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Testing of High Volume Fly Ash Concrete for Freezing and Thawing Durability - Kingsford Dam

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BACKGROUND

High-volume fly ash concrete was specified and used at the Wisconsin Electric Power Company's Kingsford Dam for rehabilitation. This dam is located near Kingsford, Michigan. Extensive technical information exists for mechanical properties of high-volume fly ash (HVFA) concrete. However, there is a lack of test data for freezing and thawing (F&T) durability of concrete produced in the field. This project was authorized by the Wisconsin Electric Power Company to obtain freezing and thawing durability data for the HVFA concrete used for the repairs and rehabilitation of the Kingsford Dam. The concrete mixture used for this project contained 54% fly ash by weight of the total cementitious materials. Test data and evaluation provided in this report should further augment the knowledge needed to promote the use of high-volume fly ash concrete. The analysis and recommendations presented in this report are based upon the F&T laboratory tests completed at the University of Wisconsin-Milwaukee Center for By-Products Utilization and additional data supplied to UWM-CBU by the Wisconsin Electric Power Company. Test results show that HVFA concrete tested has a very high resistance against freezing and thawing exposure.

SCOPE OF WORK

The work completed for this project included the following:

- Testing of concrete specimens for freezing and thawing durability per ASTM C 666, Procedure A
  - Test for the fundamental transverse frequency every 30 freezing and thawing cycles
  - Determination of the relative dynamic modulus every 30 cycles
- Test for changes in the density of concrete for the duration of the freezing and thawing test, every 30 cycles
- Test for pulse velocity of concrete every 30 cycles*
- Test for flexural strength of concrete at the start and conclusion of the freezing and thawing test*
- Test for compressive strength of concrete at the conclusion of the freezing and thawing test*

* Tests not required per ASTM or WEPCO, but run to obtain a more complete set of data

CONCRETE MIXTURE PROPORTIONS

The concrete mixture proportions used for the dam repairs is reported in Table 1. ASTM Class C fly ash was used in the concrete mixture. The amount of fly ash used in the mixture was 54% by weight of the total cementitious content. Therefore, such concrete is generally called high-volume fly ash (HVFA) concrete. The water to cementitious materials ratio used for the mixture was 0.49. This is higher than that recommended by ACI 201 (which is 0.45 or less). Air entraining and water reducing admixtures were used for the concrete mixture. The amount of air reported in the mixture was 4.1% by volume.

TEST PROCEDURES AND RESULTS

Test Specimens

The size of the test specimens specified for testing by ASTM C 666 required that the test specimens be cut prior to any F&T testing following the ASTM C 666, Procedure A. The six test specimens received from WEPCO were approximately 6"x6"x21". These specimens were cut to the size required by ASTM, 3"x4"x10-1/2". The length of the test specimens were reduced slightly from the maximum length specified by ASTM (10-1/2" cut length vs. 16" specified) so that additional test specimens would be available for further testing and evaluation. A total of 12 specimens were used for this project. Six specimens were subjected to freezing and thawing, three specimens moist cured for the duration of the project (control), and three specimens tested in flexure at the start of the F&T test.

Freezing and Thawing

In order to determine the effect of freezing and thawing on the concrete, two different curing environments were used. One group of test specimens were moist cured in a 100% relative humidity room at 72°F for the duration of the freezing and thawing tests. These specimens were designated as "control". Three control specimens were tested for changes in density, pulse velocity, and frequency, each time freezing and thawing tests were performed (at the frequency of every 30 F&T cycles). These three test specimens were designated as control (moist cured until the time of test) were tested in flexure at the start of the freezing and thawing cycles. Six specimens subjected to F&T cycles were tested every 30 freezing and thawing cycles. Figure 1 shows the test specimens undergoing rapid freezing and thawing cycles in an automatic ASTM standard F&T machine. A visual evaluation of the test specimens subjected to freezing and thawing was also conducted every 30 cycles. Photographs of the specimens were taken for comparison of the control specimens with specimens subjected to freezing and thawing, Figure 2 to 6.

Flexural Strength

Flexural strength of the concrete was measured in accordance with ASTM C 78 at the start and completion of the freezing and thawing tests. Three control specimens were tested at the start of the freezing and thawing cycles and three additional (control) specimens were tested at the conclusion of the freezing and thawing cycles. Six specimens subjected to freezing and thawing cycles were tested in flexure at the end of 300 cycles of F&T.

Pulse Velocity

In addition to these tests, UWM-CBU conducted additional tests that were neither a part of the original WEPCO specified scope of work nor required by ASTM C 666. Pulse velocity tests were conducted every 30 freezing and thawing cycles on the six test specimens undergoing F&T cycles. Pulse velocity of the concrete was measured following ASTM C 597. Three control specimens were also tested for pulse velocity at the same time as that for the freezing and thawing specimens.

Compressive Strength

Compressive strength for concrete cylinders were reported by Collman Engineering Company, Iron Mountain, MI at the ages of 3, 7, 28, 56, and 90 days. Compressive strength of the concrete beam specimens were also measured using portions of the beam broken in flexure as part of this test program. These compressive strength measurements (modified cube compressive strength) followed the procedure of ASTM C 166. The modified cube compressive strength was measured at the start and conclusion of the freezing and thawing cycles. A total of three specimens were tested at the start of the freezing and thawing cycles and nine specimens were tested at the conclusion of F&T testing (consisting of six specimens subjected to freezing and thawing cycles and three control specimens).

RESULTS

Compressive Strength

The compressive strength data for the concrete mixture are shown in Table 2. These results were reported by WEPCO to UWM-CBU. The compressive strength of the concrete increased with increasing age, as expected. The mixture attained a compressive strength of 5,395 psi at the age of 28 days, and showed about 17% increase in the strength at the age of 90 days, 6,315 psi. This increase in strength can be attributed to the pozzolanic reaction of the fly ash.

Freezing and Thawing

The freezing and thawing resistance data are given in Table 3 to 6 and Figure 7 and 8. The change in mass and density for test specimens subjected to freezing and thawing and for control specimens (moist cured throughout the duration of the freezing and thawing tests) are given in Table 3 and 4, and Figure 7. The data show a sight decrease in the mass of the specimens and a corresponding increase in the density of the concrete. These changes are due to the paste of the formed concrete surfaces flaking off during the freezing and thawing tests. The paste fraction has a lower density than the aggregate, thus, the density should increase slightly while the mass of the test specimens decrease.

The data for the transverse frequency and relative dynamic modulus for the specimens subjected to freezing and thawing and the control specimens are shown in Table 5 and 6 and Figure 8. The relative dynamic modulus for the test specimens (also referred to as the durability factor) was approximately 90% at 300 cycles of freezing and thawing. The relative dynamic modulus of concrete that is greater that 60% is considered to have very good resistance to freezing and thawing degradation. The relative dynamic modulus of the control specimens increased by approximately two percent. This was expected since the continued moist curing of the specimens does increase strength and improve the microstructure of the concrete.

Flexural Strength

The flexural strength test data are given in Table 7. They were determined at the age of nine months (before the start of freezing and thawing cycles) and after completion of the freezing and thawing cycling (for both control specimens and those subjected to freezing and thawing). The flexural strength decreased by approximately 33% (890 psi for control specimens to 595 psi after 300 cycles of freezing and thawing). This decrease in flexural strength can be directly attributed to the physical deterioration of the specimens due to freezing and thawing.

Pulse Velocity

Pulse velocity data for the specimens subjected to freezing and thawing as well as the control specimens are given in Table 8 and 9 and Figure 9. The pulse velocity of the test specimens decreased by approximately 4% for specimens subjected to F&T. However, the control specimens gained by about one percent at the same age. The decrease in pulse velocity of the specimens subjected to freezing and thawing can be attributed to micro-cracking of the tests specimens.

Compressive Strength of Concrete Using Beams Broken in Flexure

The compressive strength of the concrete is shown in Table 10. This test data represents modified cube strength of concrete (not cylinder or core strength). This test data was determined at the age of nine months (before the start of freezing and thawing testing) and after completion of the freezing and thawing cycling (for both control specimens and those subjected to freezing and thawing). The compressive strength of the concrete decreased by approximately 16% (5855 psi for control specimens to 4935 psi after subjecting to freezing and thawing). The decrease in compressive strength is believed to be due to the micro-cracking of the specimens due to freezing and thawing.

Visual Inspection of the Test Specimens

Specimens were also inspected at the conclusion of the freezing and thawing cycling. Test specimens were cut from the cast beam specimens submitted to UWM-CBU. The test specimens, therefore, had both cut surfaces and the as-cast surface with the exterior paste intact. Figure 2 shows the cast surface of the control specimens. The paste of the control specimens is intact with no scaling of the surface. Figure 3 shows both cut surfaces and the cast surface of the control specimens. Figures 4, 5, and 6 show the condition of the cut surfaces of the control specimens.

Figures 10 to 13 show the condition of the test specimens subjected to 330 freezing and thawing cycles. Figures 10 and 11 show the condition of the cast surfaces of the specimens. These specimens exhibited extensive scaling of the paste surface compared with the initial condition of the specimens (Figure 3 and 4). The cut surfaces of the specimens subjected to freezing and thawing are shown in Figures 12 and 13. These specimens had very little surface deterioration compared with the initial condition of specimens (Figures 5 and 6).

CONCLUSIONS / RECOMMENDATIONS

The concrete durability factor after subjecting to 300 freezing and thawing cycles was 90. Concrete having a durability factor of 60 or greater at 300 cycles is considered to have passed the freezing and thawing test. The F&T test was continued to 330 cycles. At 330 cycles, the durability factor was approximately 86. This concrete therefore, is considered to have very good resistance to freezing and thawing. Flexural strength of the concrete decreased by approximately 30% and compressive strength reduced by 16% after 330 cycles of freezing and thawing. The visual appearance of the concrete after 330 cycles of freezing and thawing shows that the paste fraction of the cast surfaces scaled extensively, while the cut surfaces exhibited little surface deterioration. The surface scaling may be caused by the severe effects of the ASTM C 666, Procedure A. In Procedure A, the concrete specimens are placed in rigid metal containers in the rapid F&T machine. There is a 1/8" gap around the specimen which contains water. As the water freezes from top to bottom, the water is forced into the pores of the concrete since the container is "rigid". The water being forced into the pores of the concrete is a much more severe condition than would be expected in an actual outdoor environment. Thus, the concrete surface should perform better than what is indicated by the ASTM C 666, Procedure A. The air content of the mixture was also reported as 4.1%. ACI 201.2, "Guide to Durable Concrete" recommends that concrete (with 3/4" maximum aggregate size) subjected to a severe exposure have and air content of 6% +/- 1-1/2% entrained air. The 4.1% air content, therefore, is below the lower limit of 4.5% for a severe exposure and may also be attributing to the severe surface scaling.

The physical condition of the concrete after subjecting to freezing and thawing was very good. The high durability factor obtained from the tests support this conclusion. The visual appearance of the cast surfaces of the concrete exhibited extensive surface scaling. The concrete should not be used in a severe freezing and thawing environment where the visual appearance of the concrete would be important such as in architectural concrete or pavements.

Table 1: Mixture Proportions and Fresh Concrete Test Results*

Kingsford Dam - High Volume Fly Ash Mixture	
Cement (lb/yd^3), C	282
Fly Ash (lb/yd^3), A	330
[A/(C+A)] (%)	54
Water (lb/yd^3), W	298
[W/(C+A)]	0.49
SSD Fine Aggregate (lb/yd^3)	1,094
SSD ¾" Aggregate (lb/yd^3)	1,800
Water Reducer ($liq.oz/yd^3$)	18.6
Air Entraining Admixture ($liq.oz/yd^3$)	6.0
Air Temperature ($^{\circ}F$)	98
Fresh Concrete Temperature ($^{\circ}F$)	86
Slump (in.)	3-1/2
Air Content (%)	4.1

* Reported to UWM-CBU by WEPCO

Table 2: Cylinder Compressive Strength for the Kingsford Dam HVFA Concrete*

Test Age (days)	Specimen Number	Compressive Strength (psi)	Average Compressive Strength (psi)
3	25	2,280	2,340
	26	2,350	
	27	2,390	
7	28	3,520	3,460
	29	3,450	
	30	3,410	
28	31	5,390	5,395
	32	5,340	
	33	5,460	
56	34	5,940	5,965
	35	6,010	
	36	5,940	
90	37	6,420	6,315
	38	6,230	
	39	6,300	

* Reported to UWM-CBU by WEPCO

Table 3: Data for Change in Mass and Density of Kingsford Dam Concrete
(In accordance with ASTM C 666, Procedure A, Rapid F & T)

		Change in Mass			Change in Density		
Number of F & T Cycles	Specimen No.	Weight (lb)	% Change	Ave % Change	Density (lb/ft^3)	% Change	Ave % Change
	1	10.43	0.0		149.6	0.0	
	2	10.63	0.0		149.1	0.0	
	3	10.83	0.0		149.2	0.0	
	4	10.52	0.0		148.2	0.0	
	5	10.48	0.0		150.3	0.0	
0	6	10.62	0.0	0.0	148.9	0.0	0.0
	1	10.43	0.0		149.6	0.0	
	2	10.62	-0.1		149.3	0.1	
	3	10.83	0.0		149.2	0.0	
	4	10.52	0.0		148.2	0.0	
	5	10.48	0.0		150.3	0.0	
30	6	10.62	0.0	0.0	148.9	0.0	0.0
	1	10.3	-1.2		147.4	-1.5	
	2	10.47	-1.5		148.5	-0.4	
	3	10.78	-0.5		148.2	-0.7	
	4	10.38	-1.3		145.2	-2.0	
	5	10.39	-0.9		148.4	-1.3	
60	6	10.5	-1.1	-1.1	147.9	-0.7	-1.1
	1	10.42	-0.1		150.2	0.4	
	2	10.57	-0.6		148.9	-0.1	
	3	10.72	-1.0		149.6	0.3	
	4	10.47	-0.5		150.9	1.8	
	5	10.52	0.4		150.2	-0.1	
90	6	10.64	0.2	-0.3	148.5	-0.3	0.3
	1	10.38	-0.5		150.3	0.5	
	2	10.47	-1.5		147.8	-0.9	
	3	10.61	-2.0		148.1	-0.7	
120	4	10.47	-0.5	-0.9	150.5	1.6	-0.2

	5	10.48	0.0		149.6	-0.1	
	6	10.50	-1.1		147.2	-1.1	

Table 3 (Cont.): Data for Change in Mass and Density of Kingsford Dam Concrete
(In accordance with ASTM C 666, Procedure A, Rapid F & T)

		Change in Mass			Change in Density		
Number of F & T Cycles	Specimen No.	Weight (lb)	% Change	Ave % Change	Density (lb/ft^3)	% Change	Ave % Change
	1	10.16	-2.6		148.1	-1.0	
	2	10.28	-3.3		148.5	-0.4	
	3	10.50	-3.0		147.2	-1.3	
	4	10.41	-1.0		149.0	0.5	
	5	10.48	0.0		148.0	-1.5	
150	6	10.40	-2.1	-2.0	146.2	-1.8	-0.9
	1	10.34	-0.9		146.3	-2.2	
	2	10.53	-0.9		151.1	1.3	
	3	10.59	-2.2		149.2	0.0	
	4	10.43	-0.9		148.3	0.1	
	5	10.42	-0.6		148.8	-1.0	
180	6	10.48	-1.3	-1.1	147.9	-0.7	-0.4
	1	10.13	-2.9		146.3	-2.2	
	2	10.51	-1.1		148.4	-0.5	
	3	10.38	-4.2		147.9	-0.9	
	4	10.32	-1.9		149.1	0.6	
	5	10.33	-1.4		148.9	-0.9	
210	6	10.38	-2.3	-2.3	146.2	-1.8	-0.9
	1	10.23	-1.9		149.1	-0.3	
	2	10.38	-2.4		148.9	-0.1	
	3	10.50	-3.0		148.2	-0.7	
	4	10.26	-2.5		150.6	1.6	
	5	10.31	-1.6		149.3	-0.7	
240	6	10.43	-1.8	-2.2	148.6	-0.2	-0.1
270	1	10.27	-1.5	-1.6	151.1	1.0	1.3

	2	10.42	-2.0		151.9	1.9	
	3	10.51	-3.0		152.2	2.0	
	4	10.40	-1.1		149.8	1.1	
	5	10.37	-1.0		149.3	0.3	
	6	10.50	-1.1		148.6	1.6	

Table 3 (Cont.): Data for Change in Mass and Density of Kingsford Dam Concrete
(In accordance with ASTM C 666, Procedure A, Rapid F & T)

		Change in Mass			Change in Density		
Number of F & T Cycles	Specimen No.	Weight (lb)	% Change	Ave % Change	Density (lb/ft^3)	% Change	Ave % Change
	1	10.25	-1.7		151.9	1.5	
	2	10.49	-1.3		150.1	0.7	
	3	10.61	-2.0		148.8	-0.3	
	4	10.44	-0.8		149.4	0.8	
	5	10.40	-0.8		150.6	0.2	
300	6	10.59	-0.3	-1.1	148.8	-0.1	0.5
	1	10.26	-1.6		150.3	0.5	
	2	10.48	-1.4		15.0	0.6	
	3	10.51	-1.1		149.7	0.3	
	4	10.33	-2.8		152.4	2.8	
	5	10.37	-1.0		149.1	-0.8	
330	6	10.52	-0.9	-1.5	147.5	-0.9	0.4

* Typical specimen size: 3" x 4" x 10-1/2"

Table 4: Data for Change in Mass and Density of Kingsford Dam Concrete - Control Specimens (moist cured)

		Change in Mass			Change in Density		
Number of Cycles	Specimen No.	Weight (lb)	% Change	Ave %	Density (lb/ft^3)	% Change	Ave % Change
	1	10.68	0.0		150.4	0.0	
	2	10.95	0.0		149.8	0.0	
0	3	10.6	0.0	0.0	149.6	0.0	0.0
	1	10.68	0.0		150.4	0.0	
	2	10.95	0.0		149.8	0.0	
30	3	10.6	0.0	0.0	149.6	0.0	0.0
	1	10.55	-1.2		148.9	-1.0	
	2	10.93	-0.2		150.2	0.3	
60	3	10.48	-1.1	-0.8	145.3	-2.9	-1.2
	1	10.69	0.1		149.6	-0.5	
	2	10.94	-0.1		150.0	0.1	
90	3	10.57	-0.3	-0.1	145.9	-2.5	-1.0
	1	10.65	-0.3		150.0	-0.3	
	2	10.85	-0.9		150.5	0.5	
120	3	10.56	-0.4	-0.5	146.1	-2.3	-0.7
	1	10.51	-1.6		152.2	1.2	
	2	10.75	-1.8		150.4	0.4	
150	3	10.39	-2.0	-1.8	145.7	-2.6	-0.3
	1	10.64	-0.4		150.9	0.3	
	2	10.85	-0.9		150.5	0.5	
180	3	10.51	-0.8	-0.7	146.4	-2.1	-0.4
	1	10.57	-1.0		150.0	-0.3	
	2	10.85	-0.9		149.8	0.0	
210	3	10.46	-1.3	-1.1	149.7	0.1	-0.1
	1	10.59	-0.8		148.5	-1.3	
	2	10.86	-0.8		148.9	-0.6	
240	3	10.49	-1.0	-0.9	147.8	-1.2	-1.0
270	1	10.63	-0.5	-0.3	150.4	0.0	0.0

2	10.94	-0.1	150.4	0.0
3	10.58	-0.2	148.7	-0.1

Table 4 (Cont.): Data for Change in Mass and Density of Kingsford Dam Concrete - Control Specimens (In accordance with ASTM C 666, Procedure A, Rapid F & T)

		Change in Mass			Change in Density		
Number of Cycles	Specimen No.	Weight (lb)	% Change	Ave %	Density (lb/ft^3)	% Change	Ave % Change
	1	10.66	-0.2		152.2	1.2	
	2	10.99	0.4		151.4	1.1	
300	3	10.61	0.1	0.1	150.1	0.3	0.9
	1	10.7	0.2		150.0	-0.3	
	2	11	0.5		149.9	0.1	
330	3	10.62	0.2	0.3	148.9	-0.5	-0.2

* Typical specimen size: 3" x 4" x 10-1/2"

Table 5: Data for Transverse Frequency and Relative Dynamic Modulus of Kingsford Dam Concrete
(ASTM C 666, Procedure A, Rapid F & T)

		Transverse Frequency & Relative Dynamic Modulus				
Number of F & T Cycles	Specimen No.	FTF (Hz)	% Frequency Change	Ave Frequency Change	Relative Dynamic Modulus	Ave.
	1	3640	0.0		100.0	
	2	3661	0.0		100.0	
	3	3739	0.0		100.0	
	4	3588	0.0		100.0	
	5	3588	0.0		100.0	
0	6	3608	0.0	0.0	100.0	100.0
	1	3583	-1.6		96.9	
	2	3598	-1.7		96.6	
	3	3662	-2.1		95.9	
	4	3543	-1.3		97.5	
	5	3541	-1.3		97.4	
30	6	3546	-1.7	-1.6	96.6	96.8
	1	3582	-1.6		96.8	
	2	3590	-1.9		96.2	
	3	3651	-2.4		95.4	
	4	3530	-1.6		96.8	
	5	3530	-1.6		96.8	
60	6	3549	-1.6	-1.8	96.8	96.4
	1	3589	-1.4		97.2	
	2	3589	-2.0		96.1	
	3	3644	-2.5		95.0	
	4	3542	-1.3		97.5	
	5	3528	-1.7		96.7	
90	6	3555	-1.5	-1.7	97.1	96.6
	1	3567	-2.0		96.0	
	2	3596	-1.8		96.5	
120	3	3654	-2.3	-2.0	95.5	96.1

	4	3511	-2.1		95.8	
	5	3510	-2.2		95.7	
	6	3554	-1.5		97.0	

Table 5 (Cont.): Data for Transverse Frequency and Relative Dynamic Modulus of Kingsford Dam Concrete (ASTM C 666, Procedure A, Rapid F & T)

		Transverse Frequency & Relative Dynamic Modulus				
Number of F & T Cycles	Specimen No.	FTF (Hz)	% Frequency Change	Ave Frequency Change	Relative Dynamic Modulus	Ave
	1	3542	-2.7		94.7	
	2	3586	-2.0		95.9	
	3	3652	-2.3		95.4	
	4	3515	-2.0		96.0	
	5	3486	-2.8		94.4	
150	6	3547	-1.7	-2.3	96.7	95.5
	1	3534	-2.9		94.3	
	2	3566	-2.6		94.9	
	3	3637	-2.7		94.6	
	4	3520	-1.9		96.3	
	5	3471	-3.3		93.6	
180	6	3545	-1.7	-2.5	96.5	95.0
	1	3521	-3.3		93.6	
	2	3547	-3.1		93.9	
	3	3648	-2.4		95.2	
	4	3495	-2.6		94.9	
	5	3430	-4.4		91.4	
210	6	3545	-1.7	-2.9	96.5	94.2
	1	3425	-5.9		88.5	
	2	3516	-4.0		92.2	
	3	3618	-3.2		95.2	
	4	3440	-4.1		91.9	
	5	3386	-5.6		89.1	
240	6	3518	-2.5	-4.2	95.1	91.7

	1	3431	-5.7		88.9	
	2	3498	-4.5		91.3	
	3	3640	-2.6		93.6	
	4	3434	-4.3		91.6	
	5	3344	-6.8		86.9	
270	6	3517	-2.5	-4.4	95.0	91.4

Table 5 (Cont.): Data for Transverse Frequency and Relative Dynamic Modulus of Kingsford Dam Concrete (ASTM C 666, Procedure A, Rapid F & T)

		Transverse Frequency & Relative Dynamic Modulus				
Number of F & T Cycles	Specimen No.	FTF (Hz)	% Frequency Change	Ave. Frequency Change	Relative Dynamic Modulus	Ave
	1	3417	-6.1		88.1	
	2	3451	-5.7		88.9	
	3	3617	-3.3		93.6	
	4	3394	-5.4		89.5	
	5	3307	-7.8		85.0	
300	6	3509	-2.7	-5.2	94.6	89.9
	1	3322	-8.7		83.3	
	2	3305	-9.7		81.5	
	3	3585	-4.1		91.9	
	4	3334	-7.1		86.3	
	5	3212	-10.5		80.1	
330	6	3448	-4.4	-7.4	91.3	85.8

Table 6: Data for Transverse Frequency and Relative Dynamic Modulus of Kingsford Dam Concrete - Control Specimens (moist cured)

		Transverse Frequency & Relative Dynamic Modulus				
Number of Cycles	Specimen No.	FTF (Hz)	% Frequency Change	Ave. Frequency Change	Relative Dynamic Modulus	Ave
	1	3618	0.0		100.00	
	2	3666	0.0		100.00	
0	3	3730	0.0	0.0	100.00	100.0
	1	3636	0.5		101.00	
	2	3676	0.3		100.55	
30	3	3725	-0.1	0.2	99.73	100.4
	1	3627	0.2		100.50	
	2	3681	0.4		100.82	
60	3	3720	-0.3	0.1	99.46	100.3
	1	3625	0.2		100.39	
	2	3672	0.2		100.33	
90	3	3738	0.2	0.2	100.43	100.4
	1	3630	0.3		100.66	
	2	3680	0.4		100.77	
120	3	3745	0.4	0.4	100.81	100.7
	1	3623	0.1		100.28	
	2	3676	0.3		100.55	
150	3	3727	-0.1	0.1	99.84	100.2
	1	3628	0.3		100.55	
	2	3683	0.5		100.93	
180	3	3735	0.1	0.3	100.27	100.6
	1	3639	0.6		101.16	
	2	3688	0.6		101.20	
210	3	3751	0.6	0.6	101.13	101.2
	1	3636	0.5		101.00	
	2	3694	0.8		101.53	
240	3	3754	0.6	0.6	101.29	101.3

270	1	3637	0.5	0.6	101.05	101.3
	2	3698	0.9		101.75	
	3	3750	0.5		101.08	

Table 6 (Cont.): Data for Transverse Frequency and Relative Dynamic Modulus of Kingsford Dam Concrete - Control Specimens (moist cured)

		Transverse Frequency & Relative Dynamic Modulus				
Number of Cycles	Specimen No.	FTF (Hz)	% Frequency Change	Ave. Frequency Change	Relative Dynamic Modulus	Ave
	1	3658	1.1		102.22	
	2	3690	0.7		101.31	
300	3	3706	-0.6	0.4	98.72	100.8
	1	3641	0.6		101.28	
	2	3710	1.2		102.41	
330	3	3761	0.8	0.9	101.67	101.8

Table 7: Flexural Strength of Kingsford Dam Concrete*
According to ASTM C 78

Test Age (days)	Curing History	Specimen Number	Flexural Strength (psi)	Average Flexural Strength (psi)
9 Months	Control (Moist-cured 9 months)	1	890	890
		2	875	
		3	905	
12 Months	After F & T (Moist Cured 9 months, then subjected to 330 freezing and thawing cycles for 3 months)	1	595	595
		2	530	
		3	620	
		4	510	
		5	585	
		6	725	
12 Months	Control (Moist-cured 12 months)	1	775	850
		2	890	
		3	885	

* Typical test specimen size: 3" x 4" x 10-1/2"

Table 8: Data for Pulse Velocity of Kingsford Dam Concrete
(ASTM C 666, Procedure A, Rapid F & T)

		Pulse Velocity		
Number of F&T Cycles	Specimen No.	Velocity (ft/s)	Ave % Change	Ave %
	1	15682	0.0	
	2	15606	0.0	
	3	15553	0.0	
	4	15630	0.0	
	5	15440	0.0	
0	6	15446	0.0	0.0
	1	15403	-1.8	
	2	15303	-1.9	
	3	15580	-0.7	
	4	15274	-2.3	
	5	15250	-1.2	
30	6	15282	-1.1	-1.5
	1	15542	-0.9	
	2	15222	-2.5	
	3	15553	-0.9	
	4	15464	-1.1	
	5	15304	-0.9	
60	6	15309	-0.9	-1.2
	1	15514	-1.1	
	2	15222	-2.5	
	3	15750	0.4	
	4	15409	-1.4	
	5	15440	0.0	
90	6	15446	0.0	-0.8
	1	15654	-0.2	
	2	15303	-1.9	
	3	15306	-2.5	
120	4	14934	-4.5	-1.5

	5	15440	0.0
	6	15446	0.0

Table 8 (Cont.): Data for Pulse Velocity of Kingsford Dam Concrete
(ASTM C 666, Procedure A, Rapid F & T)

		Pulse Velocity		
Number of Cycles	Specimen No.	Velocity (ft/s)	Ave % Change	Ave %
	1	15542	-0.9	
	2	15466	-0.9	
	3	15333	-2.3	
	4	15574	-0.4	
	5	15413	-0.2	
150	6	15255	-1.2	-1.0
	1	15431	-1.6	
	2	15357	-1.6	
	3	15360	-2.1	
	4	15168	-3.0	
	5	15386	-0.4	
180	6	15282	-1.1	-1.6
	1	15654	-0.2	
	2	15303	-1.9	
	3	15360	-2.1	
	4	15355	-1.8	
	5	15331	-0.7	
210	6	14275	-7.6	-2.4
	1	15514	-1.1	
	2	15384	-1.4	
	3	15553	-0.9	
	4	15409	-1.4	
	5	15331	-0.7	
240	6	14787	-4.3	-1.6
270	1	15349	-2.1	-2.4

	2	15143	-3.0	
	3	15609	-0.5	
	4	15409	-1.4	
	5	15091	-2.3	
	6	14612	-5.4	

Table 8 (Cont.): Data for Pulse Velocity of Kingsford Dam Concrete
(ASTM C 666, Procedure A, Rapid F & T)

		Pulse Velocity		
Number of F & T Cycles	Specimen No.	Velocity (ft/s)	Ave % Change	Ave %
	1	15241	-2.8	
	2	15330	-1.8	
	3	14988	-4.5	
	4	15089	-3.5	
	5	14884	-3.6	
300	6	14965	-3.1	-3.2
	1	15081	-3.8	
	2	14607	-6.4	
	3	14963	-4.7	
	4	15037	-3.8	
	5	14808	-4.1	
330	6	14322	-7.3	-5.0

Table 9: Freeze-Thaw Resistance Data for Pulse Velocity of Kingsford Dam Concrete Control Specimens (moist cured)

		Pulse Velocity		
Number of Cycles	Specimen No.	Velocity (ft/s)	% Change	Ave %
	1	15578	0.0	
	2	15784	0.0	
0	3	15852	0.0	0.0
	1	15578	0.0	
	2	15727	-0.4	
30	3	15881	0.2	-0.1
	1	15606	0.2	
	2	15755	-0.2	
60	3	15940	0.6	0.2
	1	15662	0.5	
	2	15698	-0.5	
90	3	15622	-1.4	-0.5
	1	15690	0.7	
	2	15698	-0.5	
120	3	15881	0.2	0.1
	1	15662	0.5	
	2	15670	-0.7	
150	3	15736	-0.7	-0.3
	1	15803	1.4	
	2	15755	-0.2	
180	3	15823	-0.2	0.3
	1	15718	0.9	
	2	15784	0.0	
210	3	15794	-0.4	0.2
	1	15832	1.6	
	2	15928	0.9	
240	3	16088	1.5	1.3

270	1	15718	0.9	0.9
	2	15784	0.0	
	3	16118	1.7	

Table 9 (Cont.): Data for Pulse Velocity of Kingsford Dam Concrete - Control Specimens
(ASTM C 666, Procedure A, Rapid F & T)

		Pulse Velocity		
Number of Cycles	Specimen No.	Velocity (ft/s)	% Change	Ave %
	1	15861	1.8	
	2	15727	-0.4	
300	3	15999	0.9	0.8
	1	15414	-1.1	
	2	15642	-0.9	
330	3	15566	-1.8	-1.3

Table 10: Modified Cube Compressive Strength for Kingsford Dam HVFA Concrete
(Compressive Strength of Concrete Using Portions of Beams Broken in Flexure, in accordance with ASTM C 166)

Test Age (days)	Curing History	Specimen Number	Compressive Strength (psi)	Average Compressive Strength (psi)
9 Months	Control (Moist-cured 9 months)	1	6780	5855
		2	4620	
		3	6170	
12 Months	Control (Moist-cured 12 months)	1	5700	5925
		2	5590	
		3	6490	
12 Months	After F & T (Moist Cured 9 months, then subjected to 330 freezing and thawing cycles for 3 months)	1	4970	4935
		2	4750	
		3	4200	
		4	5330	
		5	4270	
		6	6080	

* Typical test specimen size: 3" x 4" x 6"

Figure 1: Test Specimens Undergoing Rapid Freezing and Thawing

Figure 2

Figure 2: Control Specimens - View of Cast Surface

Figure 3

Figure 3: Control Specimens -

Close-Up View of Cast Surfaces on Ends of Specimens

Figure 4

Figure 4: Control Specimens - View of Cut Surfaces

Figure 5

Figure 5: Control Specimens - Close-Up View of Cut Surfaces

Figure 6

Figure 6: Control Specimens - Close-Up View of Cut Surface on Ends of Specimens

Figure 7 Change in Mass

Figure 8 Dynamic modulus

Figure 9 Pulse velocity

Figure 10a

Figure 10a: Specimens (#1, 2, and 3) Subjected to Freezing and Thawing
View of Cast Surface on the Side of the Test Specimens

Figure 10b

Figure 10b: Specimens (#4, 5, and 6) Subjected to Freezing and Thawing

View of Cast Surface on the Side of the Test Specimens

Figure 11a

Figure 11a: Specimens (#1, 2, and 3) Subjected to Freezing and Thawing
Close-Up View of Cast Surface on the Ends of the Test Specimens

Figure 11b

Figure 11b: Specimens (#4, 5, and 6) Subjected to Freezing and Thawing

Close-Up View of Cast Surface on the Ends of the Test Specimens

Figure 12a

Figure 12a: Specimens (#1, 2, and 3) Subjected to Freezing and Thawing - View of Cut Surfaces on the Sides of the Test Specimens

Figure 12b

Figure 12b: Specimens (#4, 5, and 6) Subjected to Freezing and Thawing - View of Cut Surfaces on the Sides of the Test Specimens

Figure 13

Figure 13

Figure 13: Specimens (#4, 5, and 6) Subjected to Freezing and Thawing

View of Cut Surface on the Ends of the Test Specimens aaa

bbb

Table 11: Freeze-Thaw Resistance Data for Kingsford Dam Concrete

		Change in Mass			Change in Density			Transverse Frequency					Pulse Velocity		
Number of Cycles	Specimen No.	Weight (lb)	% Change	Ave % Change	Density (lb/ft^3)	% Change	Ave % Change	FTF (Hz)	% Frequency Change	Ave Frequency Change	Relative Dynamic Modulus	Ave.	Velocity (ft/s)	Ave % Change	Ave %
	1	10.43	0.0		149.6	0.0		3640	0.0		100.0		15682	0.0	
	2	10.63	0.0		149.1	0.0		3661	0.0		100.0		15606	0.0	
	3	10.83	0.0		149.2	0.0		3739	0.0		100.0		15553	0.0	
	4	10.52	0.0		148.2	0.0		3588	0.0		100.0		15630	0.0	
	5	10.48	0.0		150.3	0.0		3588	0.0		100.0		15440	0.0	
0	6	10.62	0.0	0.0	148.9	0.0	0.0	3608	0.0	0.0	100.0	100.0	15446	0.0	0.0
	1	10.43	0.0		149.6	0.0		3583	-1.6		96.9		15403	-1.8	
	2	10.62	-0.1		149.3	0.1		3598	-1.7		96.6		15303	-1.9	
	3	10.83	0.0		149.2	0.0		3662	-2.1		95.9		15580	-0.7	
	4	10.52	0.0		148.2	0.0		3543	-1.3		97.5		15274	-2.3	
	5	10.48	0.0		150.3	0.0		3541	-1.3		97.4		15250	-1.2	
30	6	10.62	0.0	0.0	148.9	0.0	0.0	3546	-1.7	-1.6	96.6	96.8	15282	-1.1	-1.5
	1	10.3	-1.2		147.4	-1.5		3582	-1.6		96.8		15542	-0.9	
	2	10.47	-1.5		148.5	-0.4		3590	-1.9		96.2		15222	-2.5	
	3	10.78	-0.5		148.2	-0.7		3651	-2.4		95.4		15553	-0.9	
	4	10.38	-1.3		145.2	-2.0		3530	-1.6		96.8		15464	-1.1	
	5	10.39	-0.9		148.4	-1.3		3530	-1.6		96.8		15304	-0.9	
60	6	10.5	-1.1	-1.1	147.9	-0.7	-1.1	3549	-1.6	-1.8	96.8	96.4	15309	-0.9	-1.2
	1	10.42	-0.1		150.2	0.4		3589	-1.4		97.2		15514	-1.1	
	2	10.57	-0.6		148.9	-0.1		3589	-2.0		96.1		15222	-2.5	
	3	10.72	-1.0		149.6	0.3		3644	-2.5		95.0		15750	0.4	
	4	10.47	-0.5		150.9	1.8		3542	-1.3		97.5		15409	-1.4	
	5	10.52	0.4		150.2	-0.1		3528	-1.7		96.7		15440	0.0	
90	6	10.64	0.2	-0.3	148.5	-0.3	0.3	3555	-1.5	-1.7	97.1	96.6	15446	0.0	-0.8
	1	10.38	-0.5		150.3	0.5		3567	-2.0		96.0		15654	-0.2	
	2	10.47	-1.5		147.8	-0.9		3596	-1.8		96.5		15303	-1.9	
	3	10.61	-2.0		148.1	-0.7		3654	-2.3		95.5		15306	-2.5	
	4	10.47	-0.5		150.5	1.6		3511	-2.1		95.8		14934	-4.5	
120	5	10.48	0.0	-0.9	149.6	-0.1	-0.2	3510	-2.2	-2.0	95.7	96.1	15440	0.0	-1.5

6	10.50	-1.1	147.2	-1.1	3554	-1.5	97.0	15446	0.0

Table 11 (Cont.): Freeze-Thaw Resistance Data Kingsford Dam Concrete

		Change in Mass			Change in Density			Transverse Frequency & Relative Dynamic Modulus					Pulse Velocity		
Number of Cycles	Specimen No.	Weight (lb)	% Change	Ave % Change	Density (lb/ft^3)	% Change	Ave % Change	FTF (Hz)	% Frequency Change	Ave Frequency Change	Relative Dynamic Modulus	Ave %	Velocity (ft/s)	Ave % Change	Ave %
	1	10.16	-2.6		148.1	-1.0		3542	-2.7		94.7		15542	-0.9	
	2	10.28	-3.3		148.5	-0.4		3586	-2.0		95.9		15466	-0.9	
	3	10.50	-3.0		147.2	-1.3		3652	-2.3		95.4		15333	-2.3	
	4	10.41	-1.0		149.0	0.5		3515	-2.0		96.0		15574	-0.4	
	5	10.48	0.0		148.0	-1.5		3486	-2.8		94.4		15413	-0.2	
150	6	10.40	-2.1	-2.0	146.2	-1.8	-0.9	3547	-1.7	-2.3	96.7	95.5	15255	-1.2	-1.0
	1	10.34	-0.9		146.3	-2.2		3534	-2.9		94.3		15431	-1.6	
	2	10.53	-0.9		151.1	1.3		3566	-2.6		94.9		15357	-1.6	
	3	10.59	-2.2		149.2	0.0		3637	-2.7		94.6		15360	-2.1	
	4	10.43	-0.9		148.3	0.1		3520	-1.9		96.3		15168	-3.0	
	5	10.42	-0.6		148.8	-1.0		3471	-3.3		93.6		15386	-0.4	
180	6	10.48	-1.3	-1.1	147.9	-0.7	-0.4	3545	-1.7	-2.5	96.5	95.0	15282	-1.1	-1.6
	1	10.13	-2.9		146.3	-2.2		3521	-3.3		93.6		15654	-0.2	
	2	10.51	-1.1		148.4	-0.5		3547	-3.1		93.9		15303	-1.9	
	3	10.38	-4.2		147.9	-0.9		3648	-2.4		95.2		15360	-2.1	
	4	10.32	-1.9		149.1	0.6		3495	-2.6		94.9		15355	-1.8	
	5	10.33	-1.4		148.9	-0.9		3430	-4.4		91.4		15331	-0.7	
210	6	10.38	-2.3	-2.3	146.2	-1.8	-0.9	3545	-1.7	-2.9	96.5	94.2	14275	-7.6	-2.4
	1	10.23	-1.9		149.1	-0.3		3425	-5.9		88.5		15514	-1.1	
	2	10.38	-2.4		148.9	-0.1		3516	-4.0		92.2		15384	-1.4	
	3	10.50	-3.0		148.2	-0.7		3618	-3.2		95.2		15553	-0.9	
	4	10.26	-2.5		150.6	1.6		3440	-4.1		91.9		15409	-1.4	
	5	10.31	-1.6		149.3	-0.7		3386	-5.6		89.1		15331	-0.7	
240	6	10.43	-1.8	-2.2	148.6	-0.2	-0.1	3518	-2.5	-4.2	95.1	91.7	14787	-4.3	-1.6
	1	10.27	-1.5		151.1	1.0		3431	-5.7		88.9		15349	-2.1	
	2	10.42	-2.0		151.9	1.9		3498	-4.5		91.3		15143	-3.0	
	3	10.51	-3.0		152.2	2.0		3640	-2.6		93.6		15609	-0.5	
270	4	10.40	-1.1	-1.6	149.8	1.1	1.3	3434	-4.3	-4.4	91.6	91.4	15409	-1.4	-2.4

5	10.37	-1.0	149.3	0.3	3344	-6.8	86.9	15091	-2.3
6	10.50	-1.1	148.6	1.6	3517	-2.5	95.0	14612	-5.4

Table 11 (Cont.): Freeze-Thaw Resistance Data Kingsford Dam Concrete

		Change in Mass			Change in Density			Transverse Frequency & Relative Dynamic Modulus					Pulse Velocity		
Number of Cycles	Specimen No.	Weight (lb)	% Change	Ave % Change	Density (lb/ft^3)	% Change	Ave % Change	FTF (Hz)	% Frequency Change	Ave. Frequency Change	Relative Dynamic Modulus	Ave %	Velocity (ft/s)	Ave % Change	Ave %
	1	10.25	-1.7		151.9	1.5		3417	-6.1		88.1		15241	-2.8	
	2	10.49	-1.3		150.1	0.7		3451	-5.7		88.9		15330	-1.8	
	3	10.61	-2.0		148.8	-0.3		3617	-3.3		93.6		14988	-4.5	
	4	10.44	-0.8		149.4	0.8		3394	-5.4		89.5		15089	-3.5	
	5	10.40	-0.8		150.6	0.2		3307	-7.8		85.0		14884	-3.6	
300	6	10.59	-0.3	-1.1	148.8	-0.1	0.5	3509	-2.7	-5.2	94.6	89.9	14965	-3.1	-3.2
	1	10.26	-1.6		150.3	0.5		3322	-8.7		83.3		15081	-3.8	
	2	10.48	-1.4		15.0	0.6		3305	-9.7		81.5		14607	-6.4	
	3	10.51	-1.1		149.7	0.3		3585	-4.1		91.9		14963	-4.7	
	4	10.33	-2.8		152.4	2.8		3334	-7.1		86.3		15037	-3.8	
	5	10.37	-1.0		149.1	-0.8		3212	-10.5		80.1		14808	-4.1	
330	6	10.52	-0.9	-1.5	147.5	-0.9	0.4	3448	-4.4	-7.4	91.3	85.8	14322	-7.3	-5.0

Table 12: Freeze-Thaw Resistance Data Kingsford Dam Final Concrete - Control Specimens

		Change in Mass			Change in Density			Transverse Frequency & Relative Dynamic Modulus					Pulse Velocity		
Number of Cycles	Specimen No.	Weight (lb)	% Change	Ave %	Density (lb/ft^3)	% Change	Ave % Change	FTF (Hz)	% Frequency Change	Ave. Frequency Change	Relative Dynamic Modulus	Ave	Velocity (ft/s)	% Change	Ave %
	1	10.68	0.0		150.4	0.0		3618	0.0		100.00		15578	0.0	
	2	10.95	0.0		149.8	0.0		3666	0.0		100.00		15784	0.0	
0	3	10.6	0.0	0.0	149.6	0.0	0.0	3730	0.0	0.0	100.00	100.0	15852	0.0	0.0
	1	10.68	0.0		150.4	0.0		3636	0.5		101.00		15578	0.0	
	2	10.95	0.0		149.8	0.0		3676	0.3		100.55		15727	-0.4	
30	3	10.6	0.0	0.0	149.6	0.0	0.0	3725	-0.1	0.2	99.73	100.4	15881	0.2	-0.1
	1	10.55	-1.2		148.9	-1.0		3627	0.2		100.50		15606	0.2	
	2	10.93	-0.2		150.2	0.3		3681	0.4		100.82		15755	-0.2	
60	3	10.48	-1.1	-0.8	145.3	-2.9	-1.2	3720	-0.3	0.1	99.46	100.3	15940	0.6	0.2
	1	10.69	0.1		149.6	-0.5		3625	0.2		100.39		15662	0.5	
	2	10.94	-0.1		150.0	0.1		3672	0.2		100.33		15698	-0.5	
90	3	10.57	-0.3	-0.1	145.9	-2.5	-1.0	3738	0.2	0.2	100.43	100.4	15622	-1.4	-0.5
	1	10.65	-0.3		150.0	-0.3		3630	0.3		100.66		15690	0.7	
	2	10.85	-0.9		150.5	0.5		3680	0.4		100.77		15698	-0.5	
120	3	10.56	-0.4	-0.5	146.1	-2.3	-0.7	3745	0.4	0.4	100.81	100.7	15881	0.2	0.1
	1	10.51	-1.6		152.2	1.2		3623	0.1		100.28		15662	0.5	
	2	10.75	-1.8		150.4	0.4		3676	0.3		100.55		15670	-0.7	
150	3	10.39	-2.0	-1.8	145.7	-2.6	-0.3	3727	-0.1	0.1	99.84	100.2	15736	-0.7	-0.3
	1	10.64	-0.4		150.9	0.3		3628	0.3		100.55		15803	1.4	
	2	10.85	-0.9		150.5	0.5		3683	0.5		100.93		15755	-0.2	
180	3	10.51	-0.8	-0.7	146.4	-2.1	-0.4	3735	0.1	0.3	100.27	100.6	15823	-0.2	0.3
	1	10.57	-1.0		150.0	-0.3		3639	0.6		101.16		15718	0.9	
	2	10.85	-0.9		149.8	0.0		3688	0.6		101.20		15784	0.0	
210	3	10.46	-1.3	-1.1	149.7	0.1	-0.1	3751	0.6	0.6	101.13	101.2	15794	-0.4	0.2
	1	10.59	-0.8		148.5	-1.3		3636	0.5		101.00		15832	1.6	
	2	10.86	-0.8		148.9	-0.6		3694	0.8		101.53		15928	0.9	
240	3	10.49	-1.0	-0.9	147.8	-1.2	-1.0	3754	0.6	0.6	101.29	101.3	16088	1.5	1.3
270	1	10.63	-0.5	-0.3	150.4	0.0	0.0	3637	0.5	0.6	101.05	101.3	15718	0.9	0.9

2	10.94	-0.1	150.4	0.0	3698	0.9	101.75	15784	0.0
3	10.58	-0.2	148.7	-0.1	3750	0.5	101.08	16118	1.7

Table 12 (Cont.): Freeze-Thaw Resistance Data for Kingsford Dam Final Concrete - Control Specimens

		Change in Mass			Change in Density			Transverse Frequency & Relative Dynamic Modulus					Pulse Velocity		
Number of Cycles	Specimen No.	Weight (lb)	% Change	Ave %	Density (lb/ft^3)	% Change	Ave % Change	FTF (Hz)	% Frequency Change	Ave. Frequency Change	Relative Dynamic Modulus	Ave	Velocity (ft/s)	% Change	Ave %
	1	10.66	-0.2		152.2	1.2		3658	1.1		102.22		15861	1.8	
	2	10.99	0.4		151.4	1.1		3690	0.7		101.31		15727	-0.4	
300	3	10.61	0.1	0.1	150.1	0.3	0.9	3706	-0.6	0.4	98.72	100.8	15999	0.9	0.8
	1	10.7	0.2		150.0	-0.3		3641	0.6		101.28		15414	-1.1	
	2	11	0.5		149.9	0.1		3710	1.2		102.41		15642	-0.9	
330	3	10.62	0.2	0.3	148.9	-0.5	-0.2	3761	0.8	0.9	101.67	101.8	15566	-1.8	-1.3