MODIFICATION OF ASTM C666 FOR TESTING RESISTANCE OF CONCRETE TO FREEZING AND THAWING IN SODIUM CHLORIDE SOLUTION

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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

Since 1961 the Research Council has used equipment manufactured by Conrad, Inc. for exposing concrete specimens to rapid cycles of freezing and thawing. In addition, the Materials Division of the Virginia Department of Highways and Transportation sends to the Research Council specimens of concrete mixtures and related materials not previously used in the Department's construction when freezing and thawing tests are required as part of the Department's acceptance procedures.

The Council's freezing and thawing procedures are based upon ASTM Designation C666 "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing", Procedure A (freezing and thawing in water), except that surrounding the specimens is a 2% solution of NaCl rather than water. Prior to exposure, specimens are moist cured for 14 days and air dried for 7 days.

Based upon about 17 years of experience in the use of this approach at the Council, the following criteria have been established for judging acceptability.

Weight loss, maximum at 300 cycles--------- 7%

Surface factor, maximum at 300 cycles------ 3%

Durability factor at 300 cycles------------ 60%

A limited evaluation of this procedure was made using NaCl solutions with concentrations of 4%, 3%, 2% and 0% (water). Concretes of three levels of expected durability were tested.

Based on these tests the following conclusions were drawn.

1. Freezing and thawing of specimens using the procedures of ASTM C666 as modified to use 2% NaCl solution as the surrounding medium rather than water is more severe and more discriminating than using water as required by the standard method.

2. Minor variations of salt concentration likely to be encountered during the progress of the testing do not significantly affect the results.

3. The period of drying between moist curing and exposure to freezing and thawing in an NaCl solution significantly improves the indicated performance.

4. Based upon ACI recommendations for durable concrete, the Council's current requirements for evaluating freezing and thawing resistance may be too lenient for concrete subjected to severe exposure conditions.

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BACKGROUND

The durability of concrete is influenced by every element of concrete technology. Sound materials, properly proportioned, are essential. Of particular importance for good performance are a low water-cement ratio and an adequate air void system. Construction operations such as mixing, placing, consolidation, and curing can substantially affect the resistance of concrete to freezing and thawing. The environment to which concrete is exposed also exerts a major influence on its performance, with the degree of saturation and the presence of deicing salts being of particular significance.

Because so many factors influence durability, there is little wonder that there is no universally accepted procedure for accelerated testing of the durability of concrete, and that numerous criticisms of the lack of correlation between laboratory test results and field performance have been expressed. Despite the lack of agreement, there obviously is a need for predicting from short-range tests the long-term durability of concrete exposed to freezing and thawing.

The most commonly used method for evaluating the resistance of concrete to freezing and thawing is ASTM Designation C666 "Resistance of Concrete to Rapid Freezing and Thawing". This method is described as "rapid" because it requires from 8 to 12 complete cycles of freezing and thawing every 24 hours as compared with earlier standard methods that require one cycle during a 24-hour period. Method C666 permits two procedures: Procedure A "Rapid Freezing and Thawing in Water", formerly ASTM C290, in which, as the title states, the specimens are frozen and thawed while surrounded by water; and Procedure B, "Rapid Freezing in Air and Thawing in Water", formerly ASTM C291, in which the specimen freezes in contact with air and thaws in contact with water.

Because the concrete is continuously saturated in Procedure A, deterioration occurs more rapidly than in Procedure B and the results tend to be more uniform for duplicate specimens. Some authorities believe that Procedure B, while it gives more variability in results, is more comparable to field exposure than Procedure A.

For both procedures, deterioration is evaluated by the following changes in resonant frequency as described in ASTM C215 "Fundamental Transverse, Longitudinal, and Torsional Frequencies of Concrete Specimens".

The relative dynamic modulus is calculated as

$$P_c = \left(\frac{n_1^2}{n^2}\right) \times 100,$$

where

P_c = relative dynamic modulus of elasticity, after C cycles of freezing and thawing, in percent;

n = fundamental transverse frequency at 0 cycles of freezing and thawing; and

n_1 = fundamental transverse frequency after C cycles of freezing and thawing.

The fundamental transverse frequency is determined with the specimens at a temperature of 42° ± 5°F (5.6° ± 2.8°C). Calculation of P_c assumes that the weight and dimensions of the specimens remain constant throughout the test. While this assumption is not true in many cases because of disintegration, the test is usually used to make comparisons between the relative dynamic moduli of specimens and P_c is adequate for the purpose.

The durability factor is calculated as

$$DF = \frac{PN}{M},$$

where

DF = durability factor of the test specimen;

P = relative dynamic modulus of elasticity at N cycles, in percent;

N = number of cycles at which P reaches the specified minimum value for discontinuing the test or the specified number of cycles at which the exposure is to be terminated, whichever is less; and

M = specified number of cycles at which the exposure is to be terminated.

Because of the danger of damage to specimen containers and other parts of the equipment, testing is usually terminated when the relative dynamic modulus of elasticity falls below 50%.

The scope of Method C666 states that "both procedures are intended for use in determining the effects of variations in the properties of concrete on the resistance of the concrete to the freezing and thawing cycles specified in the particular procedures. Neither procedure is intended to provide a quantitative measure of the length of service that may be expected from a specific type of concrete".

While these procedures have been used for about 50 years in research and materials testing and acceptance to evaluate the resistance of concrete and its constituent materials, Procedure A is currently required in only three ASTM specifications; namely C260: "Standard Specification for Air-Entraining Admixtures for Concrete", C494: "Standard Specification for Chemical Admixtures for Concrete", and C330: "Lightweight Aggregates for Structural Concrete". In both admixture specifications, the performance requirement is stated in terms of a "relative durability factor" calculated as

$$DF \text{ (or } DF_1) = PN/300 \text{ and}$$

$$RDF = ({}^{DF}/DF_1) \times 100,$$

where

DF = durability factor of the concrete containing the admixture under test;

DF_1 = durability factor of the concrete containing a reference admixture or, in the case of C494, only an approved air-entraining admixture;

P = relative dynamic modulus of elasticity in percent of the dynamic modulus of elasticity at zero cycles (values of P will be 60 or greater since the test is to be terminated when P falls below 60%);

N = number of cycles at which P reaches 60%, or 300 if P does not reach 60% prior to the end of the test (300 cycles); and

RDF = relative durability factor.

Both C260 and C494 require that the relative durability factor of the concrete containing the admixture under test be at least 80 when compared with the reference concrete. The value of 80 is not intended to permit poorer performance than that given by the reference concrete, but rather to assure the same level of performance, with appropriate recognition of the variability of the test method. The value of 80 was established before levels of precision were established for Method C666, but is consistent with recently published precision values.

As noted, the primary measure of deterioration is the relative dynamic modulus calculated from determinations of resonant transverse frequency. Two other characteristics that are commonly used are weight loss and length change. Determinations of reductions in tensile or compressive strength have been used infrequently because they require destructive tests.

The question of which measure of deterioration is best to use is complicated by the facts that the different available tests measure different things and the manner and extent to which the properties measured are related to freezing-and-thawing damage, especially under natural conditions, are matters of disagreement. Thus, the particular measure used often depends on the philosophy of the laboratory using it and on the particular purpose for which the tests are being made. Weight loss measures loss of material or sloughing from the surface of the specimens. Length change is based upon the fact that internal damage is accompanied by expansion rathe: than contraction during cooling or by a permanent dilation after a freezing and thawing cycle. Either weight loss due to sloughing or reduction in resonant frequency may occur without accompanying length change, and in Procedure A weight loss often occurs without a reduction in resonant frequency or expansion. Resonant frequency and expansion reflect internal disruptions such as are caused by unsound aggregates or deficient air void characteristics, while weight loss primarily reflects surface mortar deterioration. ASTM Subcommittee C09.03.15 is considering adding a requirement for length change measurements to Method C666, which presently requires weight and resonant frequency determinations.

In addition to the cyclic procedures specified in ASTM C666, ASTM Method 671 "Critical Dilation Procedures" was standardized in 1971 along with Recommended Practice C682 "Evaluation of Frost Resistance of Coarse Aggregates in Air Entrained Concrete by Critical Dilation Procedures". These are not widely used. Also in 1971, ASTM Method C672 "Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals" was standardized. In this method, water or salt solution is ponded on blocks which are then subjected to freezing and thawing cycles. Evaluation is based upon visually observed changes in the specimen surface. The Research Council has not used this procedure in the laboratory but does utilize its essential features in outdoor exposure testing.

CRITERIA FOR FROST RESISTANT CONCRETE

American Concrete Institute

In its recently published guide, ACI Committee 201 lists requirements on air contents for frost resistant concrete that contains sound aggregates as given in Table 1.

Table 1

ACI Recommended Air Contents

Nominal Maximum Aggregate Size, in. (mm)	Average air content, percent[a]	
	Severe[b] Exposure	Moderate[c] Exposure
1/2 (12.5)	7	5 1/2
3/4 (19)	6	5
1 1/2 (38)	5 1/2	4 1/2

[a]A reasonable tolerance for air content in field construction is ± 1 1/2%.

[b]Outdoor exposure in a cold climate where the concrete may be in almost continuous contact with moisture prior to freezing or where deicing salts are used. Examples are pavements, bridge decks, sidewalks, and water tanks.

[c]Outdoor exposure in a cold climate where the concrete will be only occasionally exposed to moisture prior to freezing and where no deicing salts will be used. Examples are certain exterior walls, beams, girders, and slabs not in direct contact with soil.

No nationally recognized specifications contain requirements for air void characteristics of hardened concrete. Powers (1949), on the basis of theoretical and empirical information, suggested that the maximum permissible spacing factor, $\bar{\ell}$, of concrete with 3% entrained air was 0.010 in. (0.25 mm). Mielenz and his co-workers (1958), on the basis of extensive measurements of laboratory and field concrete, suggested 0.008 in. (0.20 mm). This value has generally been accepted.

ACI Committee 201 has also suggested maximum water-cement ratios to provide durability under two levels of exposure. These are given in Table 2.

Table 2

ACI Recommended Water-Cement Ratios

Element	Maximum Water-Cement Ratio
Thin sections (bridge decks, railings, curbs, etc.) and any concrete exposed to deicing salts	0.45
All other structures	0.50

Virginia Department of Highways and Transportation

Most structural and paving concrete used by the Virginia Department of Highways and Transportation is exposed to some deicing chemicals. The requirements for the major classes of concrete are given in Table 3.

Table 3

Water-Cement Ratios and Air Contents Specified by the Virginia Department of Highways and Transportation

Class	Use	Nominal Max. Aggregate Size, in. (mm)	Water-Cement Ratio	Air Content, percent
A-3	General	1 (25)	.49	6 ± 2
A-3	Paving	2 (50)	.49	6 ± 2
A-4	Post and rails	1/2 (12.5)	.47	7 ± 2
A-4	Superstructure and bridge decks	1 (25)	.47	6 1/2 ± 1 1/2

The requirements of the Department are in general agreement with those of ACI. For class A-4 concrete the permissible water-cement ratio is slightly higher, but so are the requirements for entrained air.

The improvement of durability with increasing air content is not a continuous function but rather is like that developed by Cordon and Merrill (1963) and shown in Figure 1. No corresponding data are available for hardened concrete, but similar relationships between the durability factor and the spacing factor would be expected. A similar relationship would be expected for the combined effects of water-cement ratio and air content. Exposure to freezing and thawing in the presence of deicing chemicals would be expected to shift the curve to the right. The importance of the relationship shown in Figure 1 is that the transition zone covers a comparatively broad range of air contents and rises sharply. This means that concrete with air void or water-cement ratio characteristics in this transition zone will show a wide range of durability. Also, test results in the transition area will be more variable than those above or below the zone. This is the behavior that has been observed consistently in testing for freezing and thawing.

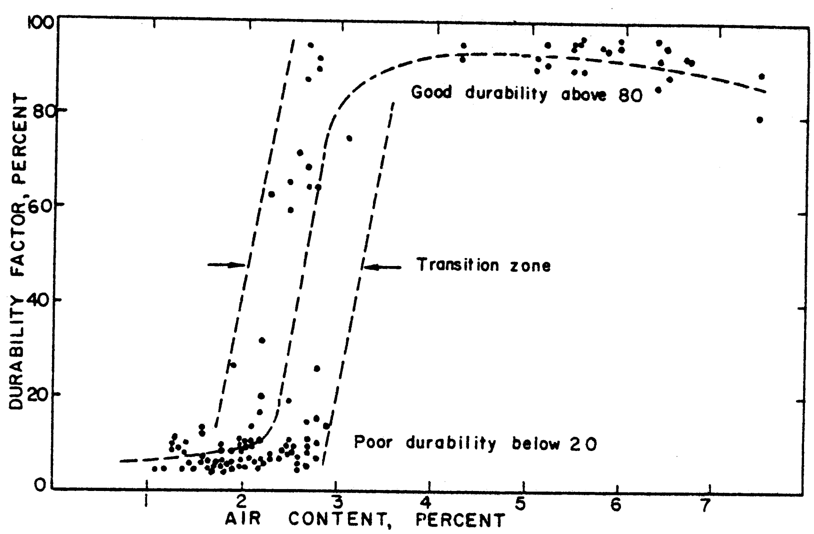

Figure 1. Durability of concrete containing various aggregates, with varying cement content, water-cement ratios and air contents (after Cordon and Merrill, 1963).

RESEARCH COUNCIL FREEZING AND THAWING TESTS

Equipment

In 1961 the Research Council installed equipment for the automatic cycling of specimens in accordance with ASTM requirements. According to information compiled by ASTM Committee C09.03.15, the equipment, manufactured by Conrad, Inc., was purchased by 17 agencies before 1968. The capacity of the Council's chamber is 30 specimens. Most other Conrad machines were of 60 specimen capacity. The evaluation tests were reported by Newlon and McGhee (1966). The conclusions from the evaluation are reproduced in the Appendix. The performance of the equipment was reported to be excellent and the laboratory results were consistent with the field performance of various concretes tested, based upon service records. The only problem reported was the creation of excessive pressures in the specimen containers during freezing in water. This not only was detrimental to the metal containers used but resulted in overly severe damage to the specimens. This condition has subsequently been alleviated by using silicone rubber relief panels in one corner of the metal containers. The equipment has performed satisfactorily in practically continuous use since 1962.

At the time the equipment was acquired there were no national standards for evaluating resistance of concrete surfaces to scaling as are now contained in ASTM C672. The need within Virginia for information on surface mortar deterioration (scaling) led to the use of the Conrad equipment and what is now ASTM C666-Procedure A, with the modification that the specimens were frozen while surrounded by a 2% solution of NaCl rather than water. Comparison of these results with those from outdoor exposure specimens essentially like those later required by ASTM C672 and field performance indicated that the results from the several methods were comparable (Newlon 1970). The objective of those earlier tests was primarily to evaluate linseed oil and other protective treatments. Because the objective of these studies was evaluation of surface damage, the deterioration was evaluated by weight loss and visual appearance as well as by the durability factor, DF. The same approach has been used in subsequent evaluations of rapid patching materials. The apparently useful results obtained and the backlog of information developed for comparing performances of various materials have resulted in the general use in Virginia of this modification of ASTM C666 for all freezing and thawing tests conducted by the Research Council, unless the requirements of ASTM C666 are specifically needed.

Council Procedure

Following fabrication, the specimens are moist cured in the molds for 24 hours, after which they are demolded and placed in the moist room for 13 days. Following the 14-day period of moist curing, they are stored in the laboratory air for 7 days. The temperature in the laboratory usually varies between 68° and 75°F (20° and 29°C), while the relative humidity normally varies between 35% and 45%.

At an age of 21 days, the specimens are weighed and placed in the freezer. During testing the specimens are in metal containers and are surrounded by a 2% NaCl solution. All other details of the procedure conform to ASTM C666: Procedure A.

Data are taken to permit calculation of (1) weight loss, (2) the relative durability factor, and (3) the surface rating factor. Because the specimens are not completely saturated at the beginning of testing, there usually is a slight weight gain during the initial cycles. In calculating the weight loss, the maximum weight achieved is used as the base rather than the weight at the time the specimen is placed in the freezer.

The surface factor is based upon the rating system shown in Table 4.

Table 4

Rating System Used for Evaluation

Condition	Surface Appearance
0	No scaling
1	Very slight scaling (1/8" (3 mm) maximum depth — no coarse aggregate visible)
2	Slight to moderate scaling
3	Moderate scaling (some coarse aggregate visible)
4	Moderate to severe scaling
5	Severe scaling (coarse aggregate visible over entire surface)

Since the degree of deterioration of a given specimen varies, a weighted rating is used such that a surface showing 30% condition 5, 35% condition 3, 20% condition 1, and 15% scale-free surface would be rated (.30 x 5 + .35 x 3 + .20 x .1 + 15.0) = 2.75. The tops, which are struck off, are rated separately from the sides and bottoms, which are cast against the steel forms.

Based upon several previous studies and observance of field performance, the following criteria are used for judging acceptable performance using the Council's modification of ASTM C666.

Weight loss, maximum at 300 cycles............. 7%

Surface factor, maximum at 300 cycles.......... 3%

Durability factor at 300 cycles................60%

PURPOSE AND SCOPE

Because freezing and thawing tests as conducted by the Research Council differ from ASTM C666 there is naturally a question as to how the differences, particularly the use of NaCl solution rather than water, influence the results. To obtain order of magnitude answers to this question, a limited evaluation was made. The purposes of the study were to —

1. determine the order of magnitude difference of results obtained using the Council's freezing and thawing procedures and those from testing in accordance with ASTM C666-Procedure A; and

2. determine the influence of salt concentration on the results, which is important because it sometimes is difficult to maintain closely the original concentration during the test.

VARIABLES AND PROCEDURES

Limited by the space available in the freezer, two variables were selected for study: (1) the level of frost resistance of the concrete as reflected by air content, and (2) the concentration of the surrounding NaCl solution.

Because non-air entrained concrete has consistently failed very rapidly in the equipment, all concrete was purposefully air entrained. To obtain two levels of frost resistance, two air contents, 3.5% and 8.0%, were used. Based upon the ACI recommendations, the 3.5% air content was slightly below the lower limit for satisfactory performance in a moderate exposure condition, while the 8% air content was slightly above that recommended for a severe exposure. Based upon the relationship that was shown in Figure 1, the 3.5% air content would be near the transition zone and might or might not be expected to provide an acceptable durability factor.

The aggregates were of excellent quality based upon service records and past testing. Type II cement was used. All specimens of a given air content were taken from the same laboratory batch. The important properties are shown in Table 5. Although no non-air entrained concrete was included in the testing program, non-air entrained specimens were prepared in a subsequent test series with the same mixture proportions and materials for testing in 2% NaCl only. In all other respects these non-air entrained specimens were treated like those in this testing program. This batch is listed in Table 5 as "Batch 0" and the results are shown later for comparison. Although the measured air content was 3%, there was no purposeful air entrainment.

Table 5

Concrete Properties

Batch	Air Content, %	Cement Content lb_f/yd^3 (kg/m^3)	Water-Cement Ratio	Slump in. (mm)
0	3.0	634 (376)	.47	0.6 (15)
1	3.5	634 (376)	.46	2.5 (63)
2	8.0	634 (376)	.46	4.2 (106)

For each condition, except for Batch 0, three specimens were exposed to freezing and thawing in each of four concentrations of NaCl solution, 0%, 2%, 3%, and 4%. The 0% solution, of course, is water corresponding to the conditions of ASTM C666, Procedure A. From each of the three batches one specimen was used for determination of the air void characteristics of the hardened concrete according to ASTM C457.

In a subsequent study of concrete containing fly ash and Type 1P cement, the general character of these concretes and their treatment were like those for the test series. The characteristics of these mixtures are given in Table 6. It was intended that these specimens receive the standard curing used at the Council; namely, 14 days moist curing followed by 7 days of drying. Due to a breakdown of the equipment, however, the specimens were continuously moist cured for 67 days and exposed to freezing and thawing without drying. These specimens thus provide some indication of the relative influence on the results of curing and/or drying.

Table 6

Properties of Concrete from Supplemental Batches

Batch	Variable	Air Content, %	Cement Content, lb./yd^3 (kg/m^3)	Water-Cement Ratio	Slump in.(mm)
3	Type II cem.	6.6	588 (348)	0.46	3.4 (86)
4	1P	6.6	588 (348)	0.46	2.9 (73)
5	I + Ash	6.1	506-cem {300} 125-f.a. {74}	0.43	3.4 (86)

RESULTS

The air void characteristics of the hardened concrete are shown in Table 7. Air void parameters of the supplemental batches were not determined.

The air void characteristics are as would be expected. Only Batch 2 meets the spacing factor criterion of Mielenz (1958). The spacing factor from batch 1 is approximately that suggested by Powers (1949). Batches 0 and 1 lie in the transition zone shown in Figure 1.

Table 7

Air Void Characteristics

Batch	Air Content, %.		Specific Surface, in^3/in^2 (mm^3/mm^2)	Spacing Factor, in. (mm)
	Freshly Mixed	Hardened		
0	3.0	3.2	200 (7.9)	0.0308 (0.78)
1	3.5	3.4	524 (20.6)	0.0106 (0.27)
2	8.0	8.8	764 (30.0)	0.0043 (0.11)

The results from freezing and thawing tests are shown in Figure 2. The data in Figure 2 indicate the average and one-sigma limits (1S) for the durability factor, weight loss, and surface factor* for each of the study variables. The 1S limits are used since these are the basis for the precision statement in ASTM C666, based upon ASTM Recommended Practice C670 "Preparing Precision Statements for Test Methods for Construction Materials". The precision statement in ASTM C666 indicates that for sets of 3 replicate beams, results are acceptable if the standard deviation is less than 0.6 when the durability factor is between 95 and 100, or 0.9 when the durability factor is between 5 and 10. The results meet these criteria. The standard deviations for both the low and high levels of air entrainment are 0.29. The results indicate that beams tested in salt solution are more variable, as might be expected. Of the six remaining combinations of air content and salt solution, two are acceptable and one is comparatively close (std. dev. = 1.0). While the variability of the data for freezing and thawing in salt solution weakens the confidence of general conclusions, several interesting and defensible trends are apparent.

As would be expected the non-air entrained concrete fails by all of the criteria listed earlier. The behavior of the two air entrained concretes is in general that expected, although the concrete with low levels of entrained air performed somewhat better than might have been anticipated with respect to durability factor and weight loss. Assuming that a limit of 3.0 on a 5-point scale would correspond to 2.5 on a 4-point scale, the concrete with the lower level of air would be "borderline" when exposed to freezing and thawing in 2% NaCl solution.

The results from testing in the salt exposure clearly distinguish between the low and high air content concretes, whereas testing in water as specified in ASTM C666 does not. As noted earlier, 3.5% is approximately the lower level for recommended satisfactory performance in a "moderate" exposure. The laboratory controls to ensure proper portioning and water-cement ratio, adequate mixing, consolidation, and curing tend to improve the concrete quality when compared with that placed under field conditions. One might thus expect that the concrete with 3.5% air would be adequate for a "moderate" exposure and clearly that with the 8% air content would be satisfactory for a severe exposure (recognizing that the water-cement ratio is slightly higher than that recommended by ACI). As reflected by the data, no significant difference is indicated when freezing and thawing occurs in water. While ASTM C666 has often been criticized as being too severe when compared with field exposures, the implication of the data when compared with the recommendations of ACI Committee 201 is that Method C666 represents the "moderate" exposure; the severe exposure is better represented by the results from freezing and thawing in the presence of salt solution.

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*Inadvertently, the surfaces were rated on a scale of 1 to 4 rather than the standard Council (ASTM) scale of 1 to 5.

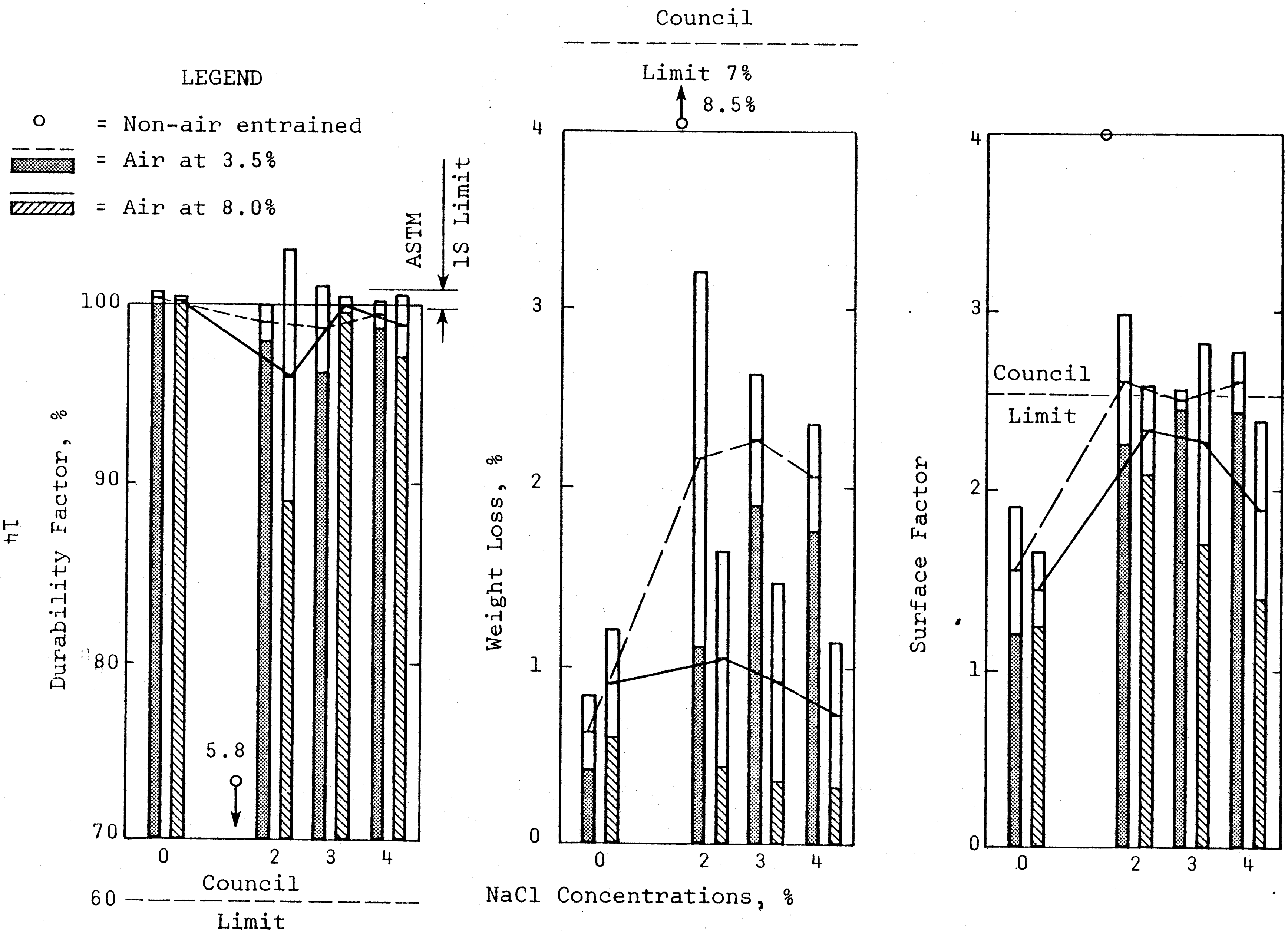

Figure 2. Results of freezing and thawing tests.

While the testing in NaCl solution separates the two levels of air entrainment, both batches 1 and 2 meet the criteria established by the Research Council for acceptable performance, except for the surface factor (on a corrected basis), where the performance is "borderline." This is true despite the fact that the spacing factor of the concrete with 3.5% air content is greater than the generally accepted value.

The results also indicate no significant difference for the several levels of salt concentration, although there is a trend toward maximum deterioration at the intermediate salt contents. This observation is consistent with the findings of Verbeck and Klieger (1957), which they explained in terms of the generation of osmotic pressures from the migration of water from areas of higher to lower salt concentration. The osmotic pressures would add to hydraulic pressures accompanying the conversion of water to ice.

Another conclusion to be drawn is that while the presence of salt accelerates the deterioration, the precise control of salt concentration is not critical in the 2% to 3% range.

From these tests both concretes would be judged acceptable, but the concrete containing 3.5% air would be suspect. Based upon ACI recommendations and other experience, the 3.5% air content would not be acceptable for severe exposures. Thus, the criteria used by the Research Council may be too lenient for judging concretes to be exposed to severe conditions.

Another factor that accounts for the better than expected performance of the concrete with 3.5% entrained air is the opportunity for drying provided in the Council's regimen. It is well known that such drying significantly increases resistance to freezing and thawing as compared with the continuous moist curing required by ASTM C666. A major reason for specifying continuous moist curing is that it is more reproducible from laboratory to laboratory. That the period of drying does not overcome the complete lack of air entrainment is clearly demonstrated by the failure of concrete from batch 0.

The results for the supplementary batches described in Table 6 are shown in Figure 3 along with the results from batch 2 for comparison. With the exception of the anomolus durability factor, results for batch 5, the results show several interesting and consistent trends.

First, as would be expected, performance was poorer by all measures where freezing and thawing took place in the NaCl solution.

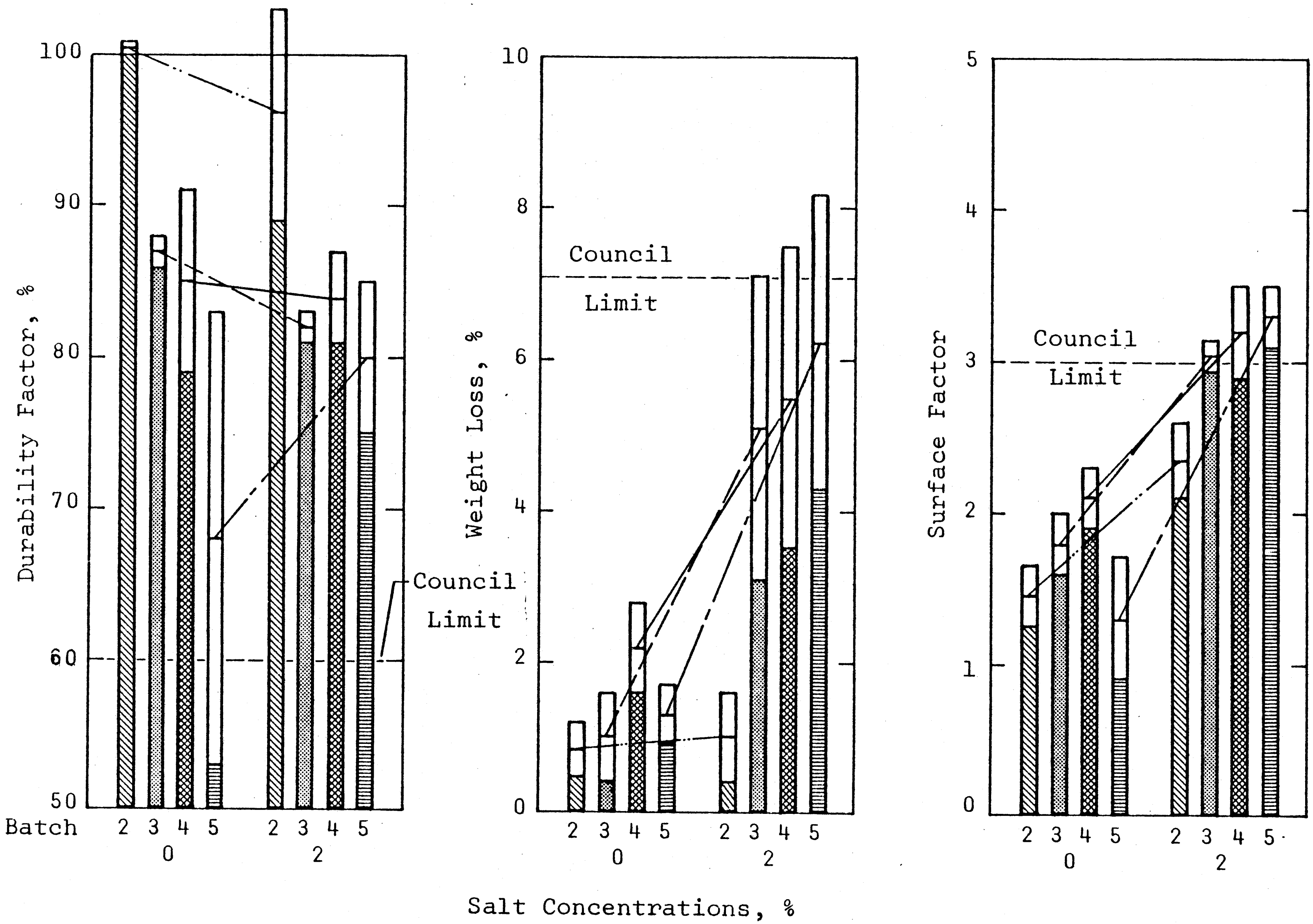

Figure 3. Results from supplemental freezing and thawing tests.

Of the three indicators the durability factor was least, and probably not significantly, affected. This would be expected since the durability factor reflects internal rather than surface damage. The results also suggest that the 7-day period of drying is particularly beneficial in improving surface performance as measured by weight loss and surface rating when freezing and thawing occurs in an NaCl solution.

A comparison of these data for batches 2 and 3 shows that the weight loss for batch 2 is the same for testing in water and in NaCl where drying took place. For batch 3, where no drying occurred, even though the moist curing period was much longer there was a significant increase in weight loss for testing in NaCl as compared with testing in water. Such behavior is not surprising since research has shown that concrete that has dried is very difficult to resaturate. This influence would be particularly evident in surface behavior.

The slightly increased tendency for scaling of concrete containing fly ash or Type IP cement indicated by testing in NaCl is consistent with results from other laboratory and field studies conducted by the Research Council.

Because exposure to rapid testing involves high rates of freezing and thawing, the deterioration is primarily the result of hydraulic pressures. The benefits of entrained air might be overemphasized as compared with field exposures, where freezing and thawing rates result in deterioration from a combination of hydraulic and osmotic pressures, as recently discussed by Powers (1975).

CONCLUSIONS

Based upon the results from this limited study it is concluded that:

1. Freezing and thawing of specimens using the procedures of ASTM C666 as modified to use 2% NaCl solution as the surrounding medium rather than water is more severe and more discriminating than using water as required by the standard method.

2. Minor variations of salt concentration likely to be encountered during the progress of the testing do not significantly affect the results.

3. The period of drying between moist curing and exposure to freezing and thawing in an NaCl solution significantly improves the indicated performance.

4. Based upon ACI recommendations for durable concrete, the Council's current requirements for evaluating freezing and thawing resistance may be too lenient for concrete subjected to severe exposure conditions.

RECOMMENDATIONS

1. The modified ASTM C666 procedure currently used by the Council should continue to be used to evaluate concretes for use by the Department. When it is deemed desirable to determine if a product also meets the requirements of standards such as ASTM C494, simultaneous tests may be made using both the standard C666 procedure and the Research Council's modification.

2. Steps should be taken to permit length change measurements in addition to the three measurements now being used.

3. The data accumulated from the Council's years of testing should be analyzed to seek relationships among durability factors, weight loss, surface ratings and the air void parameters of the hardened concrete.

4. A long-range program should be initiated consistent with available freezer space to gather information not available from past data by testing concretes reflecting different air void parameters and curing conditions. Among variables that should be included are:

   a. A wide range of spacing factors, bubble size, and/or water-cement ratios;

   b. different periods of moist curing and drying; and

   c. different strength levels at the initiation of freezing.

5. Whenever freezing and thawing specimens are fabricated, an additional specimen should be made for air void measurements. Air void characteristics should also be determined on a beam after testing for comparison of results.

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APPENDIX

CONCLUSIONS FROM NEWLON-MCGHEE REPORT (1966)

Based upon the data presented, the following conclusions appear to be warranted.

(1) The equipment is capable of providing a closely controlled and reproducible cycle meeting the requirements of ASTM Designation C291. The variation of environmental conditions among specimens within the chamber area is small.

(2) Use of the equipment for tests in accordance with ASTM C290 can result in excessive pressures and damage to both specimens and containers. It is believed that these difficulties can be overcome with relatively minor modifications. Further research to determine the effect of such modifications is needed.

(3) Mechanically, the performance of the equipment has been excellent. The efficiency over a three-year period was 96.5% based upon the ratio of the number of cycles obtained to the cycles possible.

(4) Tests conducted with the equipment resulted in classification of the various concretes consistent with field service records. Separation was obtained between concretes having relatively small differences in potential resistance to freezing and thawing.

(5) Variations between results of comparable concretes tested over a relatively long period were smaller than those reported by many previous investigators. While this might be fortuitous, at least a part is felt to be attributable to the reproducible environment provided by the equipment.

(6) The equipment and procedures appear to give excellent estimates of the sensitivity of aggregates to freezing and thawing.

(7) Concrete without entrained air fails after 10-20 cycles. Such rapid failure probably results from the high rate of cooling, although it is well known that non-air entrained concrete usually has poor resistance to freezing and thawing.

APPENDIX (continued)

(8) The limits provided in ASTM Designation C291 for termination of testing at 300 cycles or when the relative modulus of elasticity, P_c, reaches 60% of the initial modulus are compatible with the results of this project.