COMPARISON OF DIFFERENT CURING METHODS FOR HIGH-PERFORMANCE CONCRETE AND THE EFFECTS ON STRENGTH AND DURABILITY

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ABSTRACT

As a part of a larger study, the effects of different humidity and temperature conditions during curing of high-performance concrete on compressive strength and selective durability properties were compared. Cylinders from three high-performance concrete mixtures and a control mixture were prepared. The cylinders from each mixture were divided into four groups. The following curing conditions were evaluated: standard moist curing, moist curing for three days followed by curing at 50 % relative humidity, temperature-match-curing for the first day followed by moist curing, and curing in sealed plastic molds.

Results from compressive strength and electrical indication of concrete's ability to resist chloride ion penetration tests indicate that curing concrete at 50 % relative humidity compromises compressive strength development and resistance to chloride ion penetration. Curing the specimens in sealed forms from the time they were cast until they were tested yielded results that were comparable to those obtained from continuously moist cured specimens. Accelerated curing of specimens for electrical indication of concrete's ability to resist chloride ion penetration appeared to be a valid method for obtaining 28-day results that are comparable to those obtained after 91 days.

Keywords: Temperature-Match-Curing, High-Performance Concrete, Curing, Compressive Strength, Chlorides

INTRODUCTION

Standard curing of concrete test specimens normally involves moist curing such that free moisture is present on the surfaces of the specimens until they are tested. However, even under such favorable curing conditions, the low water content and porosity of high-performance concretes will leave a portion of the cement unhydrated. By continuously supplying free moisture to the specimens, absorption of water may allow the cement hydration to proceed further than would be expected for the field cured structural concrete the specimens represent. Aïtcin[1] suggested that sealing the specimens in plastic, therefore eliminating the need for moist curing, will perhaps best simulate the moisture conditions of the structural concrete.

Diffusion is generally accepted as the primary process for chloride ion transport in concrete. Given the time and effort required to measure the effective diffusion coefficient for concrete by using a ponding test such as AASHTO T 259, a rapid test, first proposed by Whiting[2], requiring considerable less effort and time has been well received and widely adopted. This test, later adopted as AASHTO T 277 and ASTM C 1202, is used to subject 51 mm (2in.) thick concrete discs to a potential of 60 V DC for six hours. Based on the charge passed through the specimen during the six-hour test, in coulombs, the resistance of the concrete to chloride ion penetration can be evaluated.

When supplementary cementitious materials are used in concrete, the time required for the concrete to refine its pore structure may be increased. Therefore, performing the ASTM C 1202 test at the age of 28 days may yield considerably higher values than would be expected at the age of 90 days or more. In an attempt to reduce the curing time required to obtain ASTM C 1202 results that resemble those of mature concrete, the Virginia Department of Transportation (VDOT) has devised an accelerated curing procedure.[3] This procedure involves one week of moist curing at room temperature and three weeks in saturated lime water at 38ºC (100ºF) before the specimens are tested.

In high performance concrete (HPC) mixtures, the cementitious materials content is often high. A high cementitious materials content may lead to excessive rise in temperature of concrete members during the initial phase of the hydration process. Sellevold[4] stated the temperature of HPC could reach 80 to 90ºC (176 to 194ºF). At curing temperature above 60 to 70ºC (140 to 158ºF), the durability characteristics of the concrete can be adversely affected[5] and the 28-day compressive strength may be reduced by 10 % or more.[6]

EXPERIMENTAL

Three high-performance concrete (HPC) mixtures and one control mixture were batched at a ready-mix plant and then mixed and delivered by front-discharge ready-mix trucks. All of the mixtures contained the same Type I cement. Two of the HPC mixtures contained 6.5 and 8 % silica fume (SF) while the third HPC mixture contained 5 % silica fume and 30 % ground granulated blast furnace slag (GGBFS). Slump, density, and air content were measured once the trucks arrived at the testing site. Chemical analyses of the cementitious materials are given in Table 1 and mixture proportions and fresh concrete properties of the four mixtures are listed in Table 2.

Table 1. Chemical analyses of the cement, silica fume, and ground granulated blast furnace slag.

	Type I Cement	Silica fume	GGBFS
Chemical analyses by mass (%)			
Silicon dioxide (SiO_2)	20.16	93.07	37.73
Aluminum oxide (Al_2O_3)	4.87	0.62	7.75
Ferric oxide (Fe_2O_3)	2.92	0.41	0.39
Calcium oxide (CaO)	64.55	0.66	39.45
Magnesium oxide (MgO)	2.43	1.16	10.77
Sodium oxide (Na_2O)	0.28	0.16	0.35
Potassium oxide (K_2O)	0.09	0.79	0.29
Sulfur trioxide (SO_3)	2.55	<0.01	2.59
Titanium dioxide (TiO_2)	0.46	<0.01	0.84
Phosphorus pentoxide (P_2O_5)	0.07	0.10	<0.01
Manganic oxide (Mn_2O_3)	0.05	0.06	0.50
Strontium oxice (SrO)	0.06	<0.01	0.04
Chromic oxide (Cr_2O_3)	0.02	0.02	<0.01
Zinc oxide (ZnO)	0.03	0.10	<0.01
Loss on ignition (950°C)	1.45	2.71	-0.82
Total	99.99	99.85	99.89
Alkalies as Na_2O	0.34	0.67	0.55
Calculated potential compounds as per ASTM C 150-00 (%)			
Tricalcium silicate (C_3S)	65		
Dicalcium silicate (C_2S)	8		
Tricalcium aluminate (C_3A)	8		
Tetracalcium aluminoferrite (C_4AF)	9		

Table 2. Mixture proportions and fresh concrete properties.

Mixture ID	F-1 (Control)	F-2	F-3	F-4
(%C-%S-%SF)	100C	93.5C-6.5SF	65C-30S-5SF	92C-8SF
Cement (kg/m^3 (lb/yd^3))	389 (655)	403 (680)	279 (470)	395 (665)
Silica fume (kg/m^3 (lb/yd^3))		28 (47)	21 (36)	34 (58)
GGBFS (kg/m^3 (lb/yd^3))			129 (218)	
Total binder cont. (kg/m^3 (lb/yd^3))	389 (655)	431 (727)	430 (724)	429 (723)
Water (kg/m^3 (lb/yd^3))	154 (260)	154 (259)	165 (277)	159 (268)
Water-binder ratio	0.397	0.356	0.383	0.370
Coarse agg. (kg/m^3 (lb/yd^3))	1026 (1730)	1026 (1730)	1020 (1720)	1020 (1720)
Fine agg. (kg/m^3 (lb/yd^3))	736 (1240)	694 (1170)	659 (1110)	664 (1120)
HRWR (mL/L (oz/cwt))		593 (9.1)	619 (9.5)	828 (12.7)
NRWR/Ret. (mL/L (oz/cwt))	130 (2.0)	196 (3.0)	196 (3.0)	196 (3.0)
AEA (mL/L (oz/cwt))	85 (1.30)	173 (2.65)	231 (3.54)	194 (2.97)
Slump (mm (in.))	140 (5.5)	203 (8)	191 (7.5)	140 (5.5)
Air content (%)	6.6	6.6	7.0	8.0
Density (kg/m^3 (lb/yd^3))	2323 (145.0)	2299 (143.5)	2287 (142.8)	2297 (143.4)

Fifty 102 by 203 mm (4 by 8 in.) compressive strength cylinders and seven 97 by 203 mm (3.8 by 8 in.) cylinders for determination of electrical indication of chloride ion penetration resistance were prepared and tested from each of the four mixtures. The compressive strength cylinders were cured under the following four different curing conditions:

1. Standard – moist cured at room temperature after being demolded at the age of one day.
2. Sealed – stored in sealed plastic forms at room temperature until placed in saturated limewater 24 hours prior to testing.
3. 50 % RH – cured as the standard cylinders (no. 1) for the first three days, then at 50 % relative humidity (RH) and room temperature until placed in saturated limewater 24 hours prior to testing.
4. TMC – temperature-match-cured for the first 24 hours, then moist cured with the standard cylinders (no. 1) until tested.

The reference temperature for the temperature-match-curing was obtained by monitoring the temperature development of 5.5 liters (335 in.^{3}) of concrete that was placed inside an insulated box at the time the cylinders were made. The concrete temperature inside the box was continuously monitored and the information was used to simultaneously temperature-match-cure the cylinders by adjusting the temperature of their enclosure so their temperature matched the temperature of the insulated concrete. The temperature development of the four mixtures during the first 26 hours after casting is shown in Figure 1.

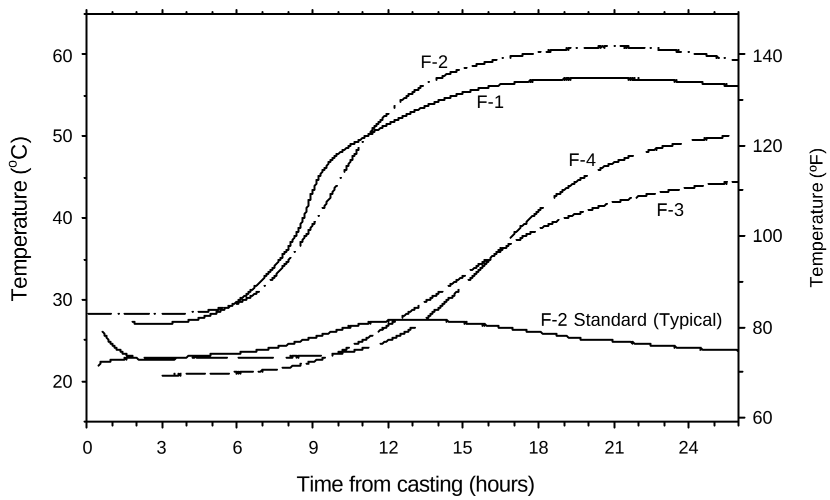

Figure 1. Temperature development of the four mixtures during the first 26 hours after casting. The temperature development of one set of standard cylinders is shown for comparison.

Two 51 mm (2 in.) thick discs were cut from each of the cylinders for electrical indication of chloride penetration resistance and tested at ages of 28 or 91 days. The compressive strength cylinders were tested 1, 3, 7, 14, 28, 56, 91, and 180 days after casting.

ELECTRICAL INDICATION OF CHLORIDE ION PENETRATION RESISTANCE

Electrical indication of chloride ion penetration resistance of the concrete was determined for all four mixtures at the ages of 28 and 91 days. At both ages, standard, 50 % RH, and sealed specimens were tested. In addition, specimens moist cured for seven days and then cured in water bath at 38°C (100°F) for an additional 21 days were tested at the age of 28 days. Two specimens from each mixture, both obtained from the same cylinder, were tested at each test date. The average charge passed for each mixture after 28 days of curing is shown in Figure 2 and after 91 days of curing in Figure 3. For comparison, the 28-day results from the specimens cured at 38°C (100°F) are also included in Figure 3 as this curing regime was developed to predict the charge passed for fully matured specimens.

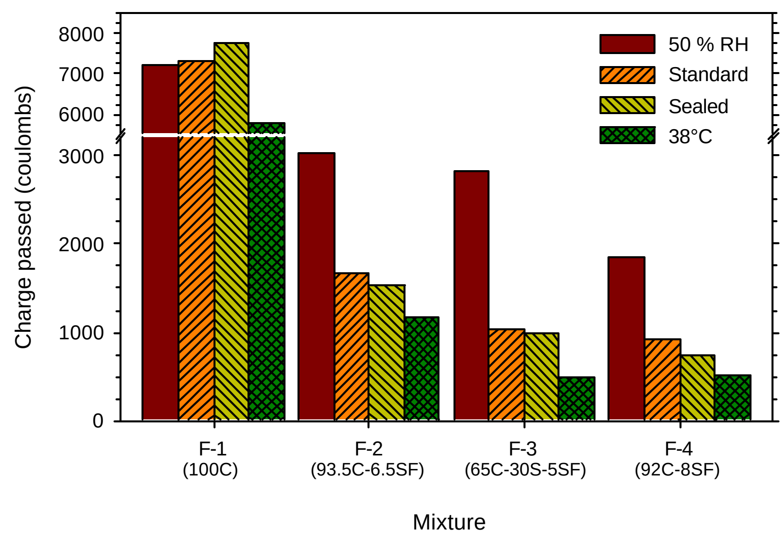

Figure 2. Charged passed after 28 days of curing.

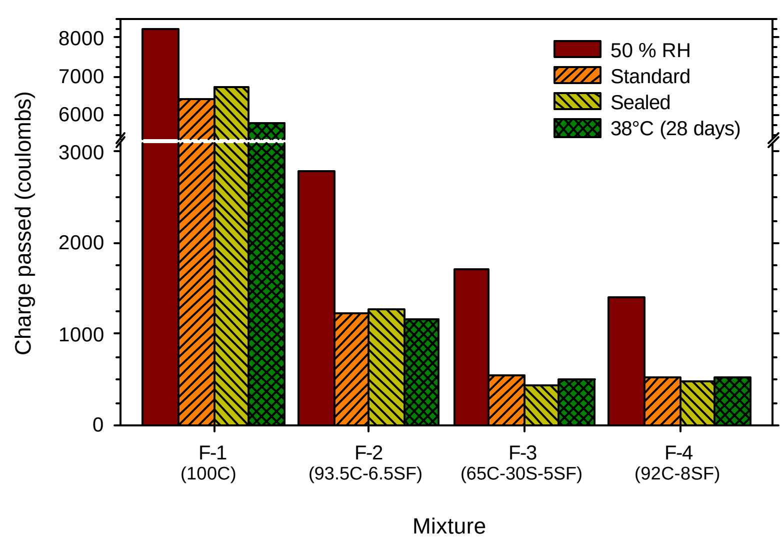

Figure 3. Charge passed after 91 days of curing. Results from specimens moist cured at room temperature for one week and then in water bath at 38ºC (100°F) for three weeks are included for reference.

The difference in the charge passed between specimens from mixture F-1 (control) and the other mixtures was considerable as F-1 was the only mixture without supplementary cementitious materials. The charge passed for specimens continuously moist cured for 28 days (standard) ranged from 910 coulombs for F-4 to 7330 coulombs for F-1. Corresponding values after 91 days of curing were 520 and 6430 coulombs. After 91 days of moist curing, the charge passed for specimens from F-3 was 560 coulombs and for specimens from F-2, it was 1230 coulombs.

In general, the charge passed measured at 91 days was lower than that measured at 28 days. The only exception was for specimens from F-1 cured at 50 % RH where a moderate increase was observed.

COMPRESSIVE STRENGTH DEVELOPMENT

The compressive strength development of specimens from all four curing regimes from all mixtures is provided in Figures 4 to 7. The compressive strength increase beyond 14 days for specimens cured at 50 % RH was limited. This corresponds well with the results of the electrical indication of chloride ion penetration resistance tests reported in the previous section where the specimens cured at 50 % RH had higher coulomb values than the other specimens. Those results also signify the importance of adequate moist curing to ensure proper hydration and development of optimum strength and durability characteristics of the concrete.

In Figure 8, compressive strength of cylinders cured at 50 % RH from the age of three days and cylinders sealed in their forms are shown as a percentage of the compressive strength of the standard cylinders. At the age of 28 days, the agreement between the results of the sealed cylinders and control cylinders was good. The relative strength of the sealed cylinders ranged from 96.1 (F-3) to 101.2 % (F-2). However, results from cylinders cured at 50 % RH did not compare as well. Corresponding values for those cylinders ranged from 71.2 (F-3) to 83.5 % (F-1).

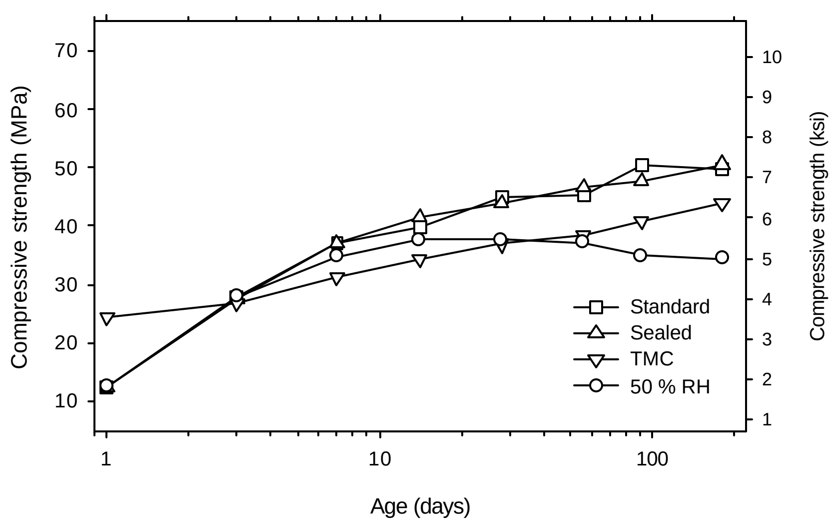

Figure 4. Compressive strength development of specimens from F-1 (100C).

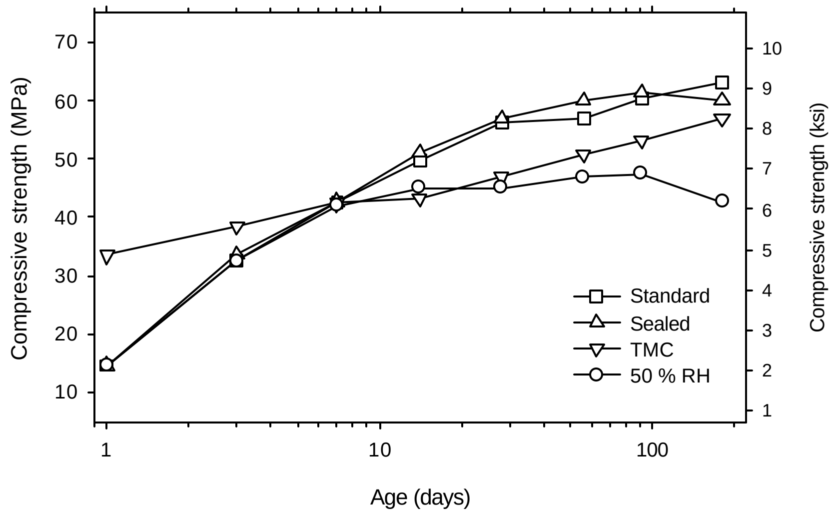

Figure 5. Compressive strength development of specimens from F-2 (93.5C-6.5SF).

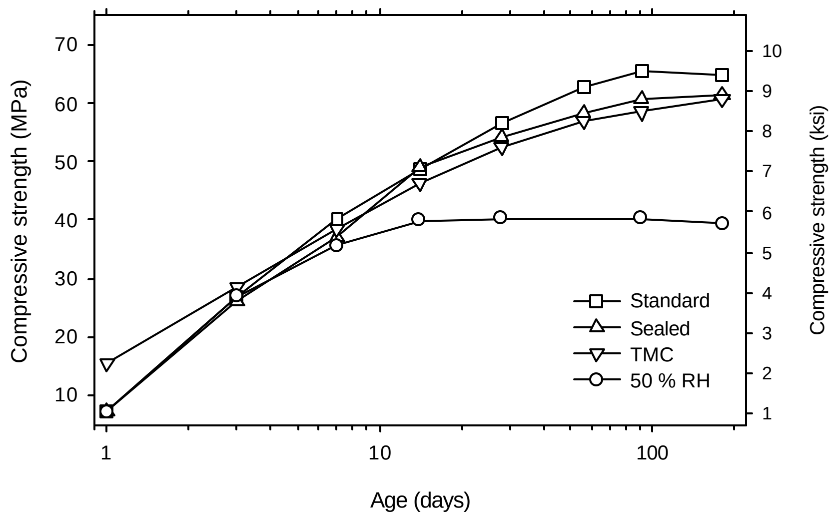

Figure 6. Compressive strength development of specimens from F-3 (65C-30S-5SF).

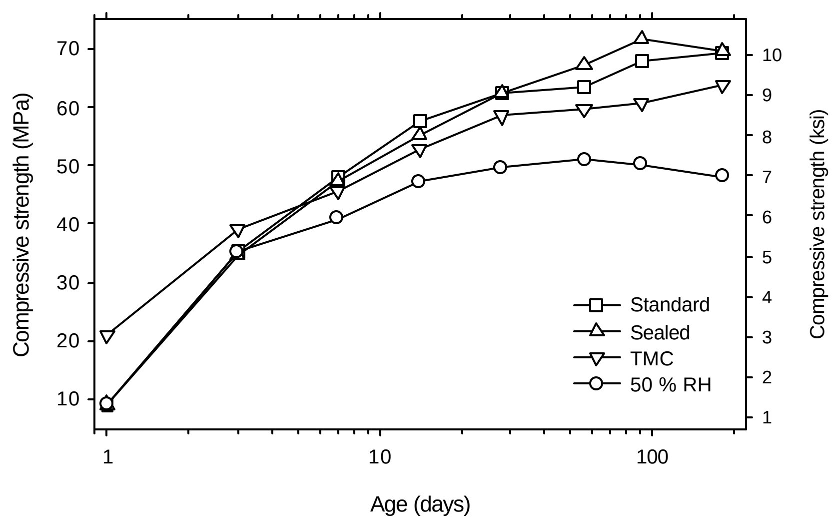

Figure 7. Compressive strength development of specimens from F-4 (92C-8SF).

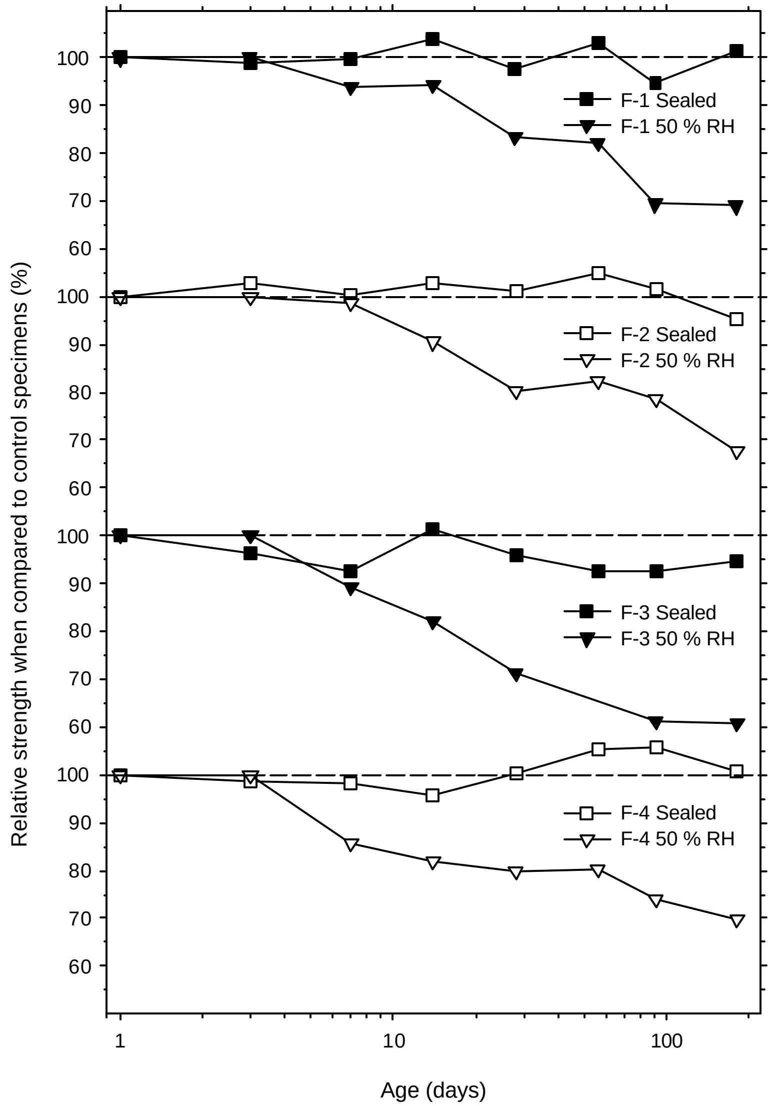

Figure 8. Relative compressive strength of different specimens from the four mixtures when compared to standard specimens. Specimens stored sealed or at 50 % RH were placed in saturated limewater 24 hours before being tested.

DISCUSSION

Moist curing the specimens for seven days and then curing them in water at 38°C (100°F) until tested at 28 days appears to be a reasonable method of predicting ASTM C 1202 charge passed values for standard specimens when tested at the age of 91 days. In all cases, the predicted values were slightly lower than the actual values. The difference ranged from 0.7 to 10.1 %. Granted, the curing regime is intended for predicting the charge passed for fully matured concrete and it is likely that values obtained at ages higher than 91 days will be lower than those obtained after only 91 days.

Curing the HPC specimens sealed in their plastic molds yielded results similar to those obtained from specimens that were cured under standard conditions and tested in accordance with ASTM C 1202. The effect of free moisture on the surfaces of the standard specimens did therefore not appear to be significant. Curing the specimens sealed in their molds instead of curing them under standard conditions appears to be a satisfactory option when the electrical indication of concrete's ability to resist chloride ion penetration is to be determined.

Limiting the moist curing to only three days, followed with curing at 50 % RH, generally increased the charge passed significantly when compared with results from all other specimens. The only result that didn't follow this trend was for F-1 (control). In terms of expected resistance to chloride ion penetration, it appears essential to extend the moist curing beyond three days. The lowest value after 91 days was 1400 coulombs for F-4. The corresponding value for continuously moist cured specimens was 520 coulombs.

Based on an equation given by Berke and Hicks[7] to calculate the effective diffusion coefficient, D_{eff}, from charge passed values, D_{eff} corresponding to 520 and 1400 coulombs is $2.0 \cdot 10^{-12}$ and $4.5 \cdot 10^{-12}$ m^2/s, respectively. Using Fick's second law and assuming that diffusion is the primary process for chloride ion transport in concrete, an increase in D_{eff} from $2.0 \cdot 10^{-12}$ to $4.5 \cdot 10^{-12}$ m^2/s will reduce the time to corrosion of steel reinforcement by approximately 50 %. If these findings hold true for bridge decks and other structures exposed to chloride ions, the cost of proper moist curing will appear low when evaluated in terms of potential benefits.

Based on the results presented in this paper, it appears acceptable to cure cylinders sealed in their forms for determination of 28-day strengths. However, providing only three days of moist curing followed with curing at 50 % RH results in considerable reduction in compressive strengths. For cylinders cured at 50 % RH, the 28-day compressive strength was reduced by approximately 20 % and the 180-day compressive strength by 30 to 40 % when compared to standard cylinders. How closely this finding relates to in-place concrete is unclear. Another research project is perhaps needed to evaluate the effects of different curing conditions on structural members of varying thicknesses.

Although the maximum curing temperatures of the TMC specimens can be considered moderate, the difference in compressive strength of TMC compared with standard specimens was considerable. The one-day increase in compressive strength of TMC specimens ranged from 94 (F-1) to 130 % (F-2 and F-4). Where early strengths are important to maintaining constructions schedules, TMC compressive strength specimens may be a viable option. However, the 28-day compressive strengths of the TMC cylinders were always lower than the compressive strengths of the standard cylinders. The reduction ranged from 6 (F-4) to 18 % (F-1).

CONCLUSIONS

Different temperature and humidity conditions during curing of HPC test specimens influence compressive strength and durability developments. Based on the results of this study, limiting the moist curing to three days may reduce the 28-day compressive strength by approximately 20 % and the 180-day compressive strength by 30 to 40 %. Furthermore, limited moist curing also compromises the concrete's resistance to the ingress of chloride ions and the time to corrosion may be reduced by approximately 50 %.

The accelerated curing method proposed by VDOT[3] for ASTM C 1202 HPC specimens yielded results after only 28 days of curing that compared well to results obtained after 91 days of standard curing. Although further research may be necessary, the method appears to provide an alternative to waiting 91 days to test ASTM C 1202 HPC specimens.

Maximum curing temperatures of around 60°C (140°F) or less are sufficient to increase the one-day compressive strength of TMC cylinders by approximately 100 %. However, despite high one-day strengths of TMC cylinders, their 28-day compressive strengths can be expected to be lower than the compressive strength of standard cylinders.

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