MATURITY METHOD

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April 2021

CONTENTS

ABSTRACT

The maturity method is a technique used to provide a more accurate estimate of the effects of time and temperature on concrete strength development. The maturity method is a non-destructive and reliable way of estimating in-situ concrete strength. It leads to better quality control, reduces both traditional testing and construction cost, and helps ensure greater safety. However, certain limitations and considerations need to be taken into account when using the maturity method. This paper shows the need for the maturity method as a standard practice for estimating concrete strength, the relevant ASTM codes applicable to it, and some recommendations as to the limitations of the technique.

INTRODUCTION

It is well known within the construction industry that concrete is one of the most widely used materials in the world – perhaps it is because the aggregates of concrete are available virtually everywhere. Due to its widespread utilization it is well known that concrete will behave differently as temperatures vary. Concrete cured in low temperatures will gain strength slower than the same concrete cured in higher temperatures. This temperature dependency can be a burden for many contractors who need to know the strength of their concrete, especially as they try to accelerate their schedules to meet deadlines. The inability to determine the strength of a concrete slab before performing critical construction operations like removing formwork can be catastrophic. The collapse of the Skyline Towers, a multi-story building under construction in Fairfax County, Va., on March 2, 1973, which killed 14 workers and injured 34 was attributed to the premature removal of formwork upon investigation by the National Institute of Standards and Technology (Carino & Lew, 2001). At the time, the concrete in the floor slab where failure occurred was only four days old, curing around an average temperature of 7 ℃. Five years later 51 workers died in the collapse of the cooling tower in Willow Island, WV on April 27, 1978, due to insufficient concrete strength to support the applied construction loads – the previous lift of concrete was exposed to an ambient temperature of 10 ℃ for only a day (Carino & Lew, 2001). This incident prompted the urgent need for standards to estimate in-situ concrete strength. The NIST research led to the standardizing of the maturity method, a concept introduced in the early 1950s, in the American Society for Testing Materials (ASTM) C1074 in 1987. This paper aims to provide an understanding of the maturity method, its use, and its limitations.

MATURITY METHOD

The maturity method is published in ASTM standard C1074 and used to estimate the combined effect of time and temperature on the strength development of concrete. The first step to applying the maturity method is choosing a maturity function to create a maturity index. There are two maturity functions recommended by ASTM C1074: Nurse-Saul maturity function and Freiesleben Hansen and Pedersen maturity function popularly known as the Arrhenius maturity function. Both functions rely heavily on the concrete temperature profile during the concrete curing period. The Nurse-Saul maturity function assumes the rate of strength gain is a linear function of temperature. This linear approximation is one of the main limitations of the Nurse-Saul maturity function. It was deemed invalid when curing temperatures vary over a wide range during the curing period or within the curing concrete member, thus leading to the proposal of a more robust maturity function, the Arrhenius maturity function (Soutsos, Kanavaris, & Hatzitheodorou, 2018). The two maturity indexes are referred to in ASTM C1074 as the ‘Time-Temperature Factor’ (TTF) for the Nurse-Saul maturity function and the ‘Equivalent Age’ for the Arrhenius maturity function, respectively.

MATURITY INDEX

Time-Temperature Factor (Nurse-Saul)

The TTF is shown in Equation 1:

$$M(t) = \sum_{o}^{t} (T_a - T_o)\Delta t \tag{1}$$

Where:

$M(t)$ = temperature-time factor, °C-days or °C-hours,

Δt = time interval, days or hours,

T_a = average concrete temperature, °C, during the time interval, Δt,

T_o = datum temperature, °C.

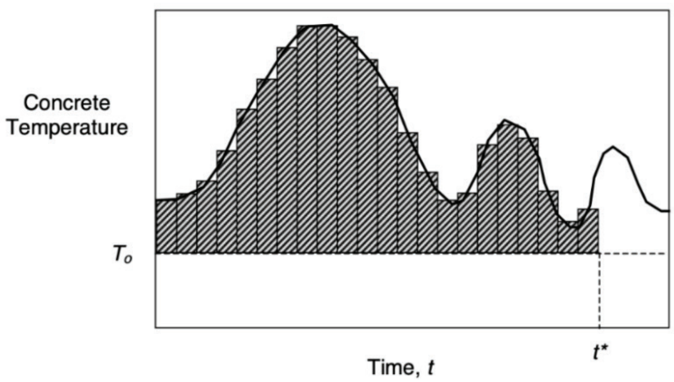

Figure 1 — Temperature-Time History (Carino & Lew, 2001).

Figure 1 shows an example of a temperature-time history used in computed the TTF using Equation 1. According to Figure 1, the TTF at time t* is the area below the temperature curve and the datum temperature. T_o is defined as the temperature below which concrete ceases to gain strength. It varies depending on the "type of cement, type and dosage of admixtures used and other additives that affect hydration rate, and on the temperature range that the concrete will experience while hardening" (ASTM C1074, 2019). Therefore, knowing the correct T_o to use is critical to estimating an accurate in-situ concrete strength. Although rarely used in commercial construction, ASTM C1074 recommends T_o value of 0 °C for Type 1 cement without admixtures and a curing temperature range of 0 to 40 °C. However, T_o can be experimentally determined to maximize the accuracy of strength estimation.

Equivalent Age (Arrhenius Method)

The Equivalent Age function introduced the calculation of the equivalent age of concrete at a specified temperature, as shown in Equation 2.

$$t_e = \sum e^{\frac{-E_a}{R}} \left(\frac{1}{T_a} + \frac{1}{T_s}\right) \Delta t \tag{2}$$

where:

t_e = equivalent age at a specified temperature, T_s, days or hours,

E_a = activation energy, J/mol,

R = gas constant, 8.31 J/(K * mol),

T_a = average temperature of concrete during the time interval, Δt, K,

T_s = specified temperature, K, and

Δt = time interval, days or hours

The Equivalent Age function with Equation 2 overcomes one of the main limitations of the Nurse-Saul function with Equation 1 by introducing E_a. E_a describes the effect of the temperature on the rate of strength development and allows for a non-linear relationship between the rate of strength development and curing temperature (Carino & Lew, 2001).

Like the T_o for the TTF, the E_a is vital to estimate the strength development efficiently. It also depends on the type of cement, the type and dosage of admixtures that affect the rate of strength development and the water-cementitious material ratio. The recommended E_a values per ASTM C1074 for a Type I cement without admixtures or additions are 38,000 to 45,000 J/mol (ASTM C1074, 2019). However, the E_a can be experimentally determined to maximize the accuracy of strength estimation.

STRENGTH-MATURITY RELATIONSHIP

In establishing the Nurse-Saul maturity function or TTF, (Saul, 1951) defined the "maturity rule," by stating that "concrete of the same mix at the same maturity [index] has approximately the same strength whatever combination of temperature and time go to make up that maturity." This means that as far as the maturity index corresponding to a particular strength is known for a given concrete mixture and constituents, the concrete strength can be estimated regardless of the curing temperature or history. This rule is shown in Figure 2. It should be noted that the equivalent age or Arrhenius maturity function obeys this rule.

The strength-maturity relationship or curve can be made using many different models, four of which are the linear hyperbolic, parabolic hyperbolic, logarithmic equation and exponential function. Among the four models, only the linear hyperbolic and logarithmic equations are shown in ASTM C1074. The logarithmic equation is simple to use compared to the linear hyperbolic, but it has its limitations. It assumes the concrete gains strength indefinitely, which is false. Therefore the linear hyperbolic model, Equation 3, is generally the most suitable model for strength development in the early ages of concrete (Carino & Lew, 2001).

$$S=S_u \frac{k(t-t_o)}{1+k(t-t_o)} \tag{3}$$

where:

- S = strength at age t, MPa
- S_u = limiting strength, MPa
- k = rate constant, 1/day
- t = test age, day, and
- t_o = age at the start of strength development, day

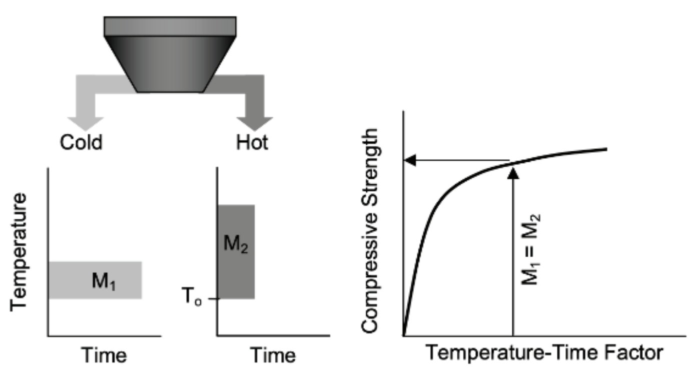

Figure 2 — Diagram of the Maturity Rule (Wade, 2005).

The parameters S_u, k, and t_o can be obtained by least-squares regression analysis or using a Solver function available in Excel or spreadsheet (ASTM C1074, 2019). Figures 3 and 4 show an exemplary plot of compressive strength as a function of the two maturity indexes, TTF, and equivalent age for a particular concrete mixture. The resulting curve from the strength-maturity relationship, as shown in Figures 3 and 4, is used to estimate the in-situ strength of the particular concrete mixture that was used for this example.

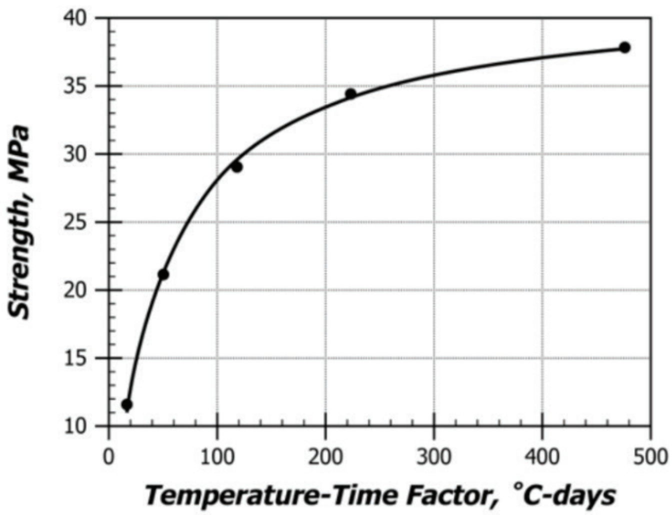

Figure 3 — Example of a Relationship between compressive strength and TTF (ASTM C1074, 2019)

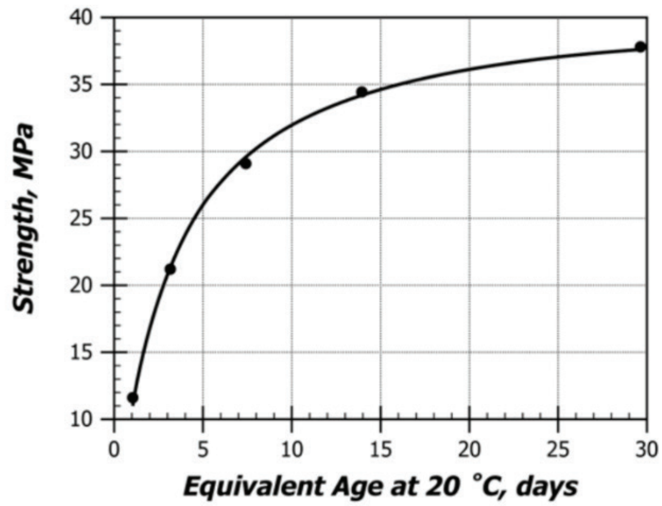

Figure 4 — Example of a Relationship between compressive strength and Equivalent Age at 20 °C (ASTM C1074, 2019)

Determination of Datum Temperature or Activation Energy

As mentioned earlier, the ability to efficiently estimate in-situ concrete strength depends heavily on choosing the right T_o or E_a for Equation 1 and Equation 2, respectively. Both of these parameters rely heavily on the curing temperature; therefore, specimens with higher early-age curing temperatures will result in higher initial strengths and lower long-term strength and vice versa, as shown in Figure 5 (Carino & Lew, 2001). This phenomenon is known as the "crossover effect." To estimate concrete strength accurately, the appropriate values for T_o and E_a should be determined by using the procedure given in ASTM C1074 Appendix X1 (ASTM C1074, 2019) as described below

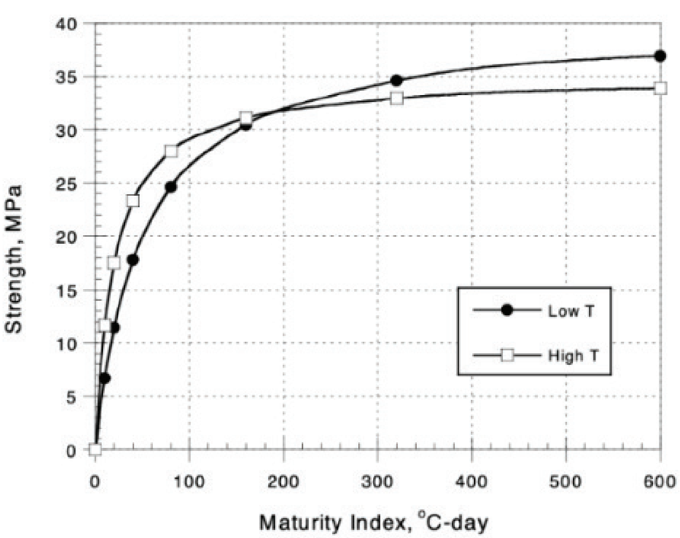

Figure 5 — The "Crossover Effect" Due to Different Early Curing Temperatures (Carino & Lew, 2001)

APPLICATION OF THE MATURITY METHOD

There are four steps required to apply the maturity test per ASTM C1074: determination of the appropriate maturity index for the specific mixture to be used, determination of the strength-maturity relationship, measurement of the in-situ concrete temperature and time, and estimation of the in-situ strength, all of which are shown in Figure 6.

To determine the maturity index, a minimum of 15 cylindrical concrete specimen are prepared. “The mixture proportions and constituents of the concrete shall be similar to those of the concrete whose strength will be estimated using this practice” (ASTM C1074, 2019). After molding the cylinders, temperature sensors are embedded “within ±15 mm of the centers of at least two cylinders” (ASTM C1074, 2019). The specimens are cured in “a water storage tank [or bath,] or a moist room meeting” ASTM C511 requirement specification (ASTM C1074, 2019). Compression tests are performed on at least two specimens at ages 1, 3, 7, 14, and 28 days. The recommended time interval of one-half hour or less should be used for the first 48 hours of the temperature record, and longer time intervals are permitted for the remainder of the curing process (ASTM C1074, 2019). The maturity index is evaluated according to Equation 1 or 2 (Carino & Lew, 2001), using the time and temperature data from the monitored cylinders.

After determining the maturity index, a plot is made of the average compressive strength as a function of the average maturity index, shown in Figures 3 and 4 (Carino & Lew, 2001). A best-fit curve is drawn, or regression analysis may be used to determine the best-fit curve for an appropriate strength-maturity relationship using Equation 3. This resulting curve will be used to estimate the in-situ strength of that concrete mixture (Carino & Lew, 2001).

Measuring in-situ maturity is required to estimate the in-situ strength. Temperature sensors should be secured within the section to be cast before concrete placement, or embedded into the fresh concrete as soon as is practical after concrete placement (Carino & Lew, 2001). These temperature sensors must be placed in locations in the structure that are not exposed to ambient temperature and are critical to structural requirements. The importance of sensor placement cannot be overstated if “strength estimates are being used for timing the start of critical construction operations,” such as removal of formwork (Carino & Lew, 2001).

The sensor’s temperature data should be recorded as soon as it is practical. When the strength at a location of a sensor is desired, the maturity index is estimated from the temperature and time record. The strength at the location can then be estimated by using the maturity values and the previously established strength-maturity curve or relationship. “Before performing critical operations such as post-tensioning or removal of formworks, that are based on estimated strength from the concrete maturity,” ASTM C1074 requires that other tests be performed to verify that the tested concrete mixture is the same mixture delivered to the construction site (ASTM C1074, 2019). Some of these tests are listed in section 9.5 of ASTM C1074.

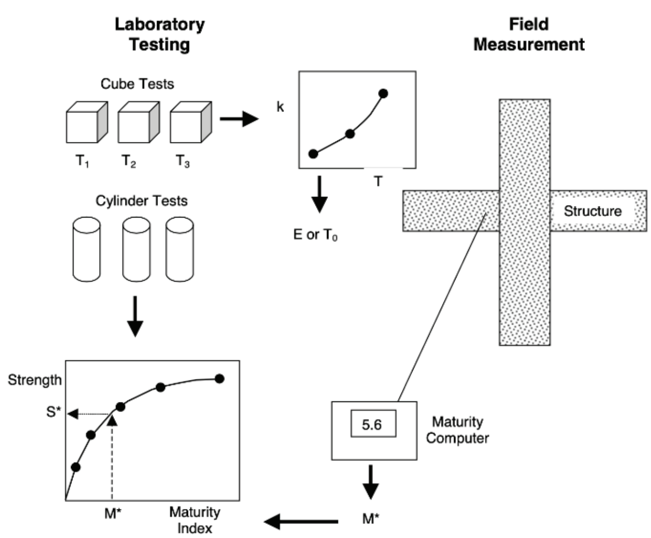

Figure 6 — Application of the Maturity Method (Carino & Lew, 2001)

LIMITATIONS OF THE MATURITY METHOD

Despite the maturity method being relatively simple, reliable, and non-destructive to the in-situ concrete, a few factors can affect the accuracy of the technique:

Appropriateness of the Maturity Index

In the early stages of applying the maturity method, choosing the right maturity index, that is choosing between Equation 1 or 2, can affect the accuracy of the final strength estimation. As mentioned earlier, Equation 1 assumes that the rate of strength gain is a linear function of temperature. This assumption has been deemed invalid when curing temperatures vary over a wide range during the curing period or within the curing concrete member.

In-place Early Age Temperature

As discussed, and shown in Figure 4, early age temperature, whether high or low, will lead to the “crossover effect.” Not only that, but when the rate of hydration increases, curing temperature increases. This increased hydration rate does not give reaction products the time to uniformly distribute.

Mixture Proportions in the Field Concrete

Using the correct mixture proportions is one of the critical steps to ensuring the accuracy of in-situ strength estimations. The concrete mixture and constituents used in developing the strength-maturity relationship must be the same mixture and constituents used in the field. If the two mixtures and constituents differ, it invalidates the strength-maturity relationship, and a new test will have to be made as a result.

CONCLUSION AND RECOMMENDATIONS

This paper discusses the maturity method and how it can be used to assist in predicting the in-situ concrete strength. The maturity method is a powerful, cost-efficient, and non-destructive way of estimating in-situ concrete strength. It is significant in the industry as it allows the start of critical construction operations such as post-tensioning of tendons, the opening of roadways to traffic, removal of formwork and reshoring, and termination of cold weather protection. It also allows for better quality control. While it was not investigated in this paper, it should be noted that concrete can cure differently in cylinders than it does in the field due to mass concreting in the field.

For reasons stated above, the following are some recommendations on the use of the maturity method. The most appropriate maturity index to use is the equivalent age (Equation 2). E_a (or T_o, if Equation 1 is preferred) should be experimentally determined. the mixture and constituents used in deriving the strength-maturity relationship must be the same mixture and constituents used to in the field, and early age in-place temperature should be monitored closely.

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