5-694.560 DEVELOPING STRENGTH-MATURITY RELATIONSHIP

The maturity method utilizes the principle that directly relates the strength of concrete to the cumulative temperature history of the concrete. Using this principle, the Engineer and Contractor can quickly and reliably estimate the field strength of concrete based on the maturity index (equivalent age or time-temperature factor) rather than by beam or cylinder tests in the field or the laboratory. The maturity as applied to a concrete mix is specific to that particular mix. When the mix design is changed, the Contractor may need to develop a new maturity relationship, or maturity curve in accordance with MnDOT Standard Specification 2461.

The development of a maturity-strength relationship requires three steps. These include:

1) Developing the maturity-strength curve in the laboratory or in the field,
2) Estimating the in-place strength in the field, and
3) Verifying the strength-maturity relationship in the field.

This procedure utilizes the Nurse-Saul method for developing strength-maturity curves, as described in ASTM C 1074. The Nurse-Saul method uses a specific datum temperature (usually -10°C, but may be determined experimentally) to calculate the time-temperature factor (TTF) and to relate this to the measured concrete flexural or compressive strength at the particular TTF value. The general form of the Nurse-Saul method is shown in Equation 1.

\[
TTF = \sum (T_a - T_0) \Delta t \quad \text{Equation 1}
\]

where
- \( TTF \) = the time-temperature factor at age \( t \), degree-days or degree-hours,
- \( \Delta t \) = time interval, days or hours,
- \( T_a \) = average concrete temperature during time interval, \( \Delta t \), °C, and
- \( T_0 \) = datum temperature, -10°C.

This test method describes the procedure for developing maturity-strength relationships to estimate concrete strength using the maturity method. This method uses either beams for flexural strength or cylinders for compressive strength. While the majority of this procedure uses dual units, measure and record all temperatures relating to the computation of maturity in degrees centigrade (°C).

A. DEFINITIONS

1. Temperature Sensor
   The device on a maturity meter or data logger that is inserted into the concrete and provides a measure of temperature.
2. **Data Logger**
   A commercially available device that record temperature measurements from a temperature sensor at various intervals.

3. **Maturity Meter**
   A commercially available device that includes a temperature sensor, data logger, and conducts maturity calculations automatically.

4. **Maturity Index**
   The cumulative area under the time-temperature curve developed as concrete cures. The units of maturity index are in degree-hours (C-hr). For the purposes of this procedure, the maturity index called the time-temperature factor (TTF).

5. **Maturity Curve**
   The relationship between the time-temperature factor and the strength of the concrete.

6. **Verification Test**
   At various intervals during construction, the maturity curve is verified by casting additional specimens and comparing the TTF-strength relationship with the original maturity curve for a particular mix.

B. **APPARATUS**

1. **Maturity Meter or Temperature Sensor and Data Logger**
   A maturity meter, for the sole purpose of recording concrete maturity, or a temperature sensor and data logger combination, accurate to ±1°C, and capable of recording data at a time interval of 1 hour or less. For high-early strength or accelerated opening mixes, provide a device capable of recording data at a time interval of 15 minutes or less.

   Calibrate maturity meters yearly to ensure proper operation and temperature sensing.

   Verify proper operation of maturity meters and temperature sensors every 30 days during normal plant production. Perform verification by comparing the temperature recorded by the maturity meter or temperature sensor to a known temperature, as provided by a calibrated thermometer. Use at least three temperature points (e.g. 40°F, 75°F, and 110°F [5°C, 25°C and 45°C]) in the sensor verification.

2. **Beam Specimen Molds**
   Developing a maturity relationship with beams, a minimum of 15 beam specimen molds are required. Use beam molds 6 in x 6 in (150 mm x 150 mm) in cross section, and with an overall length allowing for a span length in the testing apparatus of at least 3 times the depth.
3. **Cylinder Specimen Molds**
   Developing a maturity relationship with cylinders, a minimum of 17 cylinders specimen molds are required. Use cylinder molds 4 in x 8 in (100 x 200 mm). If the aggregate has a maximum size greater than 1¼ in (31.5 mm), use 6 in x 12 in (150 x 300 mm) molds.

4. **Flexural Strength Test Apparatus**
   The apparatus for testing beam strength in flexure shall conform to the requirements in Section 5-694.522 (Testing Beams for Flexural Strength) of the MnDOT Concrete Manual.

5. **Compressive Strength Test Apparatus**
   The apparatus for testing compressive strength shall conform to the requirements in Section 5-694.510 (Compressive Strength Tests) of the MnDOT Concrete Manual and AASHTO T-22 (Compressive Strength of Cylindrical Concrete Specimens).

C. **PREPARATION OF SPECIMENS**

   A. Prepare specimens according to Section 5-694.511 (cylinders) or Section 5-694.521 (beams). The preferred method is to cast, cure, store, and test specimens in the field at the beginning of the construction project. Ensure that concrete temperatures in the specimens do not drop below 50°F (10°C). If air temperatures are expected to drop below 40°F (4°C), place the specimens on foam board or plywood to insulate them from the cold ground. Place insulation on and around the specimens.

   If prepared in the laboratory, ensure that concrete used in making the specimens is identical in mixture proportions, quantities and material manufacturers to those specified on the Approved Mix Design.

   B. Test and record air content, temperature, and slump of the fresh concrete on the Concrete Maturity-Strength Development form. See Figure A for an example of a completed form using Flexural Beam Strength. See Figure B for an example of a completed form using Compressive Strength.

   C. For beams, prepare 15 specimens according to the appropriate standard listed in Section B.2 above. Use a minimum of 3 cubic yards of concrete. Embed temperature sensors in at least two of the specimens. Place all sensors so that they are approximately 3 in. (75 mm) from any surface and in one of the outside thirds (i.e. within 6 in. (150 mm) from the end of the beam). Save the specimens with the temperature sensors for testing last.

   For cylinders, prepare 17 specimens according to the appropriate standard listed in Section B.3 above. Use a minimum of 1 cubic yard of concrete. Embed temperature sensors in the center of two of the specimens, record the data and do not test for strength.
D. Protect the concrete specimens according to Section 5-694.511 (cylinders) or Section 5-694.521 (beams).

D. PROCEDURE

1. Develop Strength-Maturity Relationship

Perform strength tests according to Section 5-694.522 (beams) or AASHTO T-22 (compressive) for the type of concrete at the ages specified in the table below.

<table>
<thead>
<tr>
<th>Type of Concrete</th>
<th>Testing Ages *</th>
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<tbody>
<tr>
<td>Concrete pavement as defined in 2301</td>
<td>Determined by the Contractor ‖</td>
</tr>
<tr>
<td>Normal Strength Concrete as defined in 2461</td>
<td>1, 2, 3, 7 and 28 days</td>
</tr>
<tr>
<td>High-Early (HE) Concrete as defined in 2461</td>
<td>12 hours, 1, 2, 7 and 28 days</td>
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<tr>
<td>Ultra High-Early (UHE) Concrete as defined in 2302</td>
<td>3, 4 and 8 hours, 1 and 14 days</td>
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</tbody>
</table>

* The Contractor may adjust the testing ages if approved by the Engineer, in conjunction with the Concrete Engineer.
‖ Test at least two (2) sets of strength specimens before the anticipated opening strength.

Test three specimens at each age and compute the average strength.

If a low test is the result of an obviously defective specimen, discard the result from the average but record its value and the reason for discarding it in the data entry form.

At each test age, determine the average maturity index (TTF) at the time the specimens are tested, by averaging the values obtained from the two maturity meters or data loggers. If using a maturity meter, read the maturity index directly from the meter. If using a temperature sensor and data logger, calculate the maturity index using the time-temperature history from the logger, and Equation 1 in Section 1 of this procedure. Average the two maturity index values and report this in the appropriate location on the Concrete Maturity-Strength Development form.

The Concrete Maturity-Strength Development form is a Microsoft Excel® spreadsheet that plots the average flexural strength vs. the average maturity index for each test age, and determines the best-fit logarithmic curve using the form.

\[ S = S_0 e^{-\left(\frac{\tau}{TTF}\right)^\alpha} \]  
Equation 2

Where:

- \( S \) = flexural strength (modulus of rupture) or compressive strength, psi
TTF = the time-temperature factor at age t, degree-days or degree-hours,
Su = ultimate expected flexural strength, psi
\( \alpha \), \( \beta \) = time and shape coefficients.

Use the resulting fitted curve maturity-strength relationship for estimating the in-place strength of concrete cured under any conditions including those in the lab or in the field.

Obtain the Concrete Maturity-Strength Development form for these calculations from the Concrete Engineering website http://www.dot.state.mn.us/materials/concrete.html.

For pavements, determine the opening strength criteria for concrete pavements in accordance with 2301.3.O, “Opening Pavement to Traffic.”

For pavement repairs, determine the opening strength criteria for concrete pavements in accordance with 2302.3.B.4, “Opening to Construction Equipment and Traffic.”

For structures, determine the strength criteria for form removal or loading in accordance with 2401.3.G, “Concrete Curing and Protection.”

Enter all collected and recorded data in the Concrete Maturity-Strength Development form.

2. Estimate In-Place Concrete Strength

To estimate the in-place concrete strength in the field, place a temperature sensor in the concrete at a rate specified in MnDOT Standard Specification 2461.

Record the identification number(s) of the maturity meters or data loggers on the Maturity - Field Data form. See Figure C for an example of a completed form.

Protect any protruding wires from construction equipment. Initiate data collection and recording according to the manufacturer’s instructions. Use a datum temperature value of -10°C.

At regular intervals, check the recorded maturity index (or temperature history and compute the maturity index). Record the temperature readings and calculate the maturity values on the Maturity - Field Data form to estimate the strength of the in-place concrete.

3. Verify Strength-Maturity Relationship

At intervals specified in Standard Specification 2461, cast and cure three specimens and insert a temperature sensor in at least one of them. If using cylinders, cast an additional cylinder for inserting the temperature sensor only. Test all three specimens as described in this standard as close to the maturity
index (TTF) for the opening, loading or form removal strength criteria as possible. Compute the average strength as described in Section D.1 using the Concrete Maturity-Strength Verification form. See Figure D for an example of a completed form using Flexural Beam Strength. See Figure E for an example of a completed form using Compressive Strength.

Plot the average strength and maturity index on the Concrete Maturity-Strength Verification form and check that it falls on or near the curve. Take appropriate actions according to Standard Specification 2461.

Report the results of the validation testing on the Concrete Maturity-Strength Verification form and submit the form to the Engineer in the field.
Minnesota Department of Transportation  
Concrete Maturity - Flexural Beam Strength Development

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<th>Beam No.</th>
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<th>Ave. Depth &quot;D&quot; (in)</th>
<th>Total Test Load (psi)</th>
<th>Area Correction Factor</th>
<th>in Center Third? (Y/N)</th>
<th>Modulus of Rupture (psi)</th>
<th>TTF Sensor 1 (C-Hours)</th>
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**Figure A**

**Maturity Curve**

- Flexural Strength
- Maturity Curve

**Curve Coefficients:**

\[
\begin{align*}
S &= 836.12 \\
T &= 541.75 \\
a &= 1.1103844
\end{align*}
\]

**Comments:**

- Required Strength for Opening: 500 psi
- Required TTF for Opening: 985 C-hours
### Concrete Maturity - Compressive Strength Development

**Project No.:** 1234-45  
**Tester:** J. Tester  
**Location:** Concrete, MN  
**Contractor:** J. Contractor  
**Curve #:** 1  
**Engineer:** J. Engineer  
**Opening Strength, psi:** 3000  
**Casting Date:** 3/2/15  
**Casting Time:** 6:00am  
**Report Date:** 6/3/15

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**Maturity Curve**

![Maturity Curve](image)

**Comments:**

- **Mix Information**
  - Mix No.: 3A21-1
  - Certified Contractor Rep.: [signature]
  - Truck No.: 23
  - Air, %: 6.6
  - Slump, in.: 2.5
  - VIC Ratio: 0.39

**Figure B**
## Maturity - Field Data

**Project No.:** 1234-56  
**Tester:** J. Tester  
**Mix No.:** 3A21-1  
**Location:** Concrete, MN  
**Contractor:** J. Contractor  
**Curve #:** 1  
**Engineer:** J. Engineer  
**Probe No.:** 1  
**TTF Required:** 985

**Site No.:** TH 123  
**Or Probe Location From STA:** 105+55  
**To STA:** 120+55

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<tr>
<th>Date</th>
<th>Time</th>
<th>Age [hours]</th>
<th>Air Temp [deg F]</th>
<th>TTF [deg C-hr]</th>
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**Comments:**

**Figure C**
Fig. D

Minnesota Department of Transportation
Concrete Maturity - Flexural Beam Strength Verification

Project No.: 1234-56       Tester: J. Tester       Mix No.: 3A21
Location: Concrete, MN      Contractor: J. Contractor     Air, %: 6.5
Curve #: 1                  Engineer: J. Engineer       Slump, in.: 25

Curve Coefficients:
- \( S_e = 835.96 \) (from Maturity-Strength development report)
- \( t = 541.72 \) (Slab Thickness: ?)
- Required Strength for Opening: 500 psi
- Required TTF for Opening: 985

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Maturity Curve Verification

- Maturity Curve
- Opening Curve
- 10% Lines
- Verification Points

Comments:
Certified Contractor Representative:
Verification Test Reviewed by:

Figure D
### Concrete Maturity - Compressive Strength Verification

**Project No.:** 1234-56  
**Tester:** J. Tester  
**Mix No.:** 3A21-1  
**Location:** Concrete, MN  
**Contractor:** J. Contractor  
**Air, %:** 6.5  
**Curve:** 1  
**Engineer:** J. Engineer  
**Slump, in.:** 2.5  
**W/C Ratio:** 0.39

**Curve Coefficients**  
- $m = 43712.23$  
- $a = 244427.5$  
- $b = 0.130841$

**Opening Strength, psi:** 3300  
**Required TTF for Opening:** 1481

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<th>Cyl No.</th>
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<th>Date</th>
<th>Time</th>
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<th>Ave. Length (&quot;L&quot;) (in)</th>
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**Figure E**

**Comments:**

- Certified Contractor Representative:
- Verification Test Reviewed by:

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**Maturity Curve Verification**

- **Maturity Curve**
- **Opening Chart**
- **410% Limit**
- **Verification Point**