Compressive Strength Recommendations for Protecting Concrete from Multiple Freezing-and-Thawing Cycles

How well do they match the data?

by Ronald L. Kozikowski, James Klinger, and Bruce A. Suprenant

ACI has published three guides that provide compressive strength recommendations for protection of concrete from multiple cycles of freezing and thawing (F&T): ACI 201.2R-16, "Guide to Durable Concrete,"[1] recommends a 3500 psi (24 MPa) average in-place compressive strength; ACI 306R-16, "Guide to Cold Weather Concreting,"[2] recommends a 3500 psi compressive strength during construction; and ACI 308R-16, "Guide to Curing Concrete,"[3] recommends a 4000 psi (28 MPa) compressive strength while the concrete is in service.

Among the three ACI specifications that are commonly used in construction, only one provides a strength requirement for concrete exposed to multiple cycles of F&T during construction: Section 3.5.3 of ACI 308.1-11, "Specification for Curing Concrete,"[4] states: "Do not expose saturated concrete to cycles of freezing and thawing until the concrete has reached the compressive strength of 3500 psi." ACI 301-20, "Specifications for Structural Concrete,"[5] and ACI 306.1-90 (Reapproved 2002), "Standard Specification for Cold Weather Concreting,"[6] are silent on the topic.

In this article, we compare the recommendations in ACI 201.2R, ACI 306R, and ACI 308R and the requirement in ACI 308.1 to data from tests of normalweight and lightweight concrete specimens exposed to multiple cycles of F&T.

Tests on Concrete in a Saturated Condition

While ACI 201.2R, ACI 306R, and ACI 308R provide strength recommendations and ACI 308.1 provides a strength requirement, none of these ACI documents cite references for their strength recommendations for saturated concrete exposed to multiple cycles of F&T. Nonetheless, test data comprising measured compressive strengths and cyclic F&T test results are available from Klieger,[7] Gebler and Klieger,[8] Klieger,[9] and Klieger and Hanson[10] for the following mixtures:

- Normalweight concrete with portland cement (38 tests)[7];
- Normalweight concrete with portland cement and 25% fly ash (20 tests)[8];
- Normalweight concrete with portland cement and sand-gravel aggregates (15 tests)[9]; and
- Lightweight concrete with portland cement (40 tests).[10]

Normalweight concrete with portland cement

Klieger[7] presented the percent expansion at 800 cycles of F&T along with the corresponding cube compressive strength at the beginning of cyclic F&T. Flexural beam ends were used as 6 in. (152 mm) modified cubes for compressive strength tests and two complete cycles of F&T were obtained every 24 hours with the prisms being continually immersed in tap water. The rate of cooling was approximately 20°F/hour (11°C/hour). Periodic determination of changes in weight, length, and sonic modulus were used as durability criteria. The tests were stopped at 800 cycles of F&T or when a test specimen reached 0.10% expansion. In Fig. 1, expansion at 800 cycles is plotted as a function of cube compressive strength for 38 tests of concretes with the water-cement ratio (*w/c*) ranging from 0.42 to 0.91 and air contents from 4.3 to 16%. We excluded data for specimens with air contents below 4%.

Four specimens did not reach 800 cycles before reaching 0.10% expansion. Three of these had low strengths associated with high *w/c* values of 0.91, 0.74, and 0.62. ACI 318-19 would not permit concrete with such high *w/c* values to be exposed to F&T in a saturated condition.[11] Thus, we have

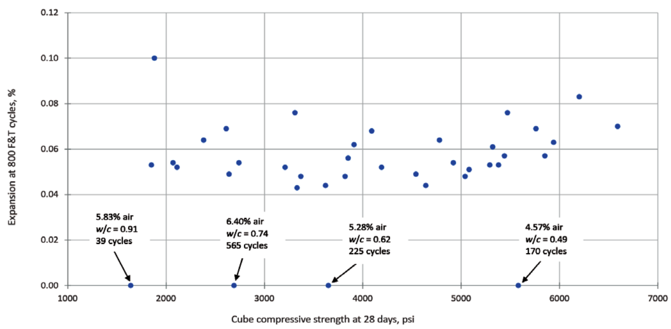

Fig. 1: Percent expansion after 800 cycles of F&T versus cube compressive strength for 38 tests (4, 5-1/2, and 7 sack/yd[3] [223, 307, and 390 kg/m[3]] cement concrete mixtures with 4.3 to 16% air and *w/c* between 0.42 and 0.91)[7] (Note: 1 psi = 0.007 MPa)

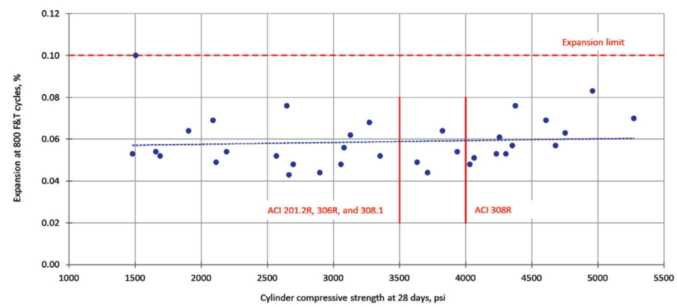

Fig. 2: Percent expansion after 800 cycles of F&T versus cylinder compressive strength for 34 tests from Klieger data[7] (Note: 1 psi = 0.007 MPa)

excluded them from consideration in the following discussion. One specimen exhibited a cube compressive strength of about 5500 psi (38 MPa) yet reached only 170 cycles before reaching 0.10% expansion. While it appears to be an outlier, the concrete mixture had a 3/8 in. (9.5 mm) maximum size aggregate (MSA), an air content of 4.6%, and a *w/c* of 0.49. For a mixture with 3/8 in. MSA, ACI 318-19 would require an air content of 7.5 ± 1.5% (at least 6.0%) and a maximum *w/c* of 0.45. Because this mixture would not be permitted by the Code, it was also discarded from consideration.

Figure 2 shows the curated Klieger data with a linear regression line. Cube compressive strengths were multiplied by 0.8 to obtain approximate cylinder compressive strengths. Vertical lines in Fig. 2 designate minimum strengths for saturated concrete as stated in four ACI documents:

- 3500 psi per ACI 306R-16, ACI 201.2R-16, and ACI 308.1; and
- 4000 psi per ACI 308R-16.

Based on these limits, a change in F&T behavior should occur in the strength range of 3500 to 4000 psi. However, as can be seen in Fig. 2, this does not happen. To the contrary, the regression line shows a slight increase in F&T resistance with decreasing compressive strengths.

Based on the test results in Fig. 2, one can argue that ACI recommendations/requirements are very conservative. ASTM C666/C666M-15, "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing," stops F&T testing at an expansion of 0.10% or 300 cycles. Klieger's data shows that saturated concretes with compressive strength as low as 1310 psi (9 MPa) are resistant to 800 F&T cycles.

Normalweight concrete with portland cement and fly ash

Gebler and Klieger[8] presented durability factors for F&T testing of concrete mixtures with water-cementitious materials ratios (*w/cm*) ranging from 0.40 to 0.45 (mixtures had 25% cement replacement with fly ash by weight) and air contents from 5.9 to 6.8%. Specimens were tested in accordance with ASTM C666/C666M, Procedure A. Concrete prisms, 3 x 3 x 11-1/4 in. (75 x 75 x 285 mm), were cast and consolidated by standard rodding techniques. Prisms were cured and tested for F&T resistance.

For Set No. 1, after 1 day in molds at 73 ± 3°F (23 ± 1.7°C), prisms were moist cured at 73 ± 3°F for 13 days followed by storage in laboratory air at 73 ± 3°F and 50 ± 5% relative humidity (RH) for 14 days.

For Set No. 2, after 1 day in molds at 40 ± 3°F (4.4 ± 1.7°C), prisms were moist cured at 40 ± 3°F for 13 days followed by storage at 40 ± 3°F and 95 ± 5% RH for 14 days.

Compressive strength at 28 days was measured using three 3 x 6 in. (76 x 152 mm) cylinders for each set of curing conditions. Cylinder compressive strengths ranged from 2910 to 5250 psi (20 to 36 MPa).

The durability factor at 300 F&T cycles versus cylinder compressive strength for 20 tests is plotted in Fig. 3.

All the durability factors exceed 80%, which is considered to indicate good-quality concrete. The trend of the data shows the durability factor decreasing slightly with lower strength. The average durability factor for concrete strengths above 4500 psi (31 MPa) was about 100%, while the average durability factor for concrete strengths less than 4500 psi was about 95%. The weight loss for concretes cured at 73°F were all below 5%. The weight loss for concretes with Class C fly ash cured at 40°F was low; however, several concrete mixtures with Class F fly ash showed weight loss of up to 18.5%. There was no significant decrease in the F&T resistance of concretes in the strength range of 3000 to 4500 psi.

Normalweight concrete with portland cement and sand-gravel aggregates

Klieger[9] evaluated the percent expansion at 300 F&T cycles along with the corresponding cube compressive strength at the time of testing. Flexural beam ends were used as 6 in. modified cubes for compressive strength tests. Two complete cycles of F&T were obtained every 24 hours, with the prisms being continually immersed in tap water. The rate of cooling was approximately 20°F/hour. Periodic determination of changes in weight, length, and sonic modulus were used as durability criteria. The F&T tests were stopped at 300 cycles or when a test specimen reached 0.10% expansion.

The percent expansion at 300 F&T cycles versus cylinder

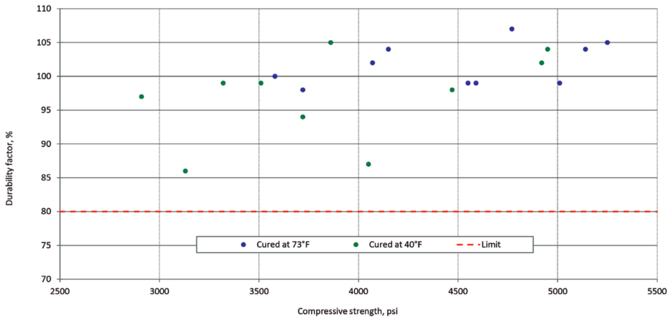

Fig. 3: Results of ASTM C666/C666M testing of two sets of specimens (20 tests) versus mean compressive strength of three 3 x 6 in. cylinders for concrete mixtures with 517 lb/yd^3 cementitious materials (75% cement and 25% fly ash), 5.9 to 6.8% air, and *w/cm* of 0.40 and 0.45[8] (Note: 1 psi = 0.007 MPa)

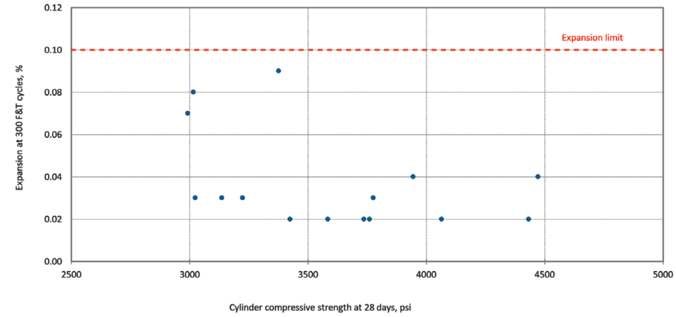

Fig. 4: Percent expansion after 300 cycles of F&T versus cylinder compressive strength for 15 tests for concrete mixtures with 5.3 to 12.4% air and *w/c* from 0.39 to 0.50[9] (Note: 1 psi = 0.007 MPa)

compressive strength for 15 tests is plotted in Fig. 4. Cube compressive strengths were multiplied by 0.8 to obtain approximate cylinder compressive strengths. The cylinder compressive strengths for concretes with air contents from 5.3 to 12.4% ranged from 2990 to 4740 psi (21 to 33 MPa).

Figure 4 shows that on average, the expansion was lower for concrete strengths ranging from 3000 to 4500 psi. Three mixtures with strengths ranging from 3000 to 3500 psi and air contents from 8.6 to 11.9% had higher expansions yet fell below the 0.10% limit.

Lightweight concrete with portland cement

Klieger and Hanson[10] evaluated durability factors for 3 x 3 x 11-1/4 in. concrete prisms made from lightweight non-air-entrained and air-entrained mixtures. They also prepared cylinders for compressive strength, unit weight, and absorption determinations. For the 3000 psi series, with air contents ranging from 1.5 to 4.5% for non-air-entrained concrete and 4.4 to 8.6% for air-entrained concrete, one 6 x 12 in. (152 x 305 mm) cylinder from each concrete mixture was cured for 28 days at 73°F and 100% RH. For the 4500 psi series, with air contents ranging from 0.7 to 3.1% for non-air-entrained concrete and 4.6 to 7.5% for air-entrained concrete, two 6 x 12 in. cylinders for each concrete were cured for 7 days at 73°F and 100% RH, followed by 21 days in air at 73°F and 50% RH.

Prisms were cured 14 days at 73°F and 100% RH followed by 14 days at 73°F and 50% RH. The prisms were then immersed in water for 3 days prior to the start of the F&T tests. The prisms were frozen and thawed while continually immersed in tap water. Two cycles of F&T were obtained every 24 hours, 7 days per week. The minimum specimen temperature attained was approximately −10°F (−23°C) and the maximum was approximately 55°F (13°C).

Klieger and Hanson[10] stated that in a recent study of F&T test procedures, this test produced results comparable to those obtained by the procedures outlined in ASTM C290-57T, "Method of Test for Resistance of Concrete Specimens to Rapid Freezing and Thawing in Water (Tentative)" (withdrawn in 1971 and replaced by ASTM C666/C666M). The test prisms were measured periodically for changes in fundamental transverse frequency (ASTM C215, "Standard Test Method for Fundamental Transverse, Longitudinal, and Torsional Resonant Frequencies of Concrete Specimens"), length (ASTM C157/C157M, "Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete"), and weight.

Durability factors at 300 F&T cycles versus cylinder compressive strengths for 40 tests of concretes with air contents between 4.0 and 8.5% are plotted in Fig. 5.

Based on the results, compressive strength may not be the best indicator of F&T resistance for lightweight concrete. Many lightweight concrete mixtures had durability factors of about 80% for compressive strengths ranging from 2000 to

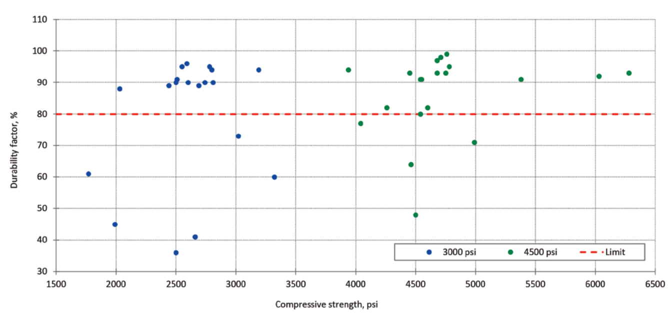

Fig. 5: Results of ASTM C666/C666M testing after 300 cycles of F&T versus 6 x 12 in. cylinder compressive strength for 40 tests. Tested concrete mixtures were designed for 3000 and 4500 psi nominal strength, included nine different lightweight aggregates, and had 4.0 to 8.5% air[10] (Note: 1 psi = 0.007 MPa)

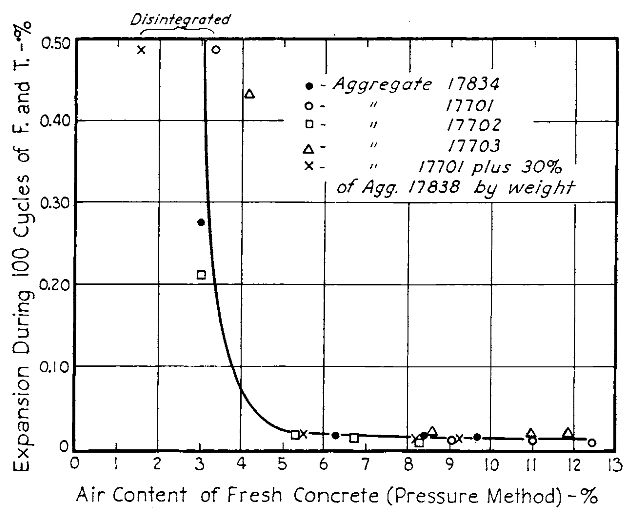

Fig. 6: Test result from Klieger[9] showing fresh air content versus expansion during 100 cycles of F&T. Note that at air contents below 4%, the expansion is high, indicating poor resistance to F&T

Table 1:
Comparison of ACI recommendations and test results

Document	Recommendation or requirement	Reference or no. of tests	Concrete resistant to F&T	Air content, %
Durable concrete (ACI 201.2R-16)	3500 psi	None	—	—
Cold weather concreting (ACI 306R-16)	3500 psi	None	—	—
External curing of concrete (ACI 308R-16)	4000 psi	None	—	—
Curing concrete (ACI 308.1-11)	3500 psi	None	—	—
Normalweight concrete (Klieger[7])	—	38	1300 psi*	6
Normalweight concrete with fly ash (Gebler and Klieger[8])	—	20	2900 psi*	6
Normalweight concrete with sand-gravel aggregates (Klieger[9])	—	15	3000 psi*	11
Lightweight concrete (Klieger and Hanson[10])	—	40	Inconclusive based on strength	NA

*No tests for specimens with a lower compressive strength were performed
(Note: 1 psi = 0.007 MPa)

6500 psi (14 to 45 MPa), and some lightweight concrete mixtures had durability factors below 80% for compressive strengths ranging from 1500 to 5000 psi (10 to 34 MPa).

Analysis and Recommendations

As shown in Table 1, the ACI compressive strength recommendations/requirements for normalweight concrete exposed to multiple F&T cycles are very conservative. Klieger[9] concluded that the resistance to multiple F&T cycles is controlled by air content. Based on the results of his research, the expansion was high at air contents below 4%, indicating poor resistance to F&T (shown in Fig. 6).

Thus, a strength recommendation may not be an appropriate parameter to determine the behavior of concrete exposed to multiple F&T cycles. Even at the lowest compressive strength, normalweight concrete specimens with appropriate air contents performed well in multiple F&T tests. Based on the analysis of the test results presented in this article, if a compressive strength recommendation needs to be provided, 1500 psi (with air content of 6%) might be an appropriate value.

The compressive strength recommendation for lightweight concrete is more complicated, as the resistance of lightweight concrete to multiple F&T cycles does not appear to be a function of strength.

From our analysis of available test data, we urge ACI Committees 201, Durability of Concrete; 306, Cold Weather Concreting; and 308, Curing Concrete, to reexamine their recommendations/requirements for compressive strength of concrete exposed to multiple cycles of F&T. In addition to reviewing existing references, this may require obtaining new test data or of the rationale for the resulting recommendations/requirements.

References

1. ACI Committee 201, "Guide to Durable Concrete (ACI 201.2R-16)," American Concrete Institute, Farmington Hills, MI, 2016, 84 pp.

2. ACI Committee 306, "Guide to Cold Weather Concreting (ACI 306R-16)," American Concrete Institute, Farmington Hills, MI, 2016, 24 pp.

3. ACI Committee 308, "Guide to External Curing of Concrete (ACI 308R-16)," American Concrete Institute, Farmington Hills, MI, 2016, 36 pp.

4. ACI Committee 308, "Specification for Curing Concrete (ACI 308.1-11)," American Concrete Institute, Farmington Hills, MI, 2011, 7 pp.

5. ACI Committee 301, "Specifications for Concrete Construction (ACI 301-20)," American Concrete Institute, Farmington Hills, MI, 2020, 69 pp.

6. ACI Committee 306, "Standard Specification for Cold Weather Concreting (ACI 306.1-90) (Reapproved 2002)," American Concrete Institute, Farmington Hills, MI, 1990, 5 pp.

7. Klieger, P., "Effect of Entrained Air on Strength and Durability of Concrete with Various Sizes of Aggregates," Highway Research Board, Bulletin 128: Durability of Concrete, Nov. 1956, pp. 1-19.

8. Gebler, S.H., and Klieger, P., "Effect of Fly Ash on the Durability of Air-Entrained Concrete," SP-91, *Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete*, American Concrete Institute, Farmington Hills, MI, 1986, pp. 483-520.

9. Klieger, P., "Effect of Entrained Air on Concretes Made with So-Called 'Sand-Gravel' Aggregates," *ACI Journal Proceedings*, V. 45, No. 10, Oct. 1948, pp. 149-163.

10. Klieger, P., and Hanson, J.A., "Freezing and Thawing Tests of Lightweight Aggregate Concrete," *ACI Journal Proceedings,* V. 57, No. 1, Jan. 1961, pp. 779-796.

11. ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary (ACI 318R-19)," American Concrete Institute, Farmington Hills, MI, 2019, 623 pp.

Note: Additional information on the ASTM standards discussed in this article can be found at **www.astm.org**.

Selected for reader interest by the editors.

ACI member **Ronald L. Kozikowski** is Vice President of North S.Tarr Concrete Consulting, P.C., Dover, NH, USA, specializing in troubleshooting of concrete construction issues. He has over 20 years of experience as a construction and materials engineer and is a member of ACI Committees 207, Mass and Thermally Controlled Concrete; 213, Lightweight Aggregate and Concrete; 301, Specifications for Structural Concrete; 306, Cold Weather Concreting; and 308, Curing Concrete; Joint ACI-ASCC Committee 117, Tolerances; and Joint ACI-CRSI Committee C680, Adhesive Anchor Installer Certification. He received his BS and MS in civil engineering from the University of New Hampshire, Durham, NH.

ACI member **James Klinger** is Concrete Construction Specialist for the American Society of Concrete Contractors (ASCC), St. Louis, MO, USA. He is a member of Joint ACI-ASCC Committee 117, Tolerances; ACI Committees 134, Concrete Constructability, and 318, Structural Concrete Building Code; and ACI Subcommittee 318-A, General, Concrete, and Construction. Klinger received his master's degree in structural engineering from the University of Maryland, College Park, MD, USA.

Bruce A. Suprenant, FACI, is the ASCC Technical Director, St. Louis, MO, USA. He is a member of ACI Committees 134, Concrete Constructability, and 302, Construction of Concrete Floors; and Joint ACI-ASCC Committees 117, Tolerances, and 310, Decorative Concrete. His honors include the 2021 ACI Arthur R. Anderson Medal, the 2020 ACI Construction Award, the 2013 ACI Certification Award, the 2010 ACI Roger H. Corbetta Concrete Constructor Award, and the 2010 ACI Construction Award.