B
Evaluation of ACI Equation for Elastic Modulus

This appendix includes MPR Calculation 0326-0062-CLC-01, *Evaluation of ACI Equation for Elastic Modulus*, Revision 0.

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CALCULATION TITLE PAGE

Client: NextEra Energy Seabrook, LLC	Page 1 of 12+ Appendix A and B
Project: Approach for Estimating Through-Wall Expansion from Alkali-Silica Reaction at Seabrook Station	Task No. 0326-1405-0074
Title: Evaluation of ACI Equation for Elastic Modulus	Calculation No. 0326-0062-CLC-01

Preparer / Date	Checker / Date	Reviewer & Approver / Date	Rev. No.
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QUALITY ASSURANCE DOCUMENT

This document has been prepared, checked, and reviewed/approved in accordance with the QA requirements of 10CFR50 Appendix B and/or ASME NQA-1, as specified in the MPR Nuclear Quality Assurance Program.

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RECORD OF REVISIONS

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Revision	Affected Pages	Description
0	All	Initial Issue

Note: *The revision number found on each individual page of the calculation carries the revision level of the calculation in effect at the time that page was last revised.*

Table of Contents

1.0 INTRODUCTION

1.1 Purpose

This calculation evaluates the applicability of the elastic modulus equation provided in Section 8.5.1 of ACI 318-71 (Reference 2) to the concrete mix used in the Beam Test Programs that MPR is sponsoring at Ferguson Structural Engineering Laboratory (FSEL).

1.2 Background

MPR is developing a methodology to determine the through-thickness expansion of concrete structures at Seabrook Station due to Alkali-Silica Reaction (ASR). The through-thickness expansion results in a reduction in the elastic modulus. One approach for estimating the original elastic modulus (i.e., the elastic modulus before ASR expansion occurs) is to calculate it using the 28-day compressive strength of the concrete and the equation provided in ACI 318-71.

2.0 SUMMARY OF RESULTS AND CONCLUSIONS

Based on the results of this calculation, the relationship between the measured 28-day compressive strength and the elastic modulus for the test specimens within the Beam Test Programs at FSEL is consistent with the ACI equation. The measured data and calculated results show a similar trend. Measured and calculated elastic modulus values for all but three data sets were within the variability range stated in Reference 2, 20%.

3.0 APPROACH

Section 8.5.1 of ACI 318-71 (Reference 2) states that the 28-day elastic modulus (E_c) of concrete can be calculated based on the density of concrete in lb/ft^3 (w_c) and the 28-day compressive strength of concrete (f_c'). This relationship is expressed using Equation 1.

$$E_c = 33w_c^{1.5}\sqrt{f_c'} \qquad (1)$$

Section R8.5.1 of ACI 318 (Reference 2) also states that measured values for elastic modulus range from 80% to 120% of the calculated value.

Reference 3 provides the basis for Equation 1 and supports Reference 2. Equation 1 is based on light weight and normal weight concrete test data from various published articles and unpublished reports from the Expanded Shale, Clay, and Slate Institute.

The elastic modulus for normal weight concrete (approximate density of $144\frac{\text{lb}}{\text{ft}^3}$) can be calculated using Equation 2, a simplified version of Equation 1. (Reference 2)

$$E_c = 57{,}000\sqrt{f_c'} \qquad (2)$$

As part of the Shear and Reinforcement Anchorage Test Programs and Instrumentation Specimen Testing, FSEL has determined the 28-day concrete elastic modulus and compressive strength for each beam specimen fabricated to date. These tests use cylinders molded at the time of concrete placement. In addition to the 28-day data, data are also available from cores removed from the test specimens used for control tests (i.e., tests performed shortly after 28 days, before the onset of deleterious ASR expansion). The results of the FSEL elastic modulus and compressive strength tests are compared to Equation 2 (and therefore Equation 1) in this calculation to confirm that the ACI equation is applicable to the concrete mix used in the Beam Test Programs.

4.0 INPUTS

As stated in Section 3.0, the 28-day elastic modulus and the 28-day compressive strength of twenty beams, collected by FSEL, were used to confirm the applicability of Equations 1 and 2. A total of [redacted] data sets were evaluated.

The data were taken from the Special Test and Inspection Records (STIRs) listed in Table 1. (Reference 5 through Reference 40)

Table 1. References for Test Data

[redacted]

Table 1. References for Test Data

[redacted]

5.0 CALCULATION

5.1 Concrete Density Verification

It is important to note that the density of concrete varies slightly among the beams that were tested. However, all test beams are composed of normal weight concrete ($144\frac{\text{lb}}{\text{ft}^3}$).

The simplified equation for normal weight concrete, Equation 2, is therefore applicable and was used to calculate the elastic moduli reported in this calculation.

The relevance of Equation 2 was verified by calculating the density of a beam and comparing it to the density of normal weight concrete. The two values agreed.

A sample density calculation is provided in Appendix A.

5.2 *Elastic Modulus Determination*

The average 28-day compressive strengths and Equation 2 were used to calculate the 28-day elastic modulus for each of the [redacted] data sets listed in Table 1. The percent error is calculated between the measured and calculated elastic modulus values.

The calculation is provided in Appendix B.

6.0 RESULTS AND CONCLUSIONS

The measured elastic modulus values for the [redacted] data sets collected at FSEL align well with the calculated elastic modulus values (from Equation 2). All but [redacted] of the measured elastic modulus values are within 80% to 120% of the calculated value.

Figure 1 compares the FSEL data to the trendline for Equation 2.

Figure 2 and Figure 3 illustrate that nearly all of the FSEL data falls within 80% and 120% of the calculated elastic modulus value, which is consistent with the statement in Section R8.5.1 of ACI 318 (Reference 2) regarding the accuracy of the equation.

It is important to note that the measured elastic modulus is plotted and compared to the trendline associated with Equation 2 in Figure 1 and Figure 2. The percent difference between measured elastic modulus and calculated elastic modulus (per Equation 2) is plotted in Figure 3. All three figures support the conclusion that Equation 2 (and therefore Equation 1) applies to the FSEL data.

The calculations required to generate Figure 1, Figure 2, and Figure 3 are also provided in Appendix B. Cylinders are depicted in blue. Cores are depicted in green.

Based on the results of this calculation, the elastic modulus equation, provided in Section 8.5.1 of ACI 318-71, is validated.

[redacted]

Figure 1. Comparison of FSEL Elastic Modulus Test Data with Equation 2

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[redacted]

Figure 2. Range of FSEL Elastic Modulus Test Data

[redacted]

Figure 3. Percent Error: FSEL Elastic Modulus Test Data vs. Equation 2 Elastic Modulus

7.0 REFERENCES

1. Seabrook Foreign Print No. 100629, "Concrete Test Report," Revision 5.
2. ACI 318-71, "Building Code Requirements for Structural Concrete and Commentary," American Concrete Institute, 1971.
3. Pauw, A., "Static Modulus of Elasticity of Concrete as Affected by Density," *Journal of the American Concrete Institute*, Vol. 32, No. 6, December 1960, pg. 679-687.
4. United Engineers Calculation No. CD-20, "Design of Mats at El. 20' 0" and 0' 0" and Walls Below Grade for Electrical Tunnels and Control Building," Revision 2.
5. MPR Special Test and Inspection Record No. STIR-0326-0062-24-9, Revision 0.
6. MPR Special Test and Inspection Record No. STIR-0326-0062-24-17, Revision 0.
7. MPR Special Test and Inspection Record No. STIR-0326-0062-24-21, Revision 0.
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9. MPR Special Test and Inspection Record No. STIR-0326-0062-24-30, Revision 0.
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18. MPR Special Test and Inspection Record No. STIR-0326-0062-24-19, Revision 0.
19. MPR Special Test and Inspection Record No. STIR-0326-0062-24-23, Revision 0.
20. MPR Special Test and Inspection Record No. STIR-0326-0062-24-26, Revision 0.

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22. MPR Special Test and Inspection Record No. STIR-0326-0062-24-35, Revision 0.
23. MPR Special Test and Inspection Record No. STIR-0326-0062-24-84, Revision 0.
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26. MPR Special Test and Inspection Record No. STIR-0326-0062-24-11, Revision 0.
27. MPR Special Test and Inspection Record No. STIR-0326-0062-24-47, Revision 0.
28. MPR Special Test and Inspection Record No. STIR-0326-0062-24-95, Revision 0.
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30. MPR Special Test and Inspection Record No. STIR-0326-0062-24-89, Revision 0.
31. MPR Special Test and Inspection Record No. STIR-0326-0062-24-98, Revision 0.
32. MPR Special Test and Inspection Record No. STIR-0326-0062-24-87, Revision 0.
33. MPR Special Test and Inspection Record No. STIR-0326-0062-24-107, Revision 0.
34. MPR Special Test and Inspection Record No. STIR-0326-0062-24-90, Revision 0.
35. MPR Special Test and Inspection Record No. STIR-0326-0062-24-123, Revision 0.
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38. MPR Special Test and Inspection Record No. STIR-0326-0062-24-128, Revision 0.
39. MPR Special Test and Inspection Record No. STIR-0326-0062-24-135, Revision 0.
40. MPR Special Test and Inspection Record No. STIR-0326-0062-24-136, Revision 0.

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A
Sample Concrete Density Calculation

The density of [redacted] was calculated using data provided in STIR-24-90. (Reference 34)

The relevant data and density calculation are provided in Table A-1.

Table A-1. Concrete Density Calculation

[redacted]

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B
Test Data and Calculations

The information used to perform this calculation and to generate the graphs included herein is provided in Table B-1and Table B-2.

Table B-1. Compressive Strength and Calculated Elastic Modulus

[redacted]

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Table B-1. Compressive Strength and Calculated Elastic Modulus

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Table B-1. Compressive Strength and Calculated Elastic Modulus

[redacted]

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Table B-1. Compressive Strength and Calculated Elastic Modulus

[redacted]

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Table B-2. Elastic Modulus

[redacted]

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Table B-2. Elastic Modulus

[redacted]

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Table B-2. Elastic Modulus

[redacted]