CONCRETE PAVEMENT
CPTP
TECHNOLOGY PROGRAM

Maturity Testing for Concrete Pavement Applications

TechBrief

The Concrete Pavement Technology Program (CPTP) is an integrated, national effort to improve the long-term performance and cost-effectiveness of concrete pavements. Managed by the Federal Highway Administration through partnerships with State highway agencies, industry, and academia, CPTP's primary goals are to reduce congestion, improve safety, lower costs, improve performance, and foster innovation. The program was designed to produce user-friendly software, procedures, methods, guidelines, and other tools for use in materials selection, mixture proportioning, and the design, construction, and rehabilitation of concrete pavements.

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U.S. Department
of Transportation
**Federal Highway
Administration**

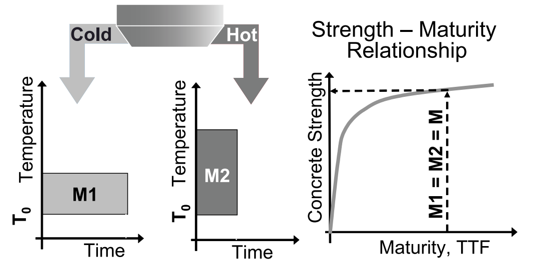
This technical brief describes the maturity method for predicting the development of concrete strength at early ages. It includes a summary of basic concepts of concrete maturity, a description of expected benefits and equipment requirements, and guidelines on using maturity testing as part of a concrete pavement construction project.

INTRODUCTION

The strength of a concrete mixture that has been properly placed, consolidated, and cured is a function of the mixture's age and temperature history (Saul 1951). Longer curing times and increases in curing temperatures lead to increases in strength development. The maturity method of testing recognizes this combined effect of time and temperature and provides a basis for estimating the in situ strength gain of concrete by monitoring its temperature over time. In concrete pavement construction, this capability, among other things, enables engineers to determine the appropriate time to open a pavement to traffic.

Maturity is an indicator of the time-temperature history of the concrete mixture and is often taken as the product of time and temperature. The inherent assumption in the maturity method is that two concrete samples with the same maturity will have the same strength, even though each may have been exposed to different curing conditions. This concept is illustrated in Figure 1 (Nelson 2003), which shows that a sample exposed to colder temperatures takes longer to reach maturity (M1), whereas a sample exposed to a hotter temperature takes less time to reach maturity (M2). If M1 = M2, then these two samples have equal strengths even though the individual curing conditions (time and temperature) are different.

The concept of maturity was first developed in the late 1940s to early 1950s, but it was not until 1987 that the American Society for Testing and Materials (ASTM) published its first standard practice for maturity (Malhotra 1994). With recent advances in equipment and technology and more emphasis on high-speed construction, the



T_0 = *datum temperature*
M = maturity
TTF = time to failure

Figure 1. Maturity concept (Nelson 2003).

practice is gaining widespread use and acceptance. In fact, a 2001 survey of State highway agencies indicated that 32 States are applying or researching maturity concepts, and 13 States have actually adopted protocols or specifications for the use of maturity (Tepke and Tikalsky 2001).

BENEFITS AND LIMITATIONS

The maturity approach provides a simple and useful means of estimating the strength gain of concrete at early ages (generally less than 14 days old) (Crawford 1997). By far its greatest benefit is that it allows engineers to assess the in-place strength of a concrete pavement structure. This valuable information can then be used to help determine the appropriate time for opening a pavement to traffic (construction or public), for sawing joints, for stripping forms, or for ceasing special concreting practices such as using insulation during cold weather. Furthermore, costs for quality assurance testing are reduced because maturity monitoring requires fewer beams or cylinders than other methods (American Concrete Pavement Association [ACPA] 2002). Because it is a nondestructive test method, maturity monitoring imparts no damage to the existing concrete pavement. Taken together, these factors can contribute to reducing overall construction costs and shortening construction schedules.

The use of maturity testing has the following limitations (Crawford 1997; ACPA 2002; Nelson 2003):

- Calibration curves must be developed based on project-specific materials. Any changes in the concrete mix design will require a new calibration curve.
- The effects of early-age concrete temperature on long-term ultimate strength may not be fully characterized. In some cases, when concrete is cured at high temperatures, it may develop higher early-age strength but reduced long-term strength.
- Some factors affecting concrete strength, e.g., consolidation, may not be reflected in maturity measurements.

MATURITY FUNCTIONS

The effects of time and temperature on concrete strength gain are quantified through a maturity function, which is indicative of how much strength the concrete has developed (Carino 2004). The two maturity functions commonly used for this purpose, the Nurse-Saul maturity relationship and the Arrhenius maturity relationship, are described below.

The Nurse-Saul maturity relationship, developed in the 1950s and the most widely accepted means of computing maturity (Crawford 1997; ACPA 2002), is the accumulated product of time and temperature:

$$M = \Sigma(T_a - T_0)\,\Delta t \qquad (1)$$

where:

M = maturity (time-temperature factor) at age t
T_a = average concrete temperature during time interval Δt
T_0 = datum temperature
Δt = time interval

The datum temperature is the temperature at which concrete strength gain ceases; as such, time periods during which temperatures are at or below this datum temperature do not contribute to strength gain. Generally, a value of -10 °C (14 °F) is used for the datum temperature in the Nurse-Saul equation (Carino 2004).

Maturity can also be determined using the Arrhenius method, which accounts for nonlinearity in the rate of cement hydration. The Arrhenius method yields a maturity index in terms of an "equivalent age," which represents the equivalent duration of curing at the reference temperature that would result in the same value of maturity as the curing period for the given average temperature:

$$t_e = \Sigma \exp\{-(E/R)[1/(273 + T_a) - 1/(273 + T_r)]\}\,\Delta t \qquad (2)$$

where:

t_e = equivalent age at reference curing temperature
E = activation energy, J/mol
= 33,500 for $T \geq 20$ °C (68 °F)
= 33,500 + 1472(20 - T) for $T < 20$ °C (68 °F)
R = universal gas constant, 8.3144 J/(mol K)
T_a = average concrete temperature during time interval Δt, °C

T_r = reference temperature, °C
Δt = time interval

According to Carino (2004), the Arrhenius equation is a better representation of time-temperature function than the Nurse-Saul equation when a wide variation in concrete temperature is expected. Furthermore, the Nurse-Saul approach is limited in that it assumes that the rate of strength gain is a linear function. Nevertheless, the Nurse-Saul methodology is more widely used by State highway agencies, largely because of its simplicity. Both maturity functions are outlined in ASTM C1074 (ASTM 2005a).

EQUIPMENT

Because maturity is dependent only on the time-temperature history of the concrete, the most basic equipment requirements for determining maturity are a temperature probe and a clock. However, the use of this basic equipment is time consuming and impractical. Over the years, various maturity devices have been developed that automatically monitor and record pavement temperatures as a function of time. These devices connect to thermocouple wires embedded in the plastic concrete and can be programmed to compute maturity by either the Nurse-Saul equation or the Arrhenius equation, with computations displayed and stored at defined intervals. Furthermore, depending on the type of maturity device, several locations within the slab can be monitored (ACPA 2002).

Recent years have seen significant developments in the use of microprocessors for pavement maturity applications. Introduced by the frozen food industry, these microprocessors are small, self-powered, and self-contained devices embedded in the plastic concrete that automatically record and store concrete temperatures at user-defined intervals. The data can then be downloaded by the user at any time, some even by wireless means. A few examples of this type of technology include iButtons®, intelliRock™ devices, and i-QT® wireless tags.

The locations of the sensors (thermocouples or microprocessors) for concrete pavement maturity applications depend on how the data will be used. Some general location guidelines are presented below (ACPA 2002):

- Sensors placed at slab middepth are useful for determining the average strength of the slab and the appropriate times for opening to traffic.
- Sensors placed within 1 in. (2.5 cm) of the surface can be used to determine the timing of joint sawing operations.
- Sensors should be placed at least 2 ft (0.6 m) away from the edge of the slab.
- Sensors should be placed at intervals between 500 and 1000 ft (150 and 300 m) along the length of the paving to account for variations in placement time and to provide estimates of optimum joint sawing times in each interval or section.
- Sensors are often affixed to stakes or rebars that are driven into the base prior to paving operations, allowing the placement of the sensor at the desired depth.

MATURITY TESTING PROCESS

The maturity testing process shown in Figure 2 essentially consists of two steps: developing the maturity calibration curve and measuring the maturity of the in-place concrete. From this information, the strength of the in-place concrete can be monitored and assessed.

Developing the Maturity Calibration Curve

Development of the maturity calibration curve for any given concrete mixture can be done in the laboratory before the actual paving construction; alternatively, it can be performed in the field at the beginning of paving construction. In either case, project-specific materials must be used because the calibration curves are dependent upon the characteristics of the specific mix; any changes in material sources, mix proportions, or mixing equipment require the development of a new calibration curve (ACPA 2002).

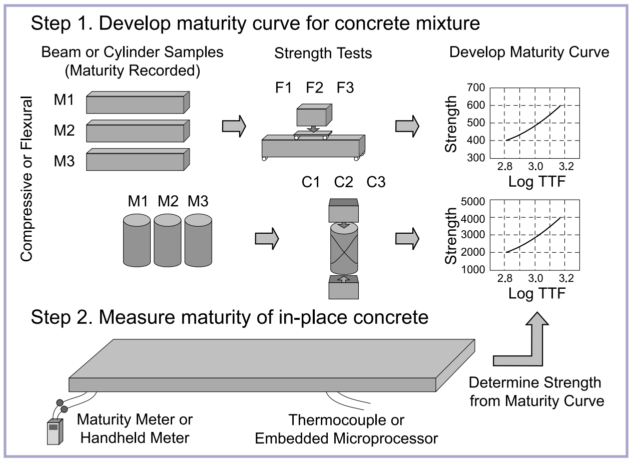


Figure 2. Maturity testing process (ACPA 2002, p. 3; reprinted by permission).

The general steps in developing a maturity curve are described below (Crawford 1997; ACPA 2002):

1. Cast beam or cylinder specimens in accordance with ASTM C192 (ASTM 2005b), being sure to test for air content and slump. Cylinders are generally preferred because they are easier to handle and because there is less variability associated with compressive strength test results compared to flexural strength test results. Generally, between 12 and 15 specimens are prepared, depending upon the number of specimens to be tested and the ages at which they will be tested.
2. Embed one or two temperature sensors (thermocouple or microprocessor) at middepth in one test cylinder or one test beam. This specimen will not be tested but will be used to monitor the maturity of the specimens.
3. Cure the specimens in accordance with either ASTM C192 (ASTM 2005b) or ASTM C31 (ASTM 2005c).
4. Test at least two specimens over a time range that will span the opening strength requirements; commonly these specimens are tested at 1, 3, 7, 14, and 28 days. Compression testing is conducted in accordance with ASTM C39 (ASTM 2005d), and flexural testing is conducted in accordance with ASTM C78 (ASTM 2005e). The average strength is computed for each specimen pair, and the corresponding maturity value is recorded for each test age.
5. Plot the average strength results as a function of the corresponding maturity values, and draw the best fit curve through the points (Figure 3 illustrates an example). This curve can then be used to estimate the in-place strength of the concrete.

Estimating In-Place Strength

In the field, the sensors (thermocouples or microprocessors) are installed in the pavement slab at locations described in the previous section and are immediately connected to the maturity device as appropriate. Maturity measurements are taken at regular intervals, and the maturity of the concrete is monitored. The in-place strength of the pavement can then be estimated using the previously developed calibration curve. For example, during monitoring activities, if it is determined that the maturity of the field slab is 4000 °C-hours (7232 °F-hours) then, referring to Figure 3, this corresponds to a compressive strength of about 34 MPa (4930 lbf/in^2).

TEMP (Total Environmental Management for Paving; see sidebar, page 5) is a software program currently being tested and evaluated by the Federal Highway Administration for use in facilitating the monitoring and assessment of in-place concrete strength using the maturity concept.

TYPICAL APPLICATIONS

As described previously, some typical applications for using maturity on a concrete paving project are to determine the appropriate times for opening to traffic, for sawing joints, for stripping forms, or for ceasing special concreting practices. The determination of opening time for traffic (either construction or public) is one of the greatest benefits, especially as more and more concrete pavements are constructed under accelerated ("fast-track") conditions. Because concrete strength development is sensitive to local curing conditions (e.g., ambient temperature and humidity), the opening of fast-track projects to traffic should be based on the actual, in-place strength rather than curing time. Minimum

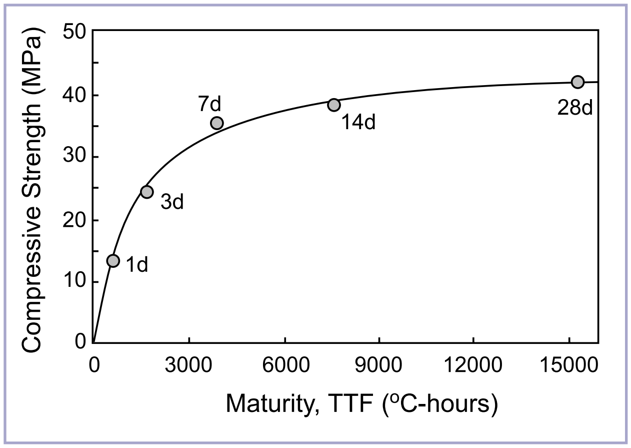


Figure 3. Example maturity calibration curve (Nelson 2003).

opening strengths will vary depending on the slab design, support conditions, and expected traffic loadings, but minimum flexural strengths (third-point loading) of 2067 kPa (300 lbf/in^2) are typical.

SUMMARY

Maturity testing is an effective means of monitoring the early strength gain of concrete pavements. The primary benefit of using the maturity approach is that it provides a relatively fast, nondestructive means for continuously monitoring concrete strength that can be used to determine when the pavement can be opened to traffic. The primary disadvantages are (1) the inherent assumption that the same materials and mix proportions used in the lab are also being used in the field and (2) the significant up-front effort and costs associated with establishing the maturity curve for a given mix. Detailed guidance on the use of the maturity method is found in several publications (Bickley 1993; ACPA 2002).

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TOTAL ENVIRONMENTAL MANAGEMENT FOR PAVING (TEMP) SYSTEM

The TEMP system combines established concrete maturity concepts with state-of-the-art computer and sensor technology to enhance current maturity monitoring methods. TEMP software combines temperature, maturity, and strength predictions into a single measurement system that can be accessed onsite or remotely with a handheld or laptop computer. It gives accurate and instantaneous feedback on temperature and concrete strength development.

The TEMP system has been implemented and evaluated on three different concrete paving projects, and the results confirm that maturity methods and the TEMP system can be used to assess the strength of concrete pavement in real time.

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