The Mechanical Properties of High Strength Concrete in Massive Structures

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Abstract High strength concrete is being used increasingly in mass structure projects. The purpose of this study is to investigate the influence of temperature during mixing, placing and curing on the strength development, hydration products and pore structures of high strength concrete in mass structures. The experiments were conducted with two different model walls, viz.: 1.5 m and 0.3 m under typical summer and winter weather conditions. The final part of this study deal with the clarification of the relationship between the long-term strength loss and the microstructure of the high strength concrete at high temperatures. Test results indicated that high elevated temperatures in mass concrete structures significantly accelerate the strength development of concrete at the early ages, while the long-term strength development is decreased. The long-term strength loss is caused by the decomposition of ettringite and increased the total porosity and amount of small pores.

Keywords: High Strength Concrete, Temperature, Compressive Strength, Hydration Products, Pore Size Distribution

1. INTRODUCTION

High performance concrete is being used increasingly in the construction of high-rise buildings, bridges and marine structures. If high strength concrete is used for columns or other large section members of massive concrete structures, the center temperature of the members will rise rapidly at early ages due to hydration heat and the high temperatures will remain in the member for a relatively long period of time due to the low thermal conductivity of concrete.

High temperatures generally accelerate the early-age strength development of concrete, while reducing the long-term strength development. These elevated high temperature results in coarser pore structure and an increase in total porosity (Kjellsen et al., 1990; Patel and Bland, 1995). Additionally, high elevated temperatures contribute to the microcracking in cement paste, which is caused by large differences in the thermal expansion coefficients of concrete constituents (Laplante and Aitcin, 1996), the decomposition

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of ettringite (Scrivener and Taylor, 1993; Lawrence, 1995), polymerization (Cong and Kirkpatrick, 1995), and the non-uniform distribution of the hydration products (Verbeck and Helmuth, 1968). Due to all of these factors, the high temperature ultimately results in long-term strength loss of concrete (de Larrard and Bostvironnois, 1991; Price and Hynes, 1996).

However, most of the research on cement paste, mortar, and concrete was conducted with the specimens hydrated at room temperature, on a level surface and during the early stages of hydration. There is not enough information available on high performance concrete curd at elevated temperatures, in mass structures. Studies on the effects of outside weather conditions on the strength development of high performance concrete in mass structures are very scarce in the technical literature.

This study was prompted by the need for more detailed information on the influence of high elevated temperature and outside weather temperature on the compressive strength development of high performance concrete. In this paper we will report on some experimental work investigating the compressive strength, microstructure and hydration products gain at varying temperatures during the mixing, placing, and curing of concrete in mass structures. The final part of the study deals with the clarification of the relationship between the long-term strength loss and the microstructure of the high strength concrete at high temperatures.

2. EXPERIMENTAL

The cement used had the following composition: Na_2O, 0.28; MgO, 2.2; Al_2O_3, 5.3; SiO_2, 21.3; SO_3, 1.9; K_2O, 0.6; CaO, 64.4; TiO_2, 0.37; MnO, 0.1; Fe_2O_3, 2.6; ignition loss, 0.7%; specific surface area (Blaine), 3280 cm^2g^{-1}. A modified Bouge calculation gave: alite, 52;

belite, 24; aluminate 9; and ferrite 9 (Taylor, 1998). Crushed sand stone (specific gravity: 2.65, water absorption: 0.72 %, fineness modulus: 6.53) with a maximum nominal size of 20 mm was used as the coarse aggregate, and a local natural sand ((specific gravity: 2.58, water absorption: 2.07 %, fineness modulus: 2.69) was used as the fine aggregate in the concrete mixtures. A high-range water reducer composed by modified naphthalene sulfonate polymer, and a synthetic resin-type air entraining admixture were used.

The proportions of the concrete mixtures are summarized in Table 1. The concretes were mixed in a twin shaft-type mixer (200 L). After first mixing the mortar for 60 sec., then the coarse aggregate was added and the resulting concrete was mixed for another 90 sec. The mixing was conducted in the summer and in the winter to provide the two types of weather conditions. The freshly mixed concretes were tested for air content, slump, temperature and unit weight. The results show in Table 1.

To investigate the variation of long-term strength in actual concrete walls subjected to different curing temperatures, two model walls were designed. The model walls and the locations of sampling are shown in Figure 1. The depths of the walls were similar to those in an actual nuclear power plant, viz.: 1.5 m and 0.3 m. In order to simulate an actual long wall, the circumference of the wall's depths direction was insulated with a layer of 200 mm thick polystyrene and the square surfaces of the wall were exposed to the open air. The walls were cast in 20 mm plywood formwork. The formwork was removed at 72 hours after casting. Core cylinders (100 x 200 mm) were taken from the walls at 3, 7, 28, and 91 days and used for compressive strength, pore structure and hydration products measurements. For comparison, concrete cylinders were also cast in steel molds. All cylinders were removed from the steel molds 24 hours after casting. The standard cured cylinders were stored in water at 20 °C.

Temperature histories at different locations in the walls were recorded using thermocouples, shown in Figure 1. Cores and standard cylinders were tested for compressive strength at 3, 7, 28, and 91 days. A portion of the concrete cylinders were cut into approximately 5 mm cubes using a diamond saw. These fragments were immediately immersed in acetone to prevent further hydration. Thereafter, some fragments for ettringite (AFt) measurement were dried in a chamber of 40 °C for 1 hour because the AFt decomposes to form the monosulfate hydrate at higher than 65 °C (Mehta and Monteiro, 2006). Then the fragments were carefully ground by hand until a sample powder was obtained, which could pass through a 45 μm sieve. The AFt contents were examined by a differential scanning calorimeter (DSC) where a 20 mg sample was heated at 20 °C/min. in an N2 atmosphere. Some fragments for the calcium hydroxide (CH) were ground by hand as the same size as AFt sample after 2 weeks D-dry. The CH contents

Table 1. Mix proportions and properties in fresh concrete.

Weather condition	W/C	S/A	Unit content (kg/m^3)			Chemical agent	Properties of fresh concrete				
			Cement	Sand	Gravel		Slump (cm)	Flow (cm)	Air (%)	Temp (°C)	Density (kg/m^3)
Summer	0.33	0.49	516	787	840	SP8SX2[*1]: Cx1.2% MA404[*2]: Cx0.001%	22.0	38.5	4.9	31.0	
Winter	0.33	0.49	516	787	840	SP8SX2[*1]: Cx1.2% MA404[*2]: Cx0.001%	23.0	41.0	4.2	8.0	2348
							23.5	42.0	4.1	8.0	2346
							24.0	43.5	4.0	8.5	2347
							24.0	41.5	4.1	9.0	2354
							23.5	41.0	4.1	9.0	2347

SP8SX2[*1]: high-range water reducer, MA404[*2]: air entraining admixture
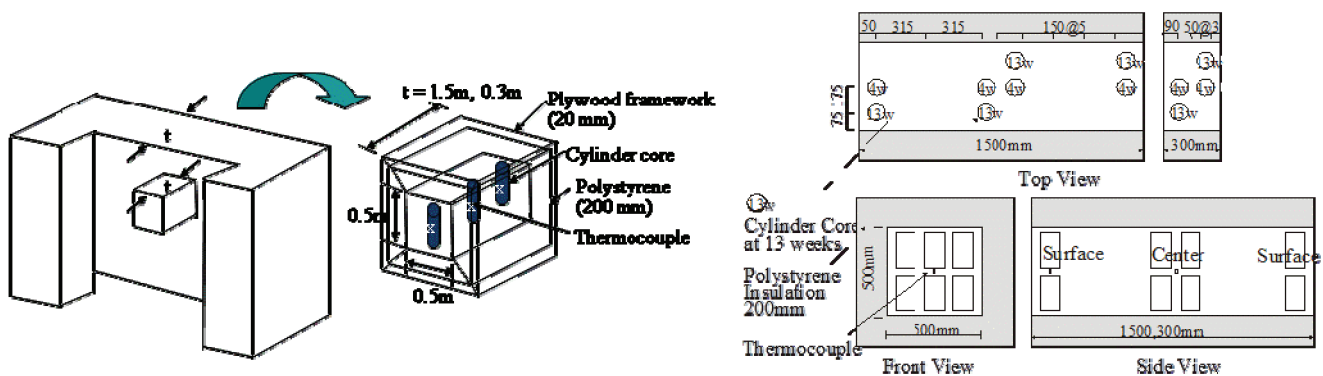

Figure 1. Model walls and position of tests.

were also examined by a differential scanning calorimeter (DSC). The total peak amount of pure AFt and CH measured by DSC were 819.64 and 1692.8, respectively. The porosity and pore size distribution were determined using mercury intrusion porosimetry (MIP). The pressure applied ranged from zero to 240 MPa. The 5 mm cubes for MIP measurements were also D-dried for about 2 weeks before testing.

3. RESULTS

The temperature histories in the concrete walls are shown in Figure 2. The maximum temperature at the center and the surface of the 1.5 m deep wall in summer (temp. 31 °C) were 94 °C and 74 °C, respectively. The maximum temperature was achieved at 22 hours and at 17 hours after casting, respectively. The maximum
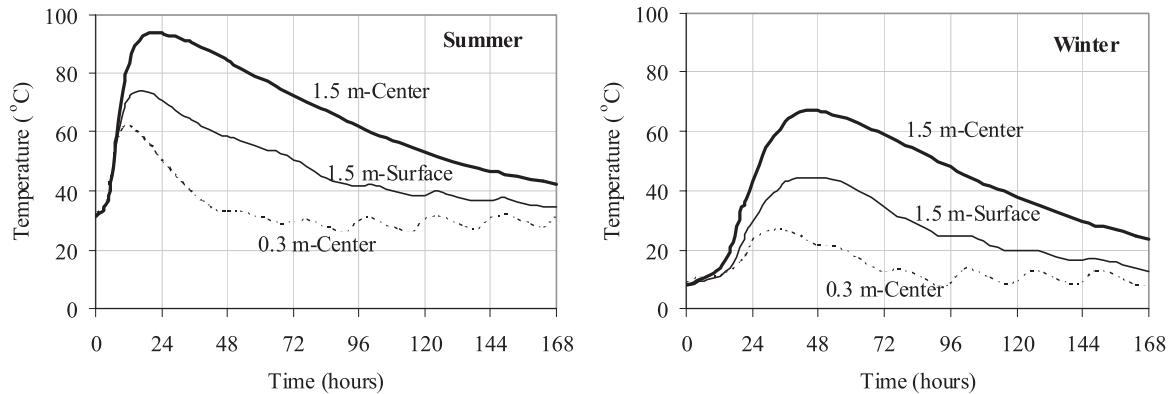
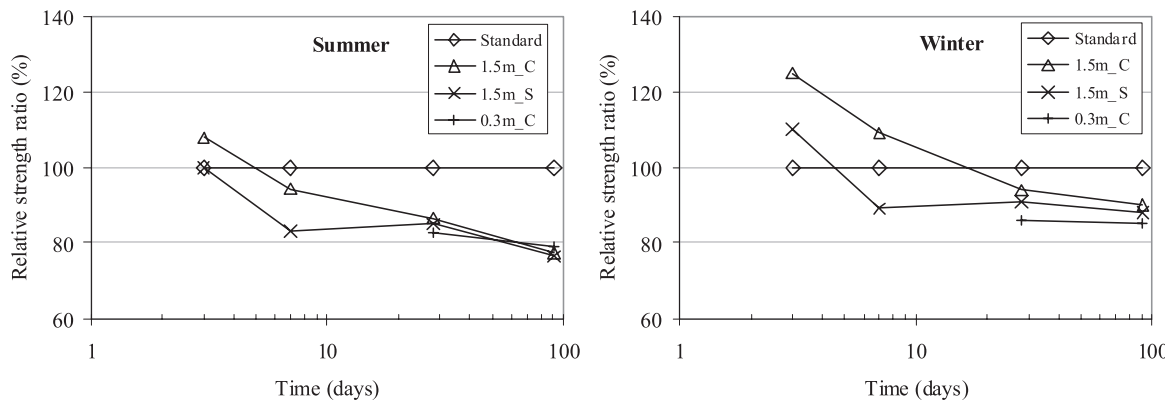Figure 2. Temperature history in model walls.

Figure 3. Effect of temperature on the compressive strength development.

Table 2. Compressive strength data

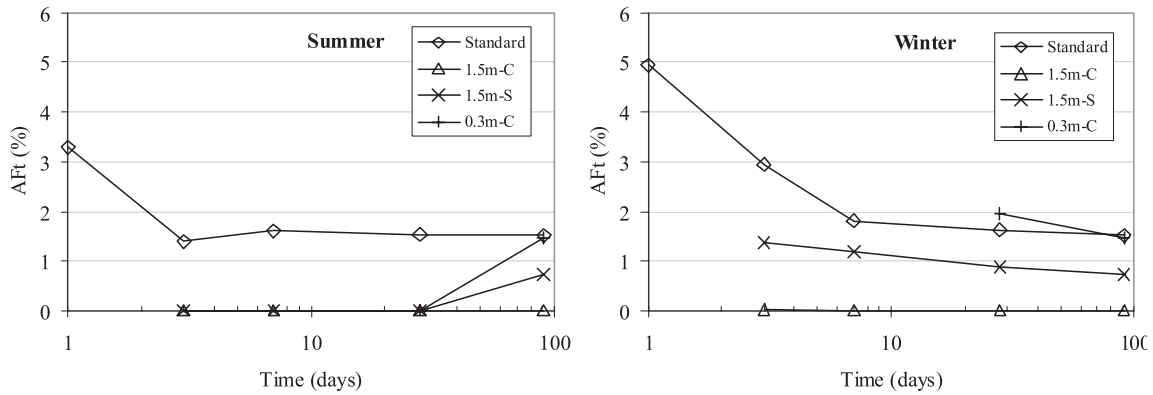|	Curing states	Compressive strength (MPa)			
		3 day	7 day	28 day	91 day
Summer	Standard	47.9	59.2	69.7	78.9
	1.5 m-Center	51.7	55.8	60.3	60.9
	1.5 m-Surface	47.0	49.2	59.2	60.3
	0.3 m-Center	-	-	57.8	62.6
Winter	Standard	51.4	65.5	78.8	82.4
	1.5 m-Center	64.0	71.7	73.7	74.0
	1.5 m-Surface	56.7	58.3	72.1	72.9
	0.3 m-Center	-	-	67.8	69.8

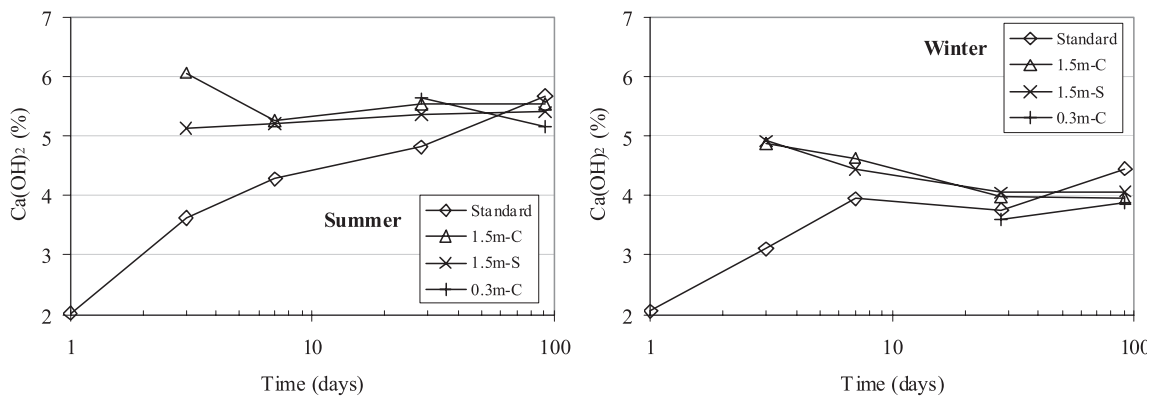Figure 4. Effect of temperature on the amount of ettringite in concrete.

Figure 5. Effect of temperature on the amount of calcium hydroxide in concrete.

temperature at the center of the 0.3 m deep wall was 62.5 °C at 12 hours after casting. Meanwhile, under winter condition (temp. 8 °C), the maximum temperature at the center and the surface of the 1.5 m wall were 67 °C at 43 hours and 44 °C at 41 hours, respectively. In case of 0.3 m deep wall the center maximum temperature was 26.7 °C at 34 hours. The outside weather conditions significantly affected the maximum peak temperature and retardation period.

The compressive strengths of core and standard specimens of concrete made under summer and winter weather conditions are listed in Table 2. The strength development of concrete made under winter weather conditions was faster than that of concrete made under summer conditions for the standard specimens. The compressive strength of the core specimen was higher than that of the standard specimen at early ages due to the higher temperatures attained in the core. However, the 1.5 m depth wall made under summer conditions behaved differently. In this sample, the elevated temperature did not affect the strength development at any age. The influence of temperature on the compressive strength can be clearly described in terms of a relative strength ratio defined against the strength of a standard specimen. Using this measure, Figure 3 shows the effect of temperature on all of the compressive strength data of concrete. As shown in Figure 3, the center of the 1.5 m deep wall made under summer conditions (max. temp. 94 °C) has a 3-day compressive strength which is 108 % of that cured

under standard conditions. By contrast, specimen from the surface of 1.5 m wall (max. temp. 74 °C) had a 3-day compressive strength which was 100 % of the standard. At 91 days, however, the strength ratios dropped to 77 % and 76 % of the standard respectively. The ages at which the compressive strength decreased below that of the standard specimen were 3-7day. Figure 3 also shows the results of compressive strength tests of concrete cured under winter weather conditions. The 3-day compressive strength at the center (max. temp. 67 °C) and the surface (max. temp. 44 C) of 1.5 m depth wall are 125 % and 110 % of that of concrete made under standard curing conditions respectively. At 91 days, however, the strength ratios were 90 % and 88 %, respectively. The strengths of winter cured concrete first fell below that of the standard sample at 7 days and after. The strength development of the core specimen made under summer weather conditions was not related to the maximum internal temperature at early ages. However, the high internal temperature of concrete made under winter weather conditions significantly increased the strength development at early ages.

Figure 4 shows the change in the amount of ettringite for the concrete produced under summer and winter weather conditions. The amount of ettringite in the standard specimen decreases with the time. However, for core specimens that experienced higher initial temperatures, there are no ettringite found at age up to 28 days. The ettringite was found at age older than 28 days which might be explained by the secondary ettringite formation.

The change in the amount of calcium hydroxide is shown in Figure 5. The amount of calcium hydroxide in the core specimen is higher than that of the standard specimen because it is directly related to the degree of hydration. In a mass structure, the higher temperature leads to an increase in the degree of hydration. However, no significant difference in calcium hydroxide content was found in any of the core specimens at long-term ages. The winter weather condition reduces the amount of the calcium hydroxide due to.

Figure 6 shows the porosity results as determined by MIP. The total porosity of the samples at center of the 1.5 m deep wall cured under summer conditions was 2.3 % less than that of the standard specimen at 3 days. After 7 days, however, the total porosity of the core specimens began to increase with increased concrete temperature. The total porosity of the center specimens was higher than that of the surface specimens in summer weather conditions. The total porosity of concrete made under winter conditions was smaller than that of concrete made under summer conditions. In particular for core samples, the amount of larger pores, greater than 100 nm, was remarkably reduced when compared with summer cured samples.
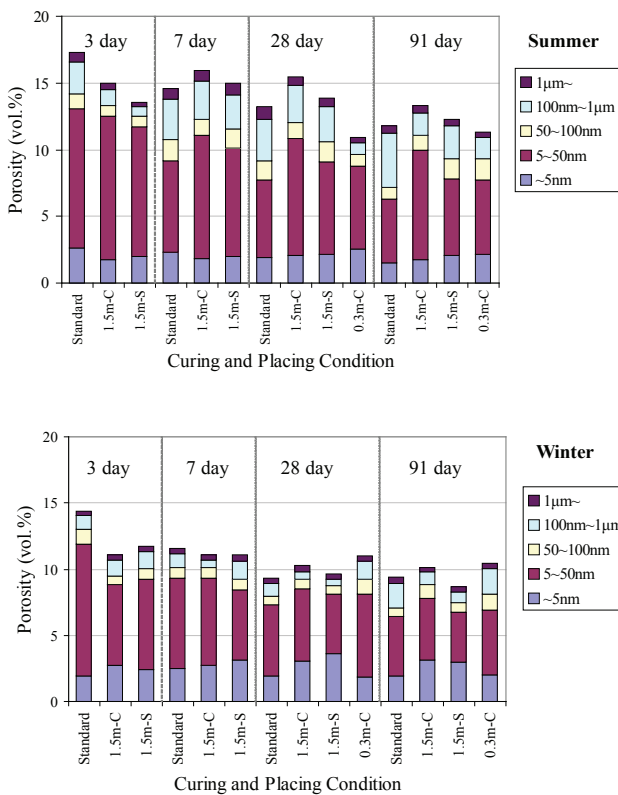

Figure 6. Effect of temperature on total porosity.

As shown in Figure 7, the pore size distribution also changed as the concrete temperature increased. With an increase in temperature, the number of larger pores decreased and the number of smaller pores increased particularly for pores in a size range between 5 and 50 nm as measured by MIP. This suggests that as the hydration process proceeds, the pore sizes are reduced and the peak of the distribution curve shifts toward smaller pores.
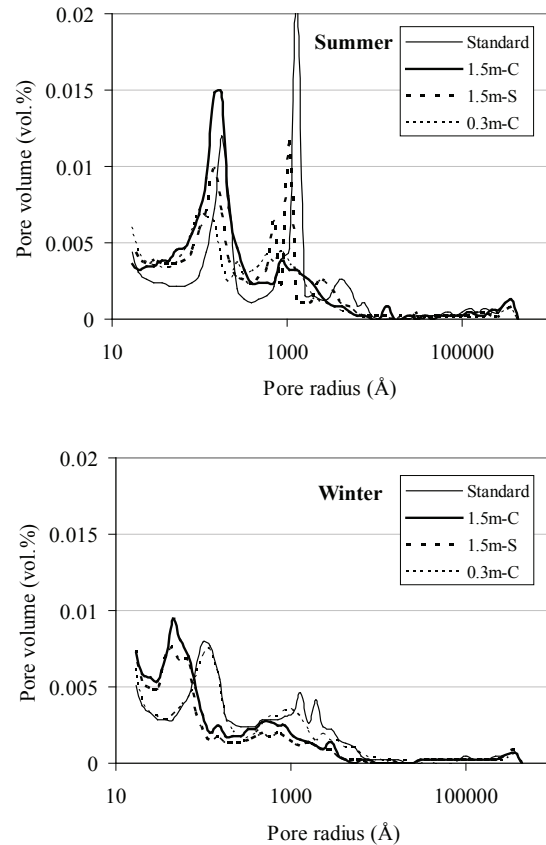

Figure 7. Effect of temperature on the pore size distribution in 91-day concrete.

4. DISCUSSION

We usually expect that a higher curing temperature leads to an increase in the early age strength because strength development comes from the hydration reaction. A fast hydration of cement from high curing temperatures will results in a high early strength due to more hydration products being formed. However, in the summer experiment with high strength concrete, the high internal temperature at early ages does not significantly affect the strength development. However, in case of a relatively lower mix and place temperature, the high internal temperature leads to an increase in the strength development at early ages. Klieger (1958) and Khoury (1992) reported that for a given mix proportion, an increasing the initial and curing temperatures result in considerably lower strength at long-term ages. Similar results are shown in Figure 3. At long-term ages, the retardation in hydration as a result of a dense shell around the hydrating cement grains will result in a more porous structure and reduced strength. Kjellsen et al. (1990) support the concept that a dense shell around the hydrating cement grains is formed at higher curing temperatures. Verbeck and Helmuth (1968) theorized that the products of cement hydration have low solubility and diffusivity at high curing temperatures, the rapid hydration does not allow for ample time for the products to diffuse within the voids between the cement grains. This results in a high concentration of hydration products in a zone immediately surrounding the grains. This forms a relatively impermeable rim around the cement grains, which subsequently retards any subsequent hydration.

However, one interesting observation is that in summer experiments, the amount of reduction of strength at 91-day was not changed by the initial internal temperature of concrete. Rostasy et al. (1980) explained about that the long-term strength decreases with increasing curing temperature even when the effects of other related factors, such as self desiccation, are precluded. Various researchers attempted to explain that with physical and chemical transformations in concrete. On the other hand in many cases of damages on heat treated concrete units a connection with secondary ettringite formation has been suggested. Siedel et al. (1993) has examined that the effect of high temperature on secondary ettringite formation. Re-formation of that ettringite in the hardened cement or concrete structure may lead to pressure of crystallization and to expansion if not enough space is provided for the products of the reaction. Ettringite can decrease the long-term strength. As shown in Figure 4, the secondary ettringite at center of the 1.5 m deep wall cured under summer conditions was found at age older than 28 days. Additionally, the elevated curing temperatures result in the progress of calcium hydroxide at early ages in Figure 5. Carde and Francois (1999) reported that the total leaching of massive crystals of the calcium hydroxide creates a macroporosity (capillary porosity) which has a great effect on the loss of strength. Kjellsen et al. (1990) also found that increases in curing temperature resulted in increased porosity, particularly for pores of radius 200-1000Å as measured by mercury intrusion, as see in Figure 7. This result also indicates the formation of larger pores at elevated curing temperatures and has significant implications for the strength development of the concrete.

5. CONCLUSION

The structural member size, and the curing climate was shown to significantly affect the initial internal temperature of mass concrete structures. Elevated temperatures did not affect the early age strength gain of concrete cured under summer weather conditions, but the concrete cured under winter weather conditions showed a significant increase in early age strength development. However, the elevated high temperatures result in long-term strength loss for all specimens.

The amount of ettringite in the standard specimen decreases with the time. However, for core specimens that experienced higher initial temperatures, there are no ettringite found at age up to 28 days. The secondary ettringite was found at age older than 28 days. Re-formation of that ettringite results in considerably lower strength at long-term ages.

The amount of calcium hydroxide of the core specimen cured at high elevated temperature was larger than that of the standard specimen at early ages.

Due to the elevated internal temperatures in the structures, the peak of the pore size distribution curve was shifted toward the direction of smaller pores and the number of smaller pores was increased.

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