Fundamentals of Maturity Methods for Estimating Concrete Strength: Review

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Abstract - *This review paper encapsulates the conclusions drawn from research carried out concerning the fundamentals underlying various traditional maturity method used to predict the in-place strength of concrete. It is shown that if the temperature change of the concrete after the time of blending is not greater than a certain value, the concrete gains strength during and after treatment in relation to its "Maturity" (established in temperature-time) approximately in accordance with the same law as holds for normally cured concrete. Concrete which is elevated in temperature very quickly is shown not to obey this law, and to be severely affected the strength at a later age. The use of the too rapid early temperature rises often implemented in practice introduces various opposing variables which recommend delayed treatments, optimum temperatures, and other arrangements of the curing cycle; such pragmatism is unnecessary, however, if a slow initial temperature gradient is used. The maturity method is calculated by using different maturity models. These models are based on time-temperature record and mainly, known as The Nurse-Saul & the Arrhenius function. A strength-maturity relationship of the concrete mix is reviewed. The temperature history of the field concrete, for which strength is to be predicted, is recorded from the time of concrete placement to the time when the strength prediction is desired. The documented temperature history is used to calculate the maturity index of the field concrete. Using the calculated maturity index and the strength maturity relationship, the strength of the field concrete is predicted. The Nurse-Saul function has been broadly used in predicting gain of compressive strength of concrete cured in the temperature range of +10°C to +32°C. This papers review published studies and discusses use of maturity methods for in-situ strength.*

Key Words: *Maturity method, Maturity index, Concrete temperature, Nurse-Saul and Arrhenius function, Concrete strength at Early-age, Curing Time and Condition, Estimation of compressive strength, Equivalent Age, steam curing & Atmospheric pressure,*

1. INTRODUCTION

Determination of the strength of in-situ concrete is perceptibly crucial to contractors. Judgements such as when to strip forms, when to remove shores, when to post-tension, and when to terminate cold-weather protection are based on attaining a minimum level of concrete strength. Waiting too long to perform these operations is costly, but acting hastily may cause the structure to crack or breakdown. The information used to make these judgments is usually obtained from field pullout tests, cured cylinders, or penetration testing. The maturity method is another practice that can be used to assess the strength of in-situ concrete.[2] This non-destructive method has more popular but not been extensively used in the U.S.A. The adoption of ASTM standard practice for assessing concrete strength by maturity method (ASTM C-1074) has amplified its use. The maturity method is simply a practice for forecasting concrete strength based on the temperature history of the concrete. Strength surges as cement hydrates. The amount of cement hydrated is contingent on how long the concrete has cured and at what temperature. Maturity is a measure of how far hydration has developed.

1.1 Maturity Concept

Strength growth in concrete happens due to the hydration reaction between cement and water. The degree of strength development can be contingent upon several factors including curing conditions (temperature and age), type and source of cement, water-to-cement ratio, etc. The curing circumstances are known to have the utmost effect on the rate of strength development, especially the concrete temperature for a given mixture of concrete. [3-10] In general, the degree of strength gain for concrete cured at high temperatures are much superior compared to lower temperatures, especially at early ages. [1]

In first decade of 19th century, attempts have been made to evaluate the collective influence of time and temperature on the strength growth characteristics of concrete.[11] In the early 1950's a number of researchers suggested the combining of the effects of time and temperature by a single factor.[12-14] This parameter for the first time was called maturity by Saul.[14] The maturity is computed as the product of time and temperature above some datum temperature ensuing concrete casting. As stated by Saul, the datum temperature is -10°C. The maturity concept states that concrete samples from a given mixture will have identical strengths at identical maturity regardless of their thermal history. This means that an exclusive relation exists between maturity and strength of concrete for any combination of time and temperature.

1.2 Maturity model

A. Nurse-Saul function:

Maturity models are used to change time-temperature curing history of concrete into maturity values which can be related to concrete strength improvement. Numerous maturity functions have been anticipated since the early 1950s. Saul suggested the following relation to compute the maturity of concrete. [12]

$$M(t, T) = \sum_{0}^{t} (T - T_0)\,\Delta t \qquad \text{... Eq. 1}$$

Where,
$M(t, T)$ = Maturity of concrete as a function of time t and Temperature T,
T = Temperature of concrete,
T_0 = Datum temperature, and
Δt = Time interval.

Eq.(1) is known as the *Nurse-Saul function*. The datum temperature (T_0) is the temperature at which no rise in strength of concrete occurs with time. When linking the two different maturity functions, it is necessary that the two functions must be compared for the same datum and reference temperatures. The reference temperature is usually taken as 20°C. Then Eq.(1) for constant temperature, T_r, can be written as

$$M(t, T) = (T_r - T_0)\, t_{20} \qquad \text{... Eq. 2}$$

Where,
t_{20} = time required for reaching maturity at 20°C, and
T_r = reference temperature.

The value of T_0 is taken as -10°C.
Substituting the values T_r = 20°C and T_0 = -10°C, and using Eq. (1) and (2), the following relation can be developed.

$$t_{20} = \frac{\sum (T+10)\,\Delta t}{30} \qquad \text{... Eq. 3}$$

Where,
t_{20} is time required to reach an equivalent maturity at 20°C. This also specifies relative maturity at 20°C in hours.[15] Rastrup [16] gave a time-temperature function of the form:

$$t_1 = 2^{(T - Tr)/10}\, t_2 \qquad \text{...Eq. 4}$$

Where,
t_1 = curing time at the temperature T_r,
t_2 = the curing time at temperature T, and
T_r = reference temperature

The function suggested by Rastrup is based on a well-known physio-chemical rule which states the speed of reaction is doubled when the temperature is increased by 10°C. For the case of variable temperatures, a sum is formed over the time gap by the following relation

$$t_{20} = \sum_{0}^{t} 2^{(T - Tr)/10}\, \Delta t \qquad \text{... Eq. 5}$$

B. Arrhenius function:

A model based on the Arrhenius function for thermal activation is generally used in several European countries and also in North America. This model, as first proposed by Freiesleben-Hanson and Pedersen[17], is of the form:

$$M(t,T) = \int_{0}^{t} k\, e\left[\frac{-E}{R\,T_k}\right] dt \qquad \text{... Eq. 6}$$

Where,
k = a constant
T_k = temperature of concrete in degrees Kelvin,
E = activation energy in kilo joules per mole, and
R = universal gas constant
The model presented in Eq. 6 has been found to be capable of taking into account the influence of temperature within a range of -10° to 80°C.[17]

In concrete, hydration reaction is an exothermic and due to the same, activation energy (E) can differ with the temperature. Properties of basic cement ingredients & its composition will have great impact on the activation energy.

2. LITERATURE SURVEY

2.1 McIntosh[12] was perhaps the first to develop a parameter in 1949, which he called concept of "Basic Age", to unite the influence of temperature and time. The basic age was computed as the product of time and temperature above -1.1°C. In this study, cube specimens were cured by using electrical curing. Based on the results obtained, he concluded that the strength of treated samples was greatly dependent upon maximum temperature. To obtain a strength level, maximum temperature declined with rising basic age of the specimens, and major strength gain in concrete occurred at an early age when the temperature neared the maximum. [12]

2.2 Nurse[13] used the product of time and temperature above 0°C as a parameter to unite the effects of curing history. In this study, prism specimens were subjected to steam curing at atmospheric pressure and were tested for strength properties including compressive strength using numerous types of aggregates and cement. The test results showed that concrete made with non-reactive aggregates (assuming no reaction between cement and aggregate) displayed a non-linear relation between relative compressive strength and the product of time and temperature. However, this association was invalid for concrete made with reactive aggregates, for which most of the strength data points were well above the smallest curve. [13]

2.3 Saul[14] carried out investigation work on steam curing of concrete at atmospheric pressure. He computed the maturity by Eq.(1). His equation of strength improvement with maturity specified that concrete of the same mix at the same maturity (reckoned in temperature-time) has almost the same strength whatever permutation of temperature and time go to create that maturity. Saul stated that his relation was valid for concrete that has not reached +50°C until 01½ - 02 hrs, or about +100°C until 05-06 hrs after the time of mixing. He specified that when concrete is elevated in temperature more swiftly than above, the law of strength gain does not hold well. Under this situation, strength increase occurs more rapidly during its first few hours of treatment; afterwards, the strength was unfavourably affected. He further stated that the association is valid for the temperatures ranging between +40°C and +100°C, and times up to 28 days. Saul pointed out that concrete would not set at freezing point, but once it has set, it will continue to gain strength even at -10°C. He suggested a datum temperature of -10.5°C for long period of high and low temperatures. [14]

2.4 In 1956, Plowman[18] tried to develop a relationship between concrete strength and maturity. He used cube samples that were initially subjected to normal curing for 24 hours prior to being cured at various curing temperatures. Curing temperatures varied between -11.5°C and +18°C. Based on his test results and data derived from preceding studies he developed a relation between maturity and strength as:

$$S = A + B \log (M(t, T)) \qquad \text{... Eq. 7}$$

Where,
S is strength,
A and B are empirical constants, and
$M(t, T)$ is maturity based upon the Nurse-Saul function.

The constants A and B are linearly connected to the strength at any age. Plowman recommended a datum temperature of -11.7°C. He concluded that Eq.(7) was independent of the quality of cement, w/c, aggregate/ cement ratio, curing temperatures below 37.8°C, and the shape of test specimens. [12]

2.5 Several researchers comprising McIntosh[19], Klieger[20], and Alexander and Taplin[21] have reported that the maturity relation between strength and maturity as regulated by the Nurse-Saul function is significantly influenced by initial concrete curing temperatures. These studies pointed out that the maturity determined by Eq.(7) is not exclusively related to concrete strength when a wide variation in initial curing temperatures occurs.

In agreement with the results of these studies, the Eq.(7) is valid only under the following conditions:

(1) The linear relation between the logarithm of maturity and strength is valid within the span of maturity represented by 3 to 28 days at normal temperatures.
(2) The initial curing temperature of concrete is from +15.5°C to +26.6°C.
(3) No loss of moisture occurs during the curing period.[19][20][21]

2.6 Ordman and Bondre[22] found the Plowman's strength-maturity relation, Eq.(7), binding for concrete subjected to accelerated curing at +85°C for curing cycles of 06, 19, and 23 hours with a ½ hour period permissible before and after heating for moulding and testing of specimens. [22]

3. CASE HISTORIES

3.1 Many construction projects have successfully used the maturity notion in determining the strength gain of in-situ concrete in structures during construction. Bickley[23] and Malhotra[24] have reported the use of the maturity concept in the determination of in-situ strength of concrete during construction of the CN-tower in Toronto. The maturity-strength relation was used to decide appropriate time for formwork removal. In this project, maturity-strength relation was pre-established for each concrete blend, and was compared with the actual core test results. The maturity forecasts showed a very good correlation with core test results. The maturity method was then used for checking the strength gain of the entire structure.[23]

3.2 Mukerjee[25] also stated the use of maturity method to predict strength gain of in-place concrete in Toronto. He found that strength-maturity data could be sufficiently described by the Plowman's model (Eq.6) described earlier. The constants (A & B) of this model were determined for concretes to match local temperatures using experimentally determined data. He found that model forecasts were close to the actual strength of in-place concrete determined from the push-out cylinders cast in structures.

Also, the maturity method was used effectively by Mukerjee to predict the in-place strength of concrete slabs throughout construction of buildings at the University of Waterloo in 1971 and 1972. This method was also used to scrutinize the strength gain of lightweight concrete floor slabs of a 37-story tower completed in Toronto to determine the earliest time for post tensioning operation of slab. [25]

3.3 Hulshizer and Edgar[26] described a test program, connecting both field and laboratory tests, to judge the performance of the maturity concept for predicting the strength gain of concrete. They stated that the maturity method was a reliable technique to evaluate in-situ concrete strength and for monitoring the actual program of curing. The concept was used to determine safe formwork stripping times for a 10 km long, 5.8 m inside diameter, tunnel arch lining. In this work, the use of maturity concept moderated winter curing time which resulted in approximately 25 to 30% saving in heat relative to that of the conventional cold weather curing obligations. Additionally, further economic advantages resulted from reduction in labor, inspection and supervision cost, and reduced schedule durations. [26]

4. CONCLUSIONS

This review paper mainly focus on the concepts & fundamentals of maturity methods and presentation of work done by many research scholars, as referred below.
A large number of researchers have proven that maturity-strength relationship can be considerably influenced by several parameters. These parameters involve curing temperature, aggregate type and source, cement type and source, w/c ratio, etc. Many empirical formulae were derived to establish & solve the relationship between time and the temperature.

Numerous maturity meters are commercially accessible to automatically determine the maturity of concrete. These meters are suitable for monitoring the concrete strength gain in construction projects. Due to the ease and ability to approximate strength gain under fluctuating temperature conditions, the maturity method has been used to screen strength gain in many construction projects with considerable success. The use of maturity method for in-situ concrete strength determination can provide development in construction productivity which can result in considerable savings in energy and labor cost.

In order to have an accurate prediction of strength gain in concrete, it is advocated that maturity-strength relation must be developed for this concrete prior to its use for anticipated curing conditions, for each source and type of materials, and water to cement ratio.

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