Influence of Early Heat Curing on Properties of 100-MPa Air-Entrained Concrete

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An air-entrained, high-strength concrete was prepared in a precasting plant to evaluate the effect of initial heat treatment and subsequent outdoor storage on concrete characteristics. One set of standard specimens was cured in lime-saturated water at 23°C until testing. Another set of specimens and a large panel were heat cured on a steel bed heated by 50°C water circulating underneath it. Heating began 6 hr following concrete casting and lasted for 8 hr. Heated concrete remained on the bed for an additional 6 hr before demolding; it was then cured indoor at 15°C until the age of 7 days before outdoor storage. Investigated properties included temperature rise, compressive, splitting tensile, and flexural strengths, modulus of elasticity, chloride ion permeability, and frost durability. Mechanical properties were evaluated at 1, 4, 28, 91, and 365 days. Test results indicate that the investigated concrete can secure high early strength without early heat curing. Initial heating increased compressive strength; however, such heat treatment coupled with subsequent outdoor storage had a deleterious effect on ultimate strength, especially for concrete from the precast panel where initial peak temperature was 56°C, compared with 42°C for accompanying heated specimens. Maximum reductions in compressive, splitting tensile, and flexural strengths and modulus of elasticity of concrete subjected to early heat curing and subsequent outdoor storage compared with standard-cured specimens were approximately 15, 35, 40, and 15 percent, respectively. Regardless of curing history, the concrete exhibited excellent frost durability. Mercury intrusion porosimetry of 1-yr old samples demonstrated that heated concrete had greater porosity than standard-cured concrete and higher concentrations of pores with 1–5 μm diameter. That was confirmed by microscopical examination; however, no particular increase in microcracking in the paste or transition zone of heated concrete, as compared with moist-cured concrete, was observed.

In recent years, there has been a growing interest in the use of high-strength concrete (HSC) in the precasting industry. The increase in compressive and tensile strength capacities enable the application of greater service loads or the production of more slender and lighter structural elements at reduced cost. The use of HSC can improve the bond strength to prestressed strands and reduce the transfer and development lengths of pretensioned strands. Similarly, the relatively low creep of HSC can decrease long-term deformations and prestressing losses. The increase in the modulus of elasticity also can reduce elastic deflections and shortening losses. Finally, the improved durability of HSC can lower the maintenance cost of precast structural and architectural elements.

Soon after casting, precast concrete elements are often heated by low- or high-pressure steam, radiant heat from hot oil or water pipes, or electric-resistance heating. This is done to accelerate early-strength development and enable the early release of prestressing strands and the rapid stripping and reuse of precasting molds. Such accelerated curing increases early-age compressive strength and modulus of elasticity developments (*1–6*) and to a lesser degree splitting tensile strength (*5,6*). Whenever the concrete is subjected to elevated curing temperatures for a few hours at very early ages or cured at elevated temperatures for longer periods, the development in long-term mechanical properties may be adversely affected (*1–6*). For example, conventional concrete with a water-to-binder ratio of 0.41 to 0.55 that was cured continuously at 50°C developed 20 to 30 percent lower strength after 28 days and one year, respectively, compared with similar concrete cured at 20°C (*6*).

What causes long-term reduction of mechanical properties from early exposure to elevated temperatures is not well understood. Richartz (*7*) observes that high initial temperature affects the morphology of the hydration products. Accelerated heat curing is reported to result in rapid formation of short-fibered calcium silicate hydrate (C-S-H) instead of long-fibered C-S-H. That could occur whenever the initial hydration rate was slowed down, either by low temperature curing or by incorporating a set retarder. Unlike the long-fibered phase, the short-fibered C-S-H did not appear to span the available gel pore space in the early hydration phase. The formation of short-fibered C-S-H then could reduce the interlock between C-S-H fibers and restrict subsequent development of longer fibers; hence, it could limit ultimate strength (*7*).

High initial curing temperatures accelerate the rate of cement hydration that can exceed the rate of diffusion of hydration products. Dense hydration products then can precipitate near cement grains and decrease the rate of subsequent diffusion and precipitation of additional hydration products throughout the interstitial space between cement grains (*8*). The resulting increase in large pore volume was observed by Goto and Roy (*9*), as total porosities of cement pastes made with water-to-cement ratios of 0.35, 0.40, and 0.45 cured at 60°C were considerably greater than those of pastes hydrated at 27°C. The difference in porosity is attributed to spreads in volume of pores with diameters 150–460 nm. Pastes with substantial volumes of pores with diameters greater than 150 nm also were found to exhibit higher water permeability values. Similar observations were reported by Kjellsen et al. (*10,11*), who compared the pore structure and microstructure of two identical cement pastes made with a water-to-cement ratio of 0.50, one cured at 5°C and another at 50°C. Greater total porosity and an increase in the volume of relatively coarse pores were observed in paste subjected to the higher curing temperature after approximately 70 percent of hydration. That was especially true for pores of diameters 40–200 nm. Using a backscatter electron microscope and image analysis techniques to examine relative densities of various microstructures, cement paste cured at 5°C was reported to have a more uniform

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C-S-H phase than that cured at 50°C. The latter was reported to have a dense and strong C-S-H "shell" around cement grains but porous C-S-H in the interstices between cement particles. The presence of such porous C-S-H and the observed coarsening of capillary pores can detrimentally affect the development of mechanical properties and durability. Detwiler et al. (*12*) further reported that increase in capillary porosity in the cement paste resulting from curing at 50°C versus 5°C causes an increase in chloride ion diffusion, especially in low water-to-cement ratio systems. (0.40 versus 0.50 and 0.58).

Unlike conventional concrete, there is limited information on the effect of early-age heat curing on the long-term characteristics of HSC. Laamanen et al. (*4*) tested the effect of early heat curing on the loss of compressive strength of concrete mixtures made with water-to-binder ratios of 0.30, 0.45, and 0.60, which contained 0 or 8 percent silica fume replacements. The beginning of heat treatment was varied to allow concrete to attain initial strength varying between 0 and 15 MPa. Samples first were stored in 40°C water baths for one hour before transferring them to 60°C water baths. The heat curing lasted for 6 days, then the specimens were stored in 20°C baths until the age of testing at 28 days. The authors reported that HSC can undergo less reduction in strength from early heat curing than can conventional concrete, and that silica fume concrete can exhibit smaller reduction in compressive strength than can non-silica fume concrete. The delay period before heat treatment was found to have no significant effect on the development of compressive strength at 28 days, providing that the strength of the concrete exceeded 3 MPa before heating.

Kanda et al (*13*) investigated HSC made with 12 percent silica fume replacement and a water-to-binder ratio of 0.25. Heat treatment started 8 to 10 hours after casting and consisted of curing concrete under temperature-match conditions in water baths in which temperatures were adjusted to reflect those recorded in cast and insulated concrete blocks. Maximum curing temperatures varied between 45 and 75°C. Following a 5-day accelerated curing period, the specimens were sealed and cured at 20°C until the age of testing at 28 days. The study showed that the 28-day compressive strength of heat-treated HSC can be 10 ± 5 percent less than that of concrete cured at 20°C.

Lindgard and Sellevold (*14*) examined the influence of heat curing on compressive strength of HSC made with water-to-binder ratios of 0.30 to 0.33. Heat treatment was started 6 hr after casting and lasted for 3 days at either 40 or 60°C. Specimens gradually were cooled before storage in 20°C water bath. Reduction in strength development was found to decrease with the reduction in water-to-binder ratio and the decrease in curing temperature. Compared with concrete continuously cured in water at 20°C, HSC had 15 to 25 percent reduction in uniaxial tensile strength and 10 to 20 percent reduction in flexural strength at 60 days. No significant differences were observed for compressive strength, elastic modulus, strains at maximum compression and tensile stresses, fracture energy, and durability.

Gjørv and Martinsen (*15*) demonstrated that up to 28 days, curing HSC made with lightweight aggregate at temperatures up to 90°C had no adverse effect on compressive strength, modulus of elasticity, capillary absorption, porosity, or resistance to water permeability. However, elevated curing temperatures of 50°C and 90°C had detrimental effects on rapid chloride ion permeability, suggesting that the concrete had a more open and porous microstructure than that cured at 20°C. Similar observations were reported by Sandvik and Gjørv (*16*) on 65-MPa lightweight concrete made with 4 percent silica fume with a water-to-binder ratio of 0.43. Core samples obtained from a slab for which maximum recorded temperatures reached 85°C showed no drops in compressive strength or elastic modulus. However, rapid chloride ion permeability values were found to increase whenever the peak temperature exceeded 50°C.

Soon after production, precast elements often are put to use at early ages, or they can be stockpiled outdoor before shipment to job sites without any additional moist curing. The limitation of moist curing can affect the ultimate characteristics of HSC. Asselanis et al. (*17*) compared the gains in compressive strength and modulus of elasticity of HSC subjected to various durations of moist curing. The concrete had a water-to-binder ratio of 0.28 and incorporated 9 percent silica fume replacement. Compressive strength and elastic modulus values of air-dried concrete were found to be 18 and 15 percent lower, respectively, than moist-cured concrete after 28 days of curing. Similar results were obtained at 56 days. A minimum duration of moist curing of 7 days was recommended for such HSC (*17*).

As more construction is done using precast HSC, it is important to investigate the combined impact of accelerated early heat curing and subsequent exposure to the atmosphere without further moist curing on the development of engineering properties and potential durability to provide information on possible consequences and practical implications of such practices. In this research, methods are assessed by evaluating any reduction in compressive, flexural, and splitting tensile strengths: modulus of elasticity; chloride ion impermeability; and resistance to freezing and thawing of HSC.

EXPERIMENTAL PROGRAM

Concrete Mixture

An optimized, air-entrained HSC with an approximate 91-day compressive strength of 100 MPa was cast. A 530 kg/m^3 of a blended silica fume cement containing approximately 7.5 percent silica fume by mass was used. The concrete had a water-to-binder ratio of 0.22. The fine aggregate was a natural sand with specific gravity and absorption values of 2.67 and 0.9 percent, respectively. The coarse aggregate was a crushed dolomitic limestone with a nominal size of 10 mm and specific gravity and absorption values of 2.75 and 0.8 percent, respectively. The contents of the sand and coarse aggregate were 700 and 1080 kg/m^3, respectively.

A sulfonated napththalene-based high-range water reducer (ASTM C494, Type F) was used at 19 L/m^3. The concrete incorporated a hydroxylated carboxylic acid-based set retarding admixture (ASTM C494, Type D) and a neutralized vinsol resin-based air-entraining admixture (ASTM C260) at 0.74 and 0.30 L/m^3, respectively. The panel and standard specimens were cast from a single batch. The concrete had an initial slump of 220 mm.

Curing Conditions

The concrete was cast indoors in a precast concrete plant in Montreal, Quebec. Reference specimens were cast and covered with wet burlap and a polyethylene sheet to minimize evaporation. The specimens were demolded after one day and stored in lime-saturated water at approximately 23°C, in accordance with ACNOR CAN3-A23.2-3C and ASTM C192. The specimens were kept moist until the time of testing and were tested under moist conditions.

A second series of molded specimens was cured under an insulating blanket on a steel bed heated with 50°C water circulating

underneath through a dense network of pipes. The concrete began to harden after approximately 4.5 hr. The heat treatment was delayed for approximately 6 hr following casting, or 6.5 hr after the beginning of mixing. The circulation of hot water lasted for 8 hr, but the concrete remained on the hot steel bed for approximately 6 additional hr before demolding and removal. A concrete panel measuring 2.7 × 1 × 0.3 m was also cast on the same heating bed and subjected to early temperature curing identical to that of heated specimens. The heat rise of concrete was monitored for approximately one day using thermocouples placed in the centers of 100 × 200-mm standard-cured and heat-cured cylinders and precast panel.

After demolding, the panel along with heated specimens were kept indoors at approximately 15°C without supplemental water curing until they were aged 7 days. This was to allow gradual cooling and to minimize the formation of hairline cracks and crazing that can result from thermal and drying shrinkage. All heat-treated cast specimens were sealed using aluminum and plastic wrapping before outdoor storage to minimize water loss. The curing sequence was done in compliance with the precasting plant's standard practice for manufacturing structural elements and architectural panels using conventional concrete. Heated specimens and precast panel were stored outdoors where the concrete could be exposed to substantial temperature differentials and drying winds until testing time.

A few days before testing, molded specimens and samples from the panel were sealed and brought to the laboratory. Core ends were cut to obtain 200-mm long samples corresponding to concrete from the center of the panel, which can be less affected by drying than can surface concrete.

Test Specimens

The concrete was sampled for compressive strength, elastic modulus, flexural and splitting tensile strengths, chloride ion permeability, and frost durability. Table 1 indicates the various tests performed along with specimen dimensions. A total of 110 molded specimens and 55 cored and sawn samples obtained from the precast panel were tested. All cylinder and core ends used to evaluate compressive strength and elastic modulus were ground to ensure smooth and perpendicular end surfaces.

For each concrete, mercury intrusion porosimetry was done on two cores measuring 38 mm in length and 19 mm in diameter. The cores were taken from 1-year old specimens. Effort was made to avoid high concentrations of coarse aggregate in the cores. The samples were submerged into acetone for 6 hr then oven dried at 105°C until they reached constant mass to ensure complete drying. Water absorption was measured on similar specimens by measuring weight losses of water-saturated specimens following oven drying. The mercury intrusion porosimetry apparatus permitted the intrusion of pores with apparent pore diameters ranging between approximately 5 nm and 5μm.

TEST RESULTS

Tested mechanical properties are summarized in Table 2 along with their corresponding coefficients of variations. Results of the air-void systems of the hardened concrete, chloride ion permeability, and frost durability are also compiled in Table 2. Figure 1 shows the temperature-time history of the three concretes.

Figures 2 and 3 show cumulative pore size distributions of dry samples measured by mercury intrusion porosimetry. Figures 4 and 5 compare compressive strength, elastic modulus, flexural strength, splitting tensile strength of heated specimens and samples obtained from the panel to those of standard-cured concrete. Figures 6 and 7 compare normalized strength ratios of heat-treated concrete to those obtained for standard-cured concrete. The normalization was done by dividing the ratios of flexural-to-compressive strength, splitting tensile-to-compressive strength, and modulus of elasticity-to-

TABLE 1 Testing Program

	Dimensions of Specimens (mm)	Number of Specimens	Type of Specimens	Standard
Compressive	100 x 200	30	Cast	ASTM C39
Strength	95 x 190	15	Cored	
Modulus of	100 x 200	16	Cast	ASTM C469
Elasticity	95 x 190	8	Cored	
Flexural	100 x 100 x 400	24	Cast	ASTM C78
Strength		12	Sawn	
Splitting Tensile	150 x 300	24	Cast	ASTM C496
Strength		12	Cored	
Spacing Factor	100 x 200	4	Cast	ASTM C457
	95 x 190	2	Cored	
Chloride Ion	100 x 200	8	Cast	AASHTO T277
Permeability	95 x 190	4	Cored	
Freeze/thaw	75 x 75 x 350	4	Cast	ASTM C666
Durability		2	Sawn	(Procedure A)

TABLE 2 Summary of Test Results

	Standard Curing					Accelerated Heat Curing									
	ACNOR CAN3-A23.2-3C					Heated Specimens					Cores from Panel				
Age	33 h	4 d	28 d	91 d	1 yr	33 h	4 d	28 d	91 d	1 yr	33 h	4 d	28 d	91 d	1 yr
F_c (MPa)	36.1	63.5	89.1	103.3	108.8	53.0	57.4	76.1	87.3	109.3	55.2	63.6	75.4	82.6	102.5
C.O.V. (%)	2.9	0.5	1.5	2.0	0.1	0.9	6.5	0.8	0.7	6.9	7.3	4.3	3.5	1.2	3.1
E_c (GPa)	-	35	44	46	49	-	36	38	41	48	-	35	37	40	44
C.O.V. (%)	-	0.4	3.1	4.9	0.7	-	5.3	4.5	0	0	-	3.8	1.9	3.4	0.8
MR (MPa)	-	8.3	10.0	10.8	-	-	5.8	6.1	7.2	7.6	-	4.9	6.1	6.3	7.9
C.O.V. (%)	-	7.9	5.0	2.8	-	-	11	1.6	13.7	--	-	7.6	6.6	4.8	4.8
F_{sp} (MPa)	-	4.5	5.2	6.1	6.9	-	3.9	4.3	4.9	4.9	-	3.4	3.3	4.1	4.7
C.O.V. (%)	-	19.8	3.3	8.7	4.2	-	7.5	11.1	11.4	6.1	-	6.2	7.6	22.3	4.3
MR/F_c (%)	-	13.1	11.2	10.5	-	-	10.1	8.0	8.3	7.0	-	7.7	8.1	7.6	7.7
F_{sp}/F_c (%)	-	7.1	5.8	5.9	6.3	-	6.8	5.7	5.6	4.5	-	5.3	4.4	5.0	4.6
						Strength Ratio of Standard-Cured Concrete									
MR/F_c (%)							77	71	79			59	72	73	
F_{sp}/F_c (%)							96	97	95	71		75	75	84	72
$E_c/(F_c)^{0.5}$							108	93	97	99		100	92	97	93
Cl^- Per. (coulombs)		1450	560	210	100		1250	1070	590	160		1050	1120	760	150
Initial Current (mA)		64	28	13	7		60	51	28	13		47	54	37	9
Water Absorb. (%)					2.7					2.9					3.3
Total Porosity (mm^3/g)					22.4					24.1					29.5
						Frost Durability									
Air Vol. Hard. Conc. (%)			4.7					4.7					5.9		
Spacing Factor (μm)			380					380					370		
Specific Surface (mm^{-1})			14					15					13		
Pulse Velocity (% V_o)			100					103					100		
Durability Factor (%)			100					106					100		
Elongation After 300 Cycles (μm/m)			460					200					400		

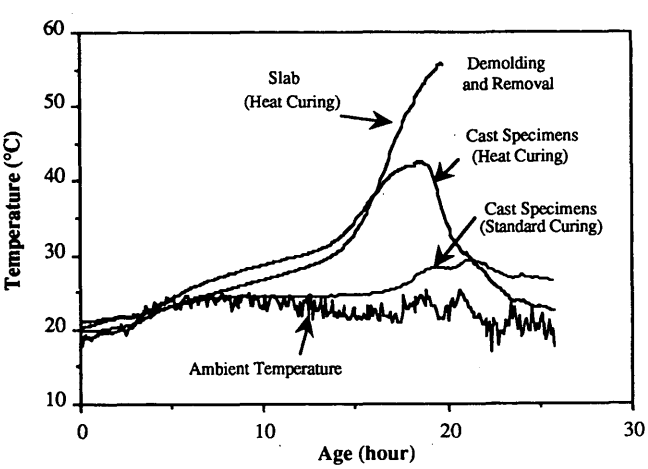

FIGURE 1 Initial temperature rise.

square root of compressive strength of heated concrete by corresponding ratios obtained from the moist-cured concrete.

Figures 8 and 9 show backscattered electron images of 1-year old standard-cured concrete as well as that taken from the precast panel.

DISCUSSION OF RESULTS

Temperature Rise

Peak concrete temperatures measured in the panel and in 100- × 200-mm specimen at the time of demolding were 56°C and 42°C, respectively. The moist-cured specimen exhibited a delay in temperature rise and had a peak temperature of 29°C. The sharp increase in temperature recorded in heated concrete after approximately 15 hr of age coincided with the increase in hydration rate of cement. Such initial temperature rise can accelerate the rate of

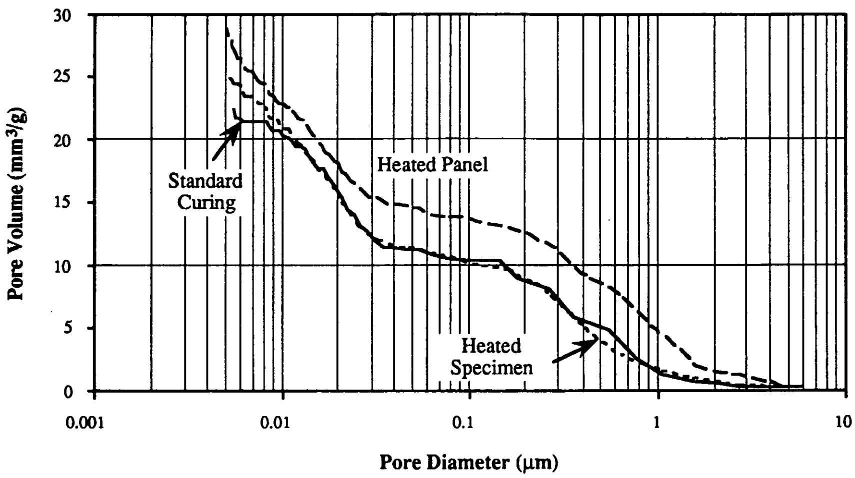

FIGURE 2 Cumulative pore size distribution.

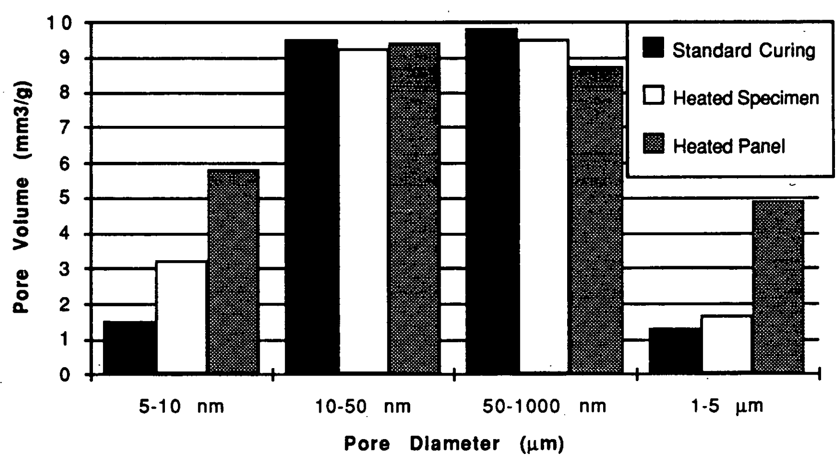

FIGURE 3 Pore size distribution.

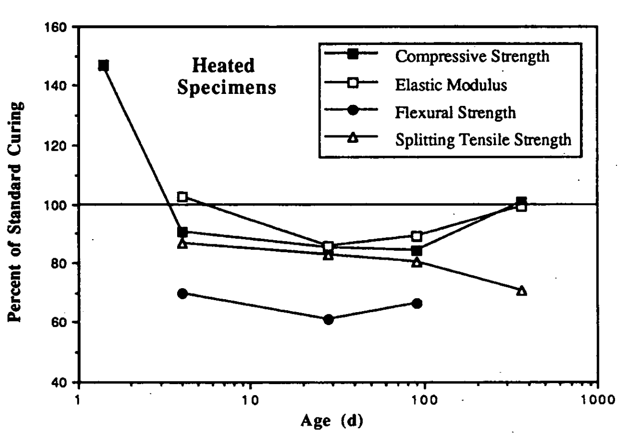

FIGURE 4 Mechanical properties of heated specimens versus standard specimens.

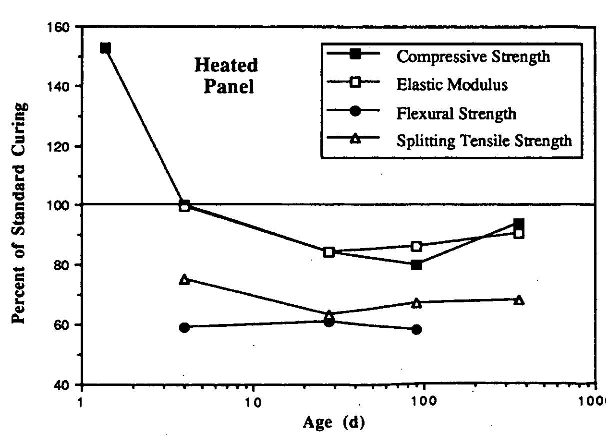

FIGURE 5 Mechanical properties of heated panel versus standard specimens.

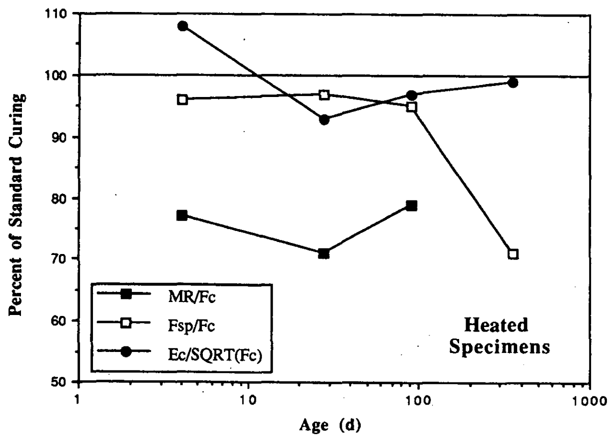

FIGURE 6 Normalized properties of heated versus standard specimens.

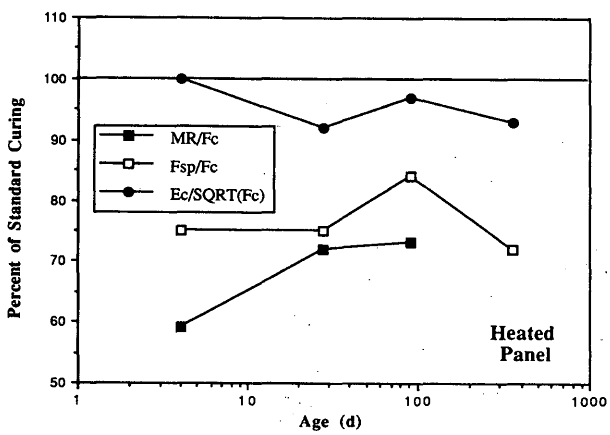

FIGURE 7 Normalized properties of panel samples versus standard specimens.

hydration of cement, which may adversely affect the development of engineering properties.

Mercury Intrusion Porosimetry

Cumulative pore size distribution curves indicate that concrete from the heat-treated panel developed greater total porosity and coarser pore volume than standard-cured and heated specimens. The latter two concretes had almost identical porosity and pore-size distribution values. The mean measured total porosity of 1-year old samples taken from the moist-cured concrete, heated-cylinders, and heated-panel were 22.4, 24.1, and 29.5 mm^3/g, respectively. Similarly, the mean values of water absorption were 2.7, 2.9, and 3.3 percent, respectively.

A comparison of pore size distribution of capillary pores indicates that an increase in total measured capillary porosity is mostly the result of increases in pores with diameters 5–10 nm and 1–5 μm. Mehta and Manmohan (*18*) suggest that capillary pores measured by mercury intrusion porosimetry with diameters greater than 100 nm can be considered to be relatively large pores, ones that can affect permeability and strength. The greater volume of large pores with diameters 1–5 μm in the heat-treated panel can therefore be expected to have a deleterious effect on permeability and strength.

Compressive Strength and Elasticity Modulus

Heat-cured cylinders and core samples had mean compressive strengths of 53.0 and 55.2 MPa, respectively, at 33 hr of age compared to 36.1 MPa for standard-cured concrete. However, beyond 4 days of age, the compressive strength of the standard-cured concrete was greater than that of heat-cured concrete. Both types of heat-treated concrete developed similar compressive strengths up to 91 days. Their compressive strengths at 28 and 91 days, respectively, were approximately 15 and 15–20 percent lower than those of standard-cured concretes. Between 91 days and 1 year, the moist-cured concrete had a slower rate of strength gain than heat-treated concretes. Both control and heated cylinders tested similar compressive strengths after 1 year; their strength was approximately 6 percent greater than the mean strength of cores from the heated panel.

As in the case of compressive strength, early temperature curing had no significant effect on the modulus of elasticity after 4 days of

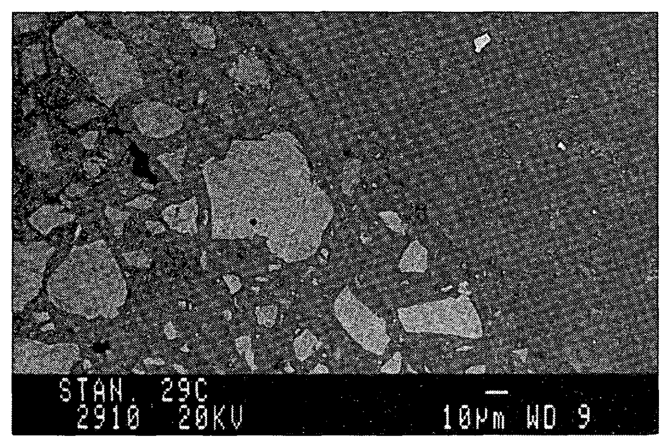

FIGURE 8 Backscattered electron images of standard-cured concrete.

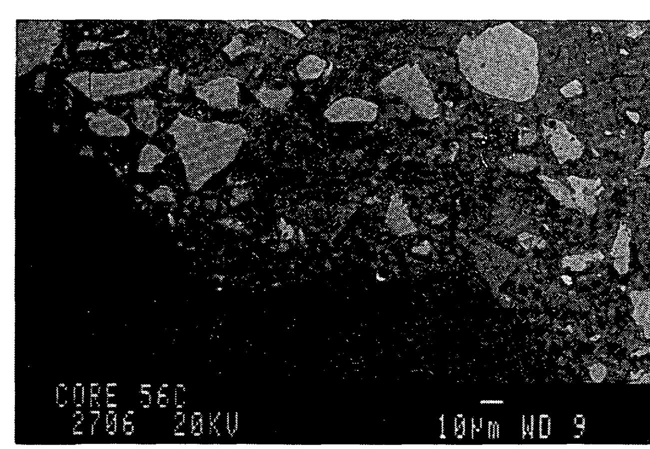

FIGURE 9 Backscattered electron images of precast panel concrete.

curing. However, there was a significant spread between the modulus of elasticity of heat-treated and standard-cured concretes at 28 and 91 days. The spread was approximately 15 and 10–15 percent at 28 and 91 days, respectively. After one year, the modulus of elasticity values of standard-cured and heat-treated molded specimens were identical, measuring approximately 9 percent more than those of cores obtained from the panel.

Flexural and Splitting Tensile Strengths

The initial increase in curing temperature and subsequent outdoor storage of the HSC had detrimental effect on flexural and splitting tensile strengths. Rates of gains in flexural strength were similar for the three concrete types. Molded specimens subjected to early heat curing and subsequent outdoor storage exhibited approximately 30 to 40 percent reduction in flexural strengths and 15 to 30 percent in splitting tensile strength, compared with standard-cured specimens. Samples obtained from the precast panel indicated approximately 40 percent reduction in flexural strength and 25 to 35 percent reduction in splitting tensile strength. In general, the spread between splitting tensile strength of heat-treated and standard-cured concretes increased with age, indicating a slowing down in the rate of strength gain of the latter concrete.

Chloride Ion Permeability

Standard-cured concrete had a slightly greater initially permeability to chloride ions than heat-treated concrete. However, after 28 and 91 days of curing the chloride ion permeabilities of standard-cured concrete were considerably lower than those of heated concrete. These differences are important since precast elements can be put into service before 91 days. The greater chloride ion permeabilities of the heated concrete may be mostly due to the greater capillary porosity and the coarser pore structure detected by mercury porosimetry compared to that of moist-cured concrete. Chloride ion permeability measurements of 1-year-old concrete showed that all three concretes had negligible chloride ion permeability levels that ranged between 100 and 160 coulomb indicating a highly discontinuous pore structure.

Frost Resistance

All concretes had similar spacing factors (370 to 380 μm) and specific surface values of air bubbles (13 to 15 mm^2/mm^3). Regardless of the temperature history and curing mode, all tested concretes exhibited excellent durability to freezing and thawing and had durability factors ranging between 100 and 106 percent.

Reduction in Mechanical Properties and Microstructure

Early heat curing appears to have a more lasting and significant effect on splitting tensile strength and modulus of rupture than on compressive strength or modulus of elasticity. That may be because of changes in the microstructure of the bulk cement paste or in the interface between aggregate and cement paste.

Using normalized strength ratios (Figures 6 and 7), it is possible to determine the percentage reduction in mechanical properties compared with those obtained for standard cured concrete. For heated specimens that developed a peak temperature of 43°C and were sealed before outdoor storage, maximum reductions in flexural strength, splitting tensile strength, and modulus of elasticity were 29, 29, and 7 percent, respectively. On the other hand, these values were 41, 28, and 7 percent, respectively, for samples obtained from the heated panel for which the recorded maximum temperature was 56°C.

In general, mechanical properties of heat-treated molded samples were superior to those obtained for the precast panel. The former concrete had a peak temperature of 14°C lower than that measured in the panel. The variation in peak temperature at early ages may have resulted in some reduction in the rate of initial cement hydration that could have improved the pore structure of the cement paste (*7–11*). The lower peak temperature also can reduce initial differential thermal expansions that adversely affect the quality of the interface between aggregate and cement paste. Furthermore, molded specimens were sealed before exposure to the atmosphere to minimize drying a method that can favor cement hydration and assure longer gains in strength.

Backscattered electron imaging of polished concrete samples was carried out on 1-year-old samples to examine differences in microstructure. However, such examination did not reveal any specific difference in the concentrations of microcracks, either at the interface between cement paste and coarse aggregate, or in the paste itself. Comparison of the microstructure of polished concrete surfaces did reveal greater concentrations of relatively large pores in the case of concrete from the precast panel compared with other two concretes. The pores appear as black areas in the micrographs shown in Figures 8 and 9. This finding is in agreement with the increase in the volume of large capillary pores detected by mercury intrusion porosimetry.

Secondary electron microscopy was used also to observe fractured surfaces at very high magnifications. Again, no specific differences in the densities of microcracking were observed. All three concretes appeared to have excellent interface regions between the aggregate and paste and a minimum of microcracking and calcium hydroxide deposits. The microstructure also was observed to examine any changes in the morphology of hydration products between the various concretes, in particular the form of the C-S-H. High initial temperature can be expected to increase the rapid formation of short-fibered C-S-H, instead of long-fibered C-S-H, which can reduce the interlocking between C-S-H fibers and reduce ultimate strength development (*7*). However, careful examination of the morphology of the C-S-H revealed that all three concretes had similar types of C-S-H gel.

Except for variations in pore size distribution and total porosity, it is not clear from the microstructural examination whether there are other significant differences in the concentrations of microcracking or hydration reaction morphology that could explain the large spreads in splitting and flexural strengths. Further research is warranted.

CONCLUSION

The combination of initial heat curing of a 100-MPa air-entrained concrete at approximately 50°C and subsequent air drying for 6 days at 15°C before exposure to harsh climatic conditions can

result in significant reductions in mechanical properties. On the basis of test results, the the following conclusions can be drawn:

- The evaluated air-entrained HSC developed high initial strength without heat curing.
- Higher strengths were obtained in heat-treated concrete after approximately 1 day of age. However, beyond 4 days, standard-cured concrete developed approximately 15 percent greater compressive strength and modulus of elasticity than heat-treated precast concrete (peak temperature of 56°C). The spread was approximately 10 to 15 percent and 15 to 20 percent, respectively, for heat-treated and subsequently sealed samples (peak temperatures of 42°C).
- Heat-treated concrete exhibited a 30 to 40 percent reduction in flexural strength compared with standard-cured prisms, samples from the panel showing lower relative strength than heat-molded prisms.
- The spreads in splitting tensile strengths between heated and standard-cured specimens varied from 15 to 30 percent and from 25 to 35 percent, respectively, for concretes from the panel and those tested on heated cylinders.
- Heat-treated and subsequently air-dried concrete had greater capillary porosity than did moist-cured concrete. Additional porosity mostly was attributed to increases in pores with diameters 5–10 nm and 1–5 μm.
- Heat-treated concrete developed a lower initial chloride ion permeability compared with standard-cured concrete but higher values after 4 days. No significant difference existed after 1 year of curing.
- Regardless of the heat treatment and mode of curing, the evaluated air-entrained concrete developed excellent resistance to freezing and thawing.

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