used in the computation of the dynamic elasticity modulus (DME) for various specimens. At least three readings from replicate concrete specimens were used as the test value; the results of which were very close.

Chloride determination Tests

Chloride Penetration Test: Heat-damaged and control SSC prismatic specimens (100x100x300 mm) were used to conduct chloride profile measurements. For this, fiber glass frames were affixed around the periphery of each prism using a strong adhesive to obtain 20 mm height dam, as shown in Fig. 1. Chloride solution at NaCl concentration of 3% (by weight) was filled on the top surface and kept at constant for the entire treatment period of 35 days; according AASHTO T277-86 (AASHTO 1990). Finally, water was removed and surfaces of specimens were cleaned by removing the deposits of salts before allowed to dry for one day at a room temperature of 23°C and a relative humidity of about 75%, ready for powder extraction.

Collecting Dust Samples: Concrete dust samples were collected from depths that ranged from 0 to 35 mm using the drill press machine at an increment of 5 mm, shown in Fig. 2. Samples were obtained from each depth range from three different drilling positions using 10 mm drilling bit, before stored inside special containers till time of testing for chloride content.

Determining chloride ion content using RCT procedure: A rapid chloride test (RCT) system manufactured by Germann Instruments was used to determine the chloride ion content of powdered samples, according to AASHTO T277-86 (1990). A 1.5 gram of the powdered sample, represented a certain depth range of a single hole, was added to a vial containing 10 ml of chloride extraction liquid, before the vial was shaken for 5 minutes, and an electrode immersed to obtain a voltage reading. Using a pre-prepared calibration curve, the voltage reading is converted into chloride concentration in SCC powder sample. The average of three reading from three holes was used at each depth as the test value with

their coefficient of variation (COV) determined and list in Table 5. As noticed, the COV averaged from 0.3% to 4.1% for readings; representing different mixtures and exposure temperatures; indicating very low variability. The latter COV values reflected the effect of: (a) inherent variability in tested powder materials; and (b) the operator. Accordingly, an average COV at $\pm 2.5\%$ for the percentage increase in diffusion coefficients was estimated upon COV values for diffusion coefficients computed and listed in Table 5. A further statistical analysis using t-test was carried out to determine the significance in differences between diffusion coefficients of Table 5: analysis results are summarized in Table 6.

Rapid Chloride Penetration Test: Rapid chloride penetration test (RCPT) allows determination of the total charge through concrete, as measured by the electrical conductance during the period of the test. It reflects the presence of cracking and the status of the pore structure of the concrete. The RCPT procedure was performed on moist SCC cores using an electric conductance unit as that shown in Fig. 3; according to ASTM test method C 1202 (ASTM-C1202 2000; Tang and Nilsson 1997). SCC cores (70 mm-in-diameter and 50 mm thick) in triplicates were obtained from SCC prisms, contaminated with chloride and companion controls. The readings from three cores were taken as the test value; the results of which were very close, as indicated by the COV at less than 0.5%.

Results and Discussion

Chloride profile

The chloride content profiles for control, and thermally damaged SCC made with limestone aggregate at varying water-to-cement ratios were depicted graphically in Figs. 4

through 6. The chloride profiles followed typical trend behavior that is compatible with the error function by Fick's (Stanish et al. 1997). Similar chloride profile was noticed for those conditioned to varying internal moisture contents (prior to heating). The effect of exposure temperature and basic properties (w/c ratio, and relative humidity) on chloride ingress in SCC is more clearly understood through the evaluation of chloride-ion diffusion coefficient, addressed in the section to follow.

Chloride diffusion coefficient

The chloride ion diffusion coefficient, D_c , pertaining to different mixtures and exposure temperature of up to 400°C, were computed and listed in Table 5. The diffusion coefficient was computed by substituting in the error function of equation (1) for chloride concentrations at surface (C_s) and a depth of 25 mm (AASHTO 1990). The value C_s was determined by backward extrapolation following the ASTM C1556-04 (ASTM-C1556 2004). It should be indicated that although available, SCC specimens exposed to temperatures greater than 400°C were excluded from this investigation because immersion water tended to leak out from the specimens sides; indicating that the water transfer mechanism was through flow rather typical intrusion.

$$C(x, t) = C_s \operatorname{erfc} \left[\frac{x}{2\sqrt{D_c t}} \right] \quad (1)$$

Where $C(x, t)$ = chloride concentration at the distance x from the exposed surface after the exposure time t ; C_s is the chloride concentration at the exposed surface (at $x = 0$); and erfc is the error function.

To investigate the effect of the study key parameters on chloride ingress, the percentage increase in diffusion coefficient of Table 5 were computed with respect to that of corresponding controls, and then depicted graphically. The effect of w/c ratio and relative internal humidity (RH) in conjunction with exposure temperature upon the percentage increase in apparent diffusion coefficient can be understood by referring to Fig. 7. As can be clearly noticed, the diffusion coefficient increased with temperature; reaching as high as about 40 and 80% at 300 and 400°C, respectively. This indicates that although imparted moderate changes to mechanical properties, thermally induced cracks, especially irreversible ones concentrated in the transition zone between aggregate and cement paste, have led to dramatic increase in permeability (Chen et al. 2013): Fig. 8 shows damage index in SCC in terms of dynamic elasticity modulus.

SCC mixtures at water-to-cement (w/c) ratios of 0.4 and 0.5 showed significant differences in the percentage increase of their diffusion coefficients, Fig. 7. It is noticed that SCC at a w/c ratio of 0.5 attained higher and lower percentage increase in diffusion coefficients when pre-heated at 300 and 400°C, respectively. These behaviors are explained as follows. When heated to 300°C, SCC at a w/c ratio of 0.4 received closer yet higher damage extent by vapor pressure than that at a w/c ratio of 0.5. Yet, the divergence in damage extent between the two SCC mixtures was greatly increased when temperature was raised to 400°C: the results from heat-damage index in terms of dynamic modulus, as defined by equation (3) and represented graphically in Fig. 8, supported this argument. As

a result, the permeability of SCC at a w/c ratio of 0.5, rather high, was more aggravated by heat damage than that of SCC at a w/c ratio of 0.4. On contrary, the significant cracking extent induced in SCC at a w/c ratio of 0.4, when pre-heated to 400°C, increased greatly its diffusivity beyond that of SCC at a w/c ratio of 0.5. These arguments explain why SCC, prepared a w/c ratio of 0.45 and pre-conditioned at a RH of 99%, prior to heating to 300 and 400°C, attained the lowest increase in diffusion coefficients at 17 and 57%, respectively, as compared to those of SCC prepared at w/c ratios of 0.4 and 0.5.

Results of Fig. 7 showed that the percentage increase in diffusion coefficient for SCC at a w/c ratio of 0.4, preconditioned at RH values of 99, 82, 58, and 28% then exposed to (300 and 400°C), reached (30, 80), (31, 62), (28, 64), and (21% and 51%), respectively. The corresponding percentages for SCC at a w/c ratio of 0.5 were (28, 76), (40, 57), (39, 48), and (38% and 57%), respectively. The error bars, estimated at $\pm 2.5\%$, indicated that only SCC mixtures with divergent relative humidity values showed significant differences in the percentage increase of their diffusion and that significant differences in percentage increase in diffusion coefficients cannot be substantiated for SCC with close relative humidity values; especially for SCC pre-heated to 300°C: the error bars were estimated upon the average for the coefficients of variation for different mixture and exposure temperatures, as reported in Table 5. These arguments are supported by the t-test results, reported in Table 6 based upon a significance level of 95%. The present findings agreed well with the findings by Haddad et al. (2013), which indicated that post-heated moist SCC mixtures received the highest cracking extent followed, in sequence, by air and oven-dried ones, respectively.

Electrical Conduction in Thermally Damaged SSC

The electrical conductance of charge through thermally damaged SSC was measured for various concrete specimens using SSC three cores of 70-mm-diameter from three prisms, post-heated at 300 and 400°C, and companion ones, kept at room temperature as controls: results are listed in Table 7. As can be noticed, the percentage increase in electrical charge (coulombs) passed through the SSC cores increased with exposure temperatures. Furthermore, the percentage increase in electrical charging correlated well with that of diffusion coefficient with regard to the impact of relative humidity, prior to heating, as well as w/c ratio.

Modeling Chloride Diffusion in SCC

In this part, the damage extent, as evaluated destructively and nondestructively, is related to percentage increase in diffusion coefficient for SCC, being exposed to elevated temperatures. The data from measurements of ultrasonic pulse velocity (UPV), dynamic elasticity modulus (DME), and compressive strength (CS) were analyzed for experimental error with results summarized in Table 8. As can be noticed, the ranges for COV for the data from measurements of UPV, DME, and CS were (0.9-8.8%), (0.1-3.3%), and (1.3-10.4%) with corresponding averages of 3.8, 1.4, and 3.8%, respectively. Considering the heterogeneity of SCC and the randomness in the distributed heat-generated cracks, it would be logically to conclude that the error in experiments is limited; even though such an error may be magnified for damage indices being computed according to equations 2-4,

discussed next. It should be noticed that the hardened density of SCC mixtures, having varying moisture contents, was used in the computation of DME for SCC along with resonance frequency measurements and that the resulting variability in DME with temperature reflected solely heat-damage rather possible experimental errors related to the estimation of hardened density.

Definition of Damage Indices: Three damage indicators, based upon UPV, DME, and CS, are presented to quantify the damage resulting from exposing SCC to high temperatures.

(1) the damage index in terms of UPV, $(DI)_{UPV}$, was computed using equation (2) as follows:

$$DI_{UPV} = 1 - \left(\frac{UPV^{dam}}{UPV^o} \right)^2 \quad (2)$$

Where, UPV^o is the initial ultrasonic pulse velocity and UPV^{dam} is the ultrasonic pulse velocity of heat-damaged SCC.

(2) the damage index in terms of the initial dynamic elasticity modulus, DI_{DME} , is written as:

$$DI_{DME} = 1 - \frac{(E_d)_{dam}}{(E_d)_o} \quad (3)$$

Where, $(E_d)_o$ is the initial or undamaged dynamic elastic modulus and $(E_d)_{dam}$ is the dynamic elastic modulus of the damaged SCC.

(3) the damage index in terms of compressive strength, DI_{cs} , was calculated from formula (4) as follows:

$$DI_{cs} = 1 - \frac{(C_s)_{dam}}{(C_s)_0} \quad (4)$$

Where, $(C_s)_0$ is the initial compressive strength and $(C_s)_{dam}$ is the compressive strength of the damaged concrete.

Correlations between diffusion coefficient and damage indices: Empirical models were generated to correlate the damage indices, defined earlier, to the percentage increase in chloride-ion diffusion coefficient using the statistical software. The relationship between the damage indices in terms of UPV, DME, or CS and the percentage increase in diffusion coefficient is described by the linear model of equation (5) and depicted graphically in Figs. 9 through 11, respectively. The corresponding regression constants were obtained and listed in Table 8 along with different statistical parameters; considering a confidence level of 95%.

$$P_{(DC)} = A * DI \quad (5)$$

Where,

DI = Damage index as defined by equations 3 through 5.

A = model constant.

Diffusion Coefficient versus Electrical Charge: Fig. 12 shows a linear relationship between percentage increase in diffusion coefficient and that in electrical charge. The empirical relationship is given as:

$$P_{(DC)} = A * P_{EC} \quad (6)$$

Where:

P_{DC} = Percentage increase in chloride-ion diffusion coefficient with respect to companion undamaged SCC .

P_{EC} = Percentage increase in electrical charge with respect to companion undamaged SCC .

A = model constant.

As deduced from Table 9, the multiple coefficients of determination (R^2) for different models varied from 0.76 to 0.88. Hence, the fit of these models of present data can be rated as good to very good, respectively; considering the variability in concrete composition and moisture content prior to thermal treatment and the randomness in the distribution of thermally generated cracks. The standard error of regression (SE) represents the average distance that the observed values fall from the regression line. For present models, SE ranged from 3 to 9.7% suggesting limited deviation between the models predictions and the actual ones. The p-value for the models' constant is much less than 0.05; indicating that the null hypothesis ($A=zero$) can be rejected. The t-test led to similar conclusions with regard to the significance of the different models' constants. Furthermore, the residual plots for all models showed limited numbers of outliers without specific trend behavior that may suggest that the models are inappropriate.

Conclusions

In light of the results reported in this work, the following conclusions can be made:

1. The post-thermal damage and cracking in SCC increased the permeability thus chloride-ion diffusion proportional to exposure temperature. The increase in chloride diffusion coefficients reach as high as 80 and 40% for moist SCC exposed to 300 and 400°C, respectively.
2. The resistance of SSC to chloride penetration depended upon both w/c ratio and exposure temperature: the resistance of SCC of relatively low w/c ratio to chloride diffusion was detrimentally affected when pre-heating temperature was raised from 300°C to 400°C; owing to its brittleness.
3. Moist and thermally-treated SCC allowed more intrusion of chloride as compared to that of companion drier ones. Furthermore, significant changes in percentage increase in diffusion coefficients were clearly recognized between SCC mixtures having divergent contents of moisture; especially for an exposure temperature of 300°C.
4. A reasonable correlation was achieved between the percentage increase in chloride-ion diffusion coefficient and different damage indexes, defined in terms of ultrasonic pulse velocity, dynamic elasticity modulus, and compressive strength.
5. The total charge passed in SSC was proportional to amount of heat damage induced, and hence chloride-ion diffusion coefficient. The correlation between the percentage increase in chloride-ion diffusion coefficient and that in charge passed in concrete can be rated as excellent.

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Table 1. Detailing of testing program.

Number of specimens								
T(°C)	Limestone Aggregate						Basalt Aggregate	
	w/c = 0.4*		w/c = 0.45		w/c = 0.5*		w/c = 0.45	
	Cylinder	Prism	Cylinder	Prism	Cylinder	Prism	Cylinder	Prism
23	2	2	2	0	8	2	2	0
300	8	8	2	2	8	8	2	2
400	8	8	2	2	8	8	2	2

*, specimens stored in four different environments to achieve four humidity levels inside concrete ranging from 28 to 99%.

Table 2. Physical properties of aggregate, used in different SCC mixtures.

Particles	BSG (dry)	Absorption (%)	FM	UW (loose)
Fine	2.52	2.67	2.7	N.A
Coarse	2.53	1.34	N.A	1421

B.S.G: Bulk Specific Gravity (dry basis); FM: Fine Modulus; U.W: Unit Weight (kg/m³);
N.A.: Not applicable

Table 3. Proportions of different SCC mixtures, used in present work

Mix variables		Quantities kg/m ³							
	w/c ratio	FL	Cement	FA/CA ratio	W	FA	CA	SP	R
Limestone	0.5	125	350	0.83	175	590	711	6.216	1.760
Limestone	0.45	100	375	0.80	169	571	711	8.325	1.760
Limestone	0.4	75	400	0.77	160	547	711	13.32	1.760

FL, Filler, FA: Fine aggregate, CA: Course aggregate, SP, superplasticizer, R, retarder.

Table 4. Results of self-compatibility tests on different SCC mixtures as compared to EFNARC (2002) and EU specifications (2005).

w/c Ratio	Self-Compatibility Test			Limits		
	Slump-Flow (mm)	V-Funnel (sec)	U-tube (mm)	Slump-Flow (mm)	V-Funnel (sec)	U-tube (mm)
0.40	710	10	28	650-700 ^a	6-12 ^a	0-30 ^a
0.45	690	8	17	640-800 ^b	7-27 ^b	
0.50	660	8	10			

a, EFNARC, 2002; b, EU Specifications, 2010.

Table 5. Diffusion coefficient ($\times 10^{-11} \text{ m}^2/\text{sec}$) and corresponding coefficient of variation for all tested specimen.

Temp (°C)		23°C		300°C		400°C	
w/c ratio	RH (%)	D _C	COV (%)	D _C	COV (%)	D _C	COV (%)
0.4	28	1.98	1.7	2.40	3.2	2.99	0.7
	58	1.98	1.7	2.53	0.5	3.24	0.5
	82	1.98	1.7	2.60	0.5	3.20	0.4
	99	1.98	1.7	2.58	4.1	3.58	0.3
0.5	28	2.21	1.2	3.05	0.5	3.46	0.6
	58	2.21	1.2	3.07	0.5	3.28	0.5
	82	2.21	1.2	3.10	1.2	3.46	0.5
	99	2.21	1.2	2.83	0.4	3.88	0.3
0.45	99	2.13	1.8	2.64	0.7	3.24	0.7

D_C, diffusion coefficient; RH, relative humidity; w/c, water-to-cement ratio; COV, largest coefficient of variation between chloride content readings pertaining to powder samples from three boring holes.

Table 6: T-test analysis of diffusion coefficients of post-heated SCC with various relative humidity levels (confidence level =95%).

Temp		300°C			400°C		
W/C ratio	RH (%)	58	82	99	58	82	99
0.4	28	IS	S	S	S	S	S
	58		S	IS		IS	IS
	82			IS			IS
0.5	28	S	S	S	S	IS	S
	58		IS	S		S	S
	82			S			S

IS, insignificant; S, Significant; RH, relative humidity; W/C, water-to-cement ratio.

Table 7: Total charge through post-heated limestone SCC.

Temperature (°C)		23°C	300°C	400°C	300°C	400°C
w/c ratio	RH %	Total charge (coulombs)			Percentage Increase	
0.4	28	2010	2436	3001	21	23
	58	2010	2461	3301	22	34
	82	2010	2462	3303	22	34
	99	2010	2709	3633	35	34
0.5	28	2030	2979	3637	47	22
	58	2030	2981	3755	47	26
	82	2030	2982	3636	47	22
	99	2030	3000	3867	48	29
0.45	99	2020	2751	3733	36	36

RH, relative humidity; w/c, water-to-cement ratio.

Table 8: Variability of destructive and nondestructive tests conducted on control and heat-damaged SCC specimens.

w/c ratio	T(°C)	COV (%)		
		UPV	DME	CS
0.4	23	1.9	0.6	8.2
	300	8.8	3.3	1.6
	400	4.2	1.6	3.4
0.5	23	2.2	2.1	10.4
	300	3.3	1.9	1.7
	400	3.5	0.6	2.1
0.45	23	3.6	1.6	2.6
	300	6.5	0.3	1.3
	400	0.9	0.1	2.9

COV, coefficient of variation; T, temperature; UPV, ultrasonic pulse velocity; DME, dynamic modulus of elasticity; CS, compressive strength.

Table 9. Models' constants and corresponding statistical parameters.

Independent Variable	A value	SE	t-test	p-value	R ²
$DI_{UPV} = 1 - \left(\frac{UPV^{dam}}{UPV^o} \right)^2$	136.8	8.1	19.9	0.000	0.76
$DI_{DME} = 1 - \frac{(E_d)_{dam}}{(E_d)_o}$	159.0	9.7	16.4	0.000	0.74
$DI_{CS} = 1 - \frac{(C_s)_{dam}}{(C_s)_o}$	121.5	6.2	19.5	0.000	0.82
PR_{EC}	0.78	3.0	23.0	0.000	0.88

DI, damage index; R², multiple coefficients of determination; SE, standard error of regression.

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