COMPARISON OF TWO FREEZE-THAW APPARATUS

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(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

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SUMMARY

The purpose of this study was to compare the results of rapid freezing and thawing tests conducted on machine A with results from machine B, which is intended to replace the aging machine A.

Concrete samples were prepared to attain levels of resistance to cycles of freezing and thawing. For comparison purposes, tests were conducted using the Research Council's procedure that is a modified version of ASTM C666 Procedure A. The modifications are the addition of one week of air drying following the two week moist cure and testing the specimens in a 2% NaCl solution rather than water. Also in machine B, because of its large size, some specimens were tested using the standard ASTM C666 Procedure A. The results indicate that both machines satisfactorily determine the relative freeze-thaw durabilities of concretes and that the data from one machine can be related to the data from the other. In addition, the study showed that the use of salt in test water enables the differentiation of concretes resistant to severe environments from those resistant to moderate conditions. Also, modifications to the present acceptance criteria are given to differentiate between the moderate and severe exposure conditions.

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TEST PROCEDURE AND EQUIPMENT

Concretes exposed to weathering must have adequate resistance to damage from cycles of freezing and thawing. To ensure that they do, specimens made from the mixtures to be used in construction are subjected to accelerated laboratory tests to gain an estimate of their performance under field exposure. While the relationship between the results from accelerated tests and performance in the field is a matter of controversy, procedures such as the ones described in ASTM C666, Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing have been widely used for more than 40 years, and the correlations that have been developed between the results from this test method and field performance have proven sufficiently precise for predicting poor or good performance and for providing guidance in making decisions in borderline cases.

In conducting rapid freeze-thaw tests over the past two decades, the Research Council has used equipment designated machine A in this report. With this equipment tests are conducted under a modified version of ASTM C666 Procedure A, with two significant modifications. Procedure A requires two weeks of moist curing; however, at the Research Council one week of air drying is provided following the two week moist cure, and the specimens are tested in a 2% NaCl solution rather than water.[1] These two modifications are believed to make the conditions of test more representative of the environment to which highway structures and pavements are exposed than does the standard ASTM procedure. Under this modified procedure, acceptable performance requires that at 300 cycles the average —

1. weight loss be 7% or less,
2. durability factor be 60 or more, and
3. surface rating be 3 or less.

The surface rating is determined by estimating the proportion of the surface having ratings as given in ASTM C672, and the Council's final rating is calculated by averaging the weighted ratings computed for each beam.

The above cited values evolved at the Research Council initially from studies of coatings and surface treatments and were refined from studies of various repair materials. Even though these criteria are applied to concretes subjected to moderate and severe exposures, they may be too lenient for concrete subjected to severe exposure conditions.(1)

Machine A is loaded with 30 specimens measuring 3 x 4 x 16 in. (75 x 100 x 400 mm) in metal containers with an expansion joint at one corner. The specimens are subjected to 2 hours of cooling and 1 hour of thawing in the chamber, for a 3-hour cycle, or 8 cycles a day. The temperature change between 0^{o}F. and 40^{o}F. is maintained by a cam-programmer-controller-recorder through a thermocouple embedded 1/4 in. (6 mm) inside a specimen.

In its initial evaluation at the Research Council, machine A was shown to have the capability of making a distinction between laboratory concretes having a range of expected durabilities based on field performance records of similar concretes.(2) Subsequent tests over the years have satisfactorily predicted the freeze-thaw durability of field concrete, and valuable information has been gathered on proportioning and sample preparation as they relate to freeze-thaw durability. Over this time, many agencies conducting rapid freezing and thawing tests have purchased and used similar machines with satisfaction.

Recently it became necessary to replace machine A because of its age and frequent mechanical failures, and a new machine supplied by a different manufacturer was acquired. The new machine, designated machine B here, has a 60-specimen capacity. The 60 specimens are frozen in 2.4 hours and thawed in 0.9 hour, for a 3.3-hour cycle rather than the 3-hour cycle achieved by machine A.

Because of possible differences between results with the two machines, a comparative study was conducted so that the results of one could be correlated to those of the other. Such a correlation preserves the value of the mass of data obtained with machine A at the Council and elsewhere over the years.

OBJECTIVE AND SCOPE

The purpose of the study was to compare the results of rapid freezing and thawing tests conducted on machine A with results from machine B.

From 6 batches of concrete, seventy-four 3 x 4 x 16 (75 x 100 x 400 mm) beams were fabricated and subjected to rapid freezing and thawing tests. The number of specimens tested and the procedures followed are shown in Table 1 for three levels of resistance to cycles of freezing and thawing. As also shown in Table 1, 6 specimens, one from each batch, were subjected to linear traverse analysis and eighteen 4 x 8 in. (100 x 200 mm) cylinders were molded and tested in compression.

In evaluating the freeze-thaw results, the acceptance criteria for weight loss, durability factor, and surface rating were as previously noted and were based on an average of 5 beams. The tests were terminated at 300 cycles or when the weight loss reached 7% or the relative dynamic modulus of elasticity 60%. Even though surface rating is one of the criterion for acceptance, it was not used to terminate the test since it is reflected by the weight loss and also because of its subjective nature. The Council's acceptance criteria differ from ASTM C666 in that ASTM C666 requires that tests be continued until 300 cycles are reached or until the relative dynamic modulus of elasticity is 60% or less. ASTM sets no limits on termination in terms of weight loss. Surface rating is not determined in ASTM C666.

Table 1

Number of Specimens for Different Tests

Level of Resistance	Expected w/c	Expected Air, %	Cure*	Freeze-Thaw, Beams: Machine A Water	Freeze-Thaw, Beams: Machine A Salt	Freeze-Thaw, Beams: Machine B Water	Freeze-Thaw, Beams: Machine B Salt	Linear Traverse	Compressive Strength, Cylinders
1 - High	0.44	7	1	5	5	5	5	2	6
			2			5			
2 - Mod.	0.49	5	1	5	5	5	5	2	6
			2			5			
3 - Low	0.60	3	1	4	5	5	5	2	6
			2			5			

*Cure 1 - 2 weeks moist; 1 week air dry
2 - 2 weeks moist

MATERIALS AND MIXTURE PROPORTIONS

The fine aggregate used was a quartz sand with a specific gravity of 2.61 and a fineness modulus of 2.8; the coarse aggregate a granite gneiss with a specific gravity of 2.78, a dry rodded unit weight of 103.3 lb./ft.^{3} (1,650 kg/m^3), and a nominal maximum size of 1 in. (25 mm). Type II cement and commercially available, neutralized vinsol resin were used in all the mixtures.

Concretes having three levels of resistance were prepared in the laboratory as noted in Table 2. The range of variables shown encompasses the concretes utilized by the Virginia Department of Highways and Transportation as well as the performance levels suggested by ACI Committee 201. The same types of cement and aggregate were used throughout. For each level, two batches were prepared.

Table 2

Design Mixture Proportions in lb./yd.^{3}

Level of Resistance	Cement	Air, %	w/c	Coarse Agg.	Fine Agg.
1 - High	635	7.0	0.44	1,869	1,081
2 - Mod.	588	5.0	0.49	1,869	1,184
3 - Low	517	3.0	0.60	1,869	1,274

NOTE: 1 lb./yd.^{3} = 0.59 kg/m^3

SAMPLE PREPARATION AND TESTING

For each variable, 5 freeze-thaw beams were tested. Two of the specimens for each variable came from the first batch and the remaining three from the second batch. In addition, three 4 x 8 in. (100 x 200 mm) cylinders for compressive strength tests were fabricated from each batch. Beams for the linear traverse analysis were cast from the first batch of each level of resistance and 4 x 8 in. (100 x 200 mm) cylinders for this analysis were cast from the second batch because of the limited amount of concrete. Weight losses, durability factors, and surface rating values were determined from the rapid freeze-thaw test data.

Most of the specimens were tested using the modified version of ASTM C666 Procedure previously stated, which involves a different type of curing and the presence of salt in the test water. As shown in Table 1 some additional beams were tested by ASTM C666 Procedure A without modification in machine B. This was possible since machine B has more space available. The surfaces of the beams were rated in accordance with ASTM C672.

Cylinders were prepared in accordance with ASTM C192 and tested in compression. Specimens for the linear traverse analysis were moist cured for a month and then tested in accordance with ASTM C457.

RESULTS

Characteristics of Fresh Concrete

The preparation of mixtures and specimens was conducted in accordance with the appropriate ASTM procedures. Air contents were measured using the pressure method, ASTM C231, slumps by ASTM 143, and unit weights by ASTM 138. The results are summarized in Table 3. Workable concretes were achieved and air-entraining admixtures were added at different dosages to obtain the three levels of resistance. The concrete at the first level had an average air content of 7.5%, that at the second level 5.2%, and that for the third 2.4%.

Table 3

Characteristics of Fresh Concrete

Level of Resistance	Batch	w/c	Air, %	Slump, in.	Unit Wt., lb./ft.^{3}
1 - High	1	0.44	7.1	3.1	144.0
	2	0.44	7.8	4.0	141.4
2 - Mod.	1	0.49	5.2	3.0	147.2
	2	0.49	5.3	3.2	147.4
3 - Low	1	0.60	2.4	3.3	150.0
	2	0.60	2.4	3.6	149.4

NOTE: 1 in. = 25.4 mm; 1 lb./ft.^{3} = 16.0 kg/m^3

Linear Traverse Analysis

To assure that the desired void system was achieved, one specimen from each batch was subjected to linear traverse analysis. The hardened concrete specimens were cut and a slab was lapped. Examinations under the microscope revealed the void system summarized in Table 4. The total void contents were 7.4%, 4.6%, and 2.5% for the three levels of resistance and were in close agreement with the air contents of the fresh concretes. For levels 1 and 2, the specific surface values of the voids were larger than 600 in.$^{-1}$ (24 mm^{-1}) and the spacing factor less than 0.008 in. (0.20 mm), values that are considered necessary for the protection of saturated concretes from cycles of freezing and thawing.[3] Level 1 specimens showed higher specific surfaces and lower spacing factors than did the level 2 specimens. Level 3 concretes did not have void systems adequate for proper protection.

Table 4

Void System of Hardened Concrete

Level of Resistance	Batch	Void Content, %			Specific Surface, in.$^{-1}$	Spacing Factor, in.
		>1 mm	<1 mm	Total		
1 - High	1	1.3	6.7	8.0	960	0.0037
	2	1.1	5.7	6.8	942	0.0045
2 - Mod.	1	1.0	4.1	5.1	639	0.0076
	2	0.6	3.4	4.0	820	0.0066
3 - Low	1	1.3	0.9	2.2	180	0.0206
	2	1.7	1.0	2.7	386	0.0164

NOTE: 1 in. = 25.4 mm

Freeze-Thaw Tests

The freeze-thaw data on weight loss are summarized in Table 5, durability factors are given in Table 6, and surface ratings in Table 7. The standard deviations as well as the average values are given in the tables. All the specimens from levels 1 and 2 were tested up to 300 cycles; however, the specimens from level 3 reached relative dynamic modulus of elasticity values of 60, indicating failure, at earlier cycles, and the test was terminated at those cycles as shown in Table 3. The values were extrapolated to 300 cycles.

Table 5

Weight Loss Data in Percent at 300 Cycles
(Average of 5 Specimens)

Machine	Tested In	Cure*	Level 1 Avg.	Level 1 Std. Dev.	Level 2 Avg.	Level 2 Std. Dev.	Level 3 Avg.	Level 3 Std. Dev.
A	Water	1	1.4	0.2	2.5	0.6	9.1	0.8
B	Water	1	1.8	1.1	1.2	0.6	7.5	1.6
B	Water	2	0.8	0.4	1.2	0.6	5.8	2.0
A	2% NACl	1	1.3	0.4	6.9	1.2	32.5	2.8
B	2% NaCl	1	0.8	0.6	5.0	2.0	41.9	9.0

*Cure 1 — 2 weeks moist; 1 week air dry
Cure 2 — 2 weeks moist

Table 6

Durability Factors at 300 Cycles
(Average of 5 Specimens)

Machine	Tested In	Cure*	Level 1 Avg.	Level 1 Std. Dev.	Level 2 Avg.	Level 2 Std. Dev.	Level 3 Avg.	Level 3 Std. Dev.	Level 3 Terminated
A	Water	1	102	2	92	6	30	1	150
B	Water	1	96**	7	97	7	40	15	199
B	Water	2	97	1	91	4	9	2	46
A	2% NaCl	1	104	1	97	2	28	5	139
B	2% NAcl	1	104	1	103	2	23	4	116

*Cure 1 — 2 weeks moist; 1 week air dry.
Cure 2 — 2 weeks moist

**Average of 4 specimens

Table 7

Surface Rating Data at 300 Cycles
(Average of 5 Specimens)

Machine	Tested In	Cure*	Level 1 Avg.	Level 1 Std. Dev.	Level 2 Avg.	Level 2 Std. Dev.	Level 3 Avg.	Level 3 Std. Dev.
A	Water	1	1.0	0.2	1.3	0.2	2.8	0.6
B	Water	1	0.9	0.4	0.8	0.3	2.2	1.1
B	Water	2	0.7	0.1	0.7	0.3	3.1	1.0
A	2% NACl	1	1.3	0.1	2.0	0.1	5.0	0
B	2% NACl	1	1.0	0.3	1.8	0.5	5.0	0

*Cure 1 — 2 weeks moist; 1 week air dry
Cure 2 — 2 weeks moist

The weight loss values for the level 1 concrete, which had a high air content and was intended for severe exposure, were low and comparable to each other for different test water and curing conditions in both machines, and all were within the acceptable criteria. The results, in general, indicate that specimens tested in machine B showed more variability. This could be due to the larger size of this machine. Specimens from level 2, which were designed for moderate resistance, exhibited marginal weight loss when tested in the salt solution. The values were 6.9 for machine A and 5.0 for machine B. At the 95% confidence level, there is no significant difference between the values. However, in general, the average values obtained in machine B tended to be slightly lower than those obtained in machine A, which implies that tests in machine B might be less severe. However, this trend could not be confirmed statistically at the 95% level based on the limited number of samples tested.

Level 1 concretes attained weight loss values considerably less than level 2 concretes when tested in salt solution. This suggests that the present acceptance criterion is too lenient for concretes prepared for severe exposure and that a new criterion is desirable. It is suggested that a limit of 4% be set on concretes prepared for severe exposure. This value reflects the normal material and test variability. It is also consistent with the experience gained over the years and can be refined as more data are collected.

The level 3 beams exhibited undesirably high weight losses, except for one beam with a value of 5.8%. Those tested in salt solution showed considerably higher weight losses than those tested in water.

The different curing conditions to which the specimens were subjected did not reveal any significant differences at the 95% confidence level when tested in machine B.

The durability factor (DF) values, which are indicative of the soundness of the internal structure of the concretes, were similar for both machines. The values for beams from levels 1 and 2 would be considered satisfactory in both machines, with the lowest being 96. The attainment of high values indicates that for severe exposure the establishment of high durability factors is possible, and a value of 80 is suggested. The level 3 specimens all had unacceptable durability factors, the highest being 40. The curing conditions had a considerable effect on beams with low air content obtained from level 3 concrete. Specimens moist cured for two weeks and tested in water exhibited the lowest durability factors.

The surface rating values were also comparable for both machines. For levels 1 and 2 the values were all in the acceptable range, and for level 3 only the specimens moist cured for 2 weeks, air dried for 1 week, and tested in water in both machines had acceptable values. The surface rating values for the specimens in the salt solution indicated that level 1 concretes yield lower values than level 2. Thus, for severe exposure a surface rating of 2 is suggested, and the present limit of 3 can be retained for moderate exposure conditions. In general, the surface ratings are in agreement with the weight loss data, and both are indicative of the surface scaling of concretes.

The freeze-thaw data indicated that concretes from levels 1 and 2 all had acceptable durability, which was consistent with the linear traverse data.

In summary, the results indicate that both machines satisfactorily determine the relative freeze-thaw durabilities of concretes and the data from one machine can be related to the data from the other. For severe conditions, the present acceptance criterion is lenient and a more strict one is possible and desirable.

Compressive Strength

The compressive strength data are given in Table 8. For the different levels of resistance, different cement factors, water-cement ratios and air contents were used. The low w/c gives high strengths but the increased void content reduces strength. The strength values for all the concretes were high enough to provide satisfactory freeze-thaw performance where a proper air void system was achieved.

Table 8

28-Day Compressive Strength Data
(Average of 3 Specimens)

Level	Batch	w/c	Compressive Strength, lb./in.^{2} Avg.	Std. Dev.
1	1	0.44	5,420	46
	2	0.44	5,140	103
2	1	0.49	5,780	333
	2	0.49	5,620	58
3	1	0.60	4,520	204
	2	0.60	4,860	76

NOTE: 1 lb./in.^{2} = 6.89 kPA

CONCLUSIONS

1. Freeze-thaw data obtained with the two machines were comparable and distinguished the different levels of freeze-thaw resistance of the concretes. In general, the results for replicate specimens tested in machine B indicated a greater variability, as shown by the standard deviation, than the results for replicate specimens tested in machine A. This could be attributed to the larger size of machine B. But results indicate that both machines satisfactorily determine the relative freeze-thaw durabilities of concretes and the data from one machine can be related to the data from the other.

2. Concretes intended for resistance to severe freeze-thaw conditions (level 1) and those intended for moderate conditions (level 2) had satisfactory durability factors, weight losses, and surface rating values when tested in both machines. However, in salt solution, the level 2 concretes scaled considerably, although they met the established criteria. Such high surface scaling was not observed in level 1 concretes tested in either the salt solution or in water. In both cases low weight loss and surface rating values were obtained. Thus, the presence of salt in the test water as used by the Research

Council is desirable to distinguish between concretes capable of withstanding severe exposure conditions and those for moderate conditions. The use of salt should be continued, even though it is not a standard ASTM C666 procedure.

3. Specimens from level 3 concrete, which had a low air content, failed the acceptance criteria for durable concrete in both machines. They exhibited low durability factors and a high weight loss.

4. Level 3 concretes given an additional 1-week dry cure following the 2-week moist cure and tested in water had higher durability factors than those tested without the drying period. However, the durability factors obtained were not high enough in either case to assume satisfactory performance under freeze-thaw conditions.

5. The results of the linear traverse analysis were consistent with the results of the freeze-thaw tests in both machines. Concretes from levels 1 and 2 had adequate systems based on accepted criteria, with level 1 specimens showing higher specific surfaces and lower spacing factors than level 2 specimens. Thus, level 1 concretes would be expected to have better freeze-thaw resistance as confirmed by the freeze-thaw tests. Level 3 concretes had inadequate void systems as measured in the hardened concrete as well as inadequate resistance to the freeze-thaw tests.

RECOMMENDATION

Machine B should be accepted as providing appropriate data for predicting the relative freeze-thaw durability of concrete. When needed, data obtained with machine B can be compared to data obtained with the old machine. The Council's present acceptance criteria should be applicable for moderate exposure conditions and be modified for severe conditions. In the latter case the weight loss should be 4% or less, the DF 80 or more, and the surface rating 2 or less.

In view of the confirmation from the study that the use of salt in lieu of water distinguishes between severe and moderate resistance to freeze-thaw conditions in terms of surface scaling, it is recommended that the use of salt solution in the freeze-thaw tests be continued.

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