EFFECT OF CEMENT TYPES ON CONCRETE STRENGTH-MATURITY RELATIONS

Prof. Dr. İlker Bekir TOPÇU[a] and Yrd. Doç. Dr. Cenk KARAKURT[b*]

[a] Eskişehir Osmangazi University, Engineering Faculty, Department of Civil Engineering, Eskişehir, Turkey, ilkerbt@ogu.edu.tr

[b*]Bilecik Şeyh Edebali University, Engineering Faculty, Department of Civil Engineering, Bilecik, Turkey, cenk.karakurt@bilecik.edu.tr

Abstract

The maturity concept is a basic method to estimate the strength depending on time and temperature. Maturity index, which is a factor for determining the hardening, is used as a non-destructive inspection method for estimating the concrete strength. This method gives us an ability for a simple approach to make more reliable estimates of in-situ strength development during construction. However, in order to apply the maturity, during the construction some tests should be carried out to obtain the properties of concrete before initiating the production. Here within, the variation of maturity with different cements was examined. For this reason, two different cements were used. The specimens produced were cured in three different temperatures (0 ºC, 23 ºC and 40 ºC) for 1, 3, 7 and 28 days. The compression tests were applied on the specimens at the end of the curing time. Equations for the relationship between maturity and strength were developed for the cements used in the study.

Keywords: Concrete; Maturity; Temperature; Compressive strength

1. Introduction

The engineering characteristics of a hardening cement-based material are to a very large extent depending on the microstructural development, and thus on the hydration reactions of the cement. In a fundamental approach, the relation between the driving processes on the microscopic and macroscopic engineering properties can be studied by means of the degree of hydration, using sometimes detailed general hydration models. In a more traditional approach, the effect of ongoing hydration can be estimated by defining maturity or, similarly, by considering the equivalent age of the cementitious material [1]. The strength development of the concrete is depended upon various environmental factors. Of these, the two most important ones are temperature and time [2]. Here, the temperature history is used for calculating the maturity index. Gaining strength is to do with the chemical reaction of the complex compounds of cement with water, also called hydration. This is an exothermic chemical reaction and develops slowly or fast due to the surrounding temperature in which the concrete exists. The maturity method is concerned with the relationship between concrete curing temperature and time. If determined, such a relationship can provide some information as to the early age strength of the concrete without causing any destruction in the concrete [3].

Anticipating the early-strength of the concrete is important not only for modern concrete buildings but also in producing structural concrete elements. Preparing the work procedures safely and economically such as moving, loading, installing the pre-stressed connections and removing the molds of concrete elements produced can be fulfilled by predicting early-age concrete strength. The information that will be obtained concerning the early strength of the concrete used in a structure would be particularly vital when the concrete is prepared in cold weather [4].

2. Maturity Concept for Concrete

Basically, maturity is a concept used to determine temperature-time relationship, one of the indispensable compound factors for the strength of the concrete. The surrounding effects have placed an important role for developing concrete strength by time. For this reason, the strength of the concrete at any age is a function of temperature history of the concrete. The specific strength of a concrete mixture is expressed as a function of maturity. When the common specimens taken from the same concrete mixture is kept under different curing temperatures, the strength of concrete placed in moulds can be predicted by using the temperature history of specimens and strength maturity relations. A newly cast fresh concrete gets strength in time when exothermic chemical reactions occur between the cement and water in it. When the suitable moisture conditions are provided, hydration reactions in the concrete may cause a rise in concrete temperature. This increase, in turn, accelerates this chemical reaction. Hence, environmental conditions prove effective in the development of mechanical properties of the concrete in time. Accordingly, hydration degree and strength of the concrete at any time is attributable to the function of temperature history of the concrete [5].
Determining concrete strength using maturity method can be traced to the beginning of the 20th century. Many researchers have tried to define and use this method. In one of his studies in 1915, Mc Daniel cured

the specimens at -3, 1.5, 22 and 33 ºC for two days and then tested with them when they were at age 3, 7, 10, 14 and 28 days. In their studies

Wiley, Timms and Whitey put emphasis on time and temperature factors. McIntosh first used the term "Basic Age" when he handled the problem of heating concrete with electricity current. According to the Basic Age principle, the starting temperature is shown as approximately 0 ºC (32 ºF) and the basic age is stated in terms of (ºFxhour). So these studies cause a new approach to account the combined effects of temperature and time on strength development of concrete these ideas led to the Nurse-Saul maturity function, which is the most commonly used one [6].

$$M = \sum_{i=0}^{t} (T - T_0)\Delta t \quad (1)$$

In this equation, definitions would be as follows; M maturity index, °C-hours (or °C-days), T average concrete temperature (°C) during the time interval Δt, T_0 datum temperature (the temperature that is subtracted from the measured concrete temperature for calculating maturity according to Eq. (1), usually taken to be -10 °C), t elapsed time (hours or days) and Δt time interval (hours or days) [7]. Here the value calculated using the Eq. (1) is called maturity. On the other hand, as a term, it is also used as the temperature-time factor [8].

Traditionally datum temperature is the temperature at or below which cement hydration is assumed to cease. Temperatures taken from the concrete must be referenced to the datum [9]. In 1977, Freiesleben Hansen and Pedersen suggested a new function to calculate maturity index of concrete, making use of its recorded temperature history. This function was developed based on Arrhenius equation that is used to account for the impact of the temperature on a chemical reaction. The new function has enabled us to find equivalence age of concrete [10],

$$t_e = \sum_{0}^{t} e^{\frac{-E}{R}\left(\frac{1}{T} - \frac{1}{T_r}\right)} \Delta t \quad (2)$$

where, te the equivalent age at the reference temperature, E apparent activation energy J/mol, R universal gas constant 8.314 J/mol-K, Δt time interval, T average absolute temperature of the concrete during interval Δt and Tr absolute reference temperature (°K). In the studies carried out in Europe, the relevant temperature is generally used as 20 °C and in those carried out in North America it is taken as 23 °C. The use of Eq. (2) largely eliminated the discrepancies between strength-maturity relationships developed with different initial curing temperatures, that is, it eliminated the discrepancy at early maturity shown in Figure 1. Here, maturity and correlation of temperature is stated with a value of certain amount of activation energy [11, 12].

The best known of various studies that have been carried out to predict the strength is Plowman's study, which established a relationship between strengthening of concrete against compressive and maturity of concrete. In this study Plowman pointed out that there is a relationship below between the maturity of concrete produced with normal Type I cement and 28-days compressive strength.

$$\frac{f_e}{f_{28}} = A + B.\log\frac{M}{1000} \quad (3)$$

where; A and B constant values, M maturity of the concrete in respect to ºF-hours, the compressive strength of the concrete at the value of M maturity and f28 compressive strength of the concrete for 28 days. Plowman's Eq. (3) is based on maturity concept and is applicable for concrete types cured continuously at 100 F (38 ºC) [13]. Other concrete researchers have indicated that the maturity concept for strength prediction is not applicable to concrete cured at temperatures in excess of 100 F.

2.1. Strength-Maturity Relationship

The newly cast concrete gains strength with the exothermic chemical reactions. The reaction rate increases as the concrete temperature rises. The type, amount and fineness of cement effect this hydration reaction. Maturity method is a combined technique regarding the temperature and time on strength development. When the same concrete specimens are kept under the healing conditions, the strength can be estimated through strength maturity relations for thermal history of specimens. Maturity method is considered to approximate concrete prediction.

In order to be able to determine strength-maturity relationship, cylindrical concrete specimens are prepared by means of a concrete mixture with the same properties as that which will be used in the construction area. For this purpose, concrete specimens are cast into the cylindrical moulds; thermocouples measuring temperature are put into at least two of the specimens in such a way that they will be positioned right in their centers. Then, these thermocouples are connected to a computer, which can automatically determine maturity, or to a temperature-recording machine [14].

Test specimens are cured in a water tank or in a moist curing room, with at least two of them being tested with compressive strength when they are 1, 3, 7, 14 and 28 days old. During the test, the average maturity values determined by the maturity-meter are recorded. If a maturity-meter has been used, the averages of the values obtained are recorded. If a temperature-recorder has been used, it is possible to compute maturity using equations Eq. (1) or Eq. (2). It is possible for the time-interval of the temperature to be 30 minutes or lower within the first 48 hours [8]. The curve is derived from a function of average maturity of average compressive strength. The curve drawn is suitably adapted in accordance with the data, or alternatively regression analysis can be used to determine the most suitable one to the strength-maturity relationship [15]. This method can also be applied on mass concretes and large bridge decks for the in-place strength monitoring of these types of huge concrete structures where the heat of hydration is important [16].

3. Experimental Study

Two types of concrete mixture prepared for the experiment, CEM II/B-M 32.5 and CEM I 42.5 R type Portland cements were used. The properties of cements used in experimental studies are shown in Table1. River sand and crushed stone aggregates 8-16 mm and 16-32 mm were made use of.

Cement dosage, water-cement ratio and size of the aggregates were kept constant as 400 kg/m^3 and 0.57 for two types of concrete mixture. Thus we determined the effect of cement type on strength development of concrete. For this purpose, cylindrical specimens produced for the experiments and cured in consideration of ASTM C 192 standards [15].

Table 1. Properties of cements used in experimental studies

Chemical Composition	CEM I 42.5	CEM II /B-M	Physical Properties	CEM I 42.5	CEM II /B-M
CaO	62.16	52.56	Blain fineness (cm^2/g)	2931	3546
SiO_2	20.03	26.06	Specific Gravity	3.13	2.97
Al_2O_3	4.3	6.71	Initial Setting (hour: minute)	2:10	3:10
Fe_2O_3	3.79	3.55	Final Setting (hour: minute)	4:40	6:00
MgO	2.93	2.66	Trass (%)	-	20.21
SO_3	2.36	1.87	Limestone (%)	-	9.85
C_3S	59.79	-	Compressive Strength, MPa		
C_2S	12.32	-	2-day	26.6	19.2
C_3A	4.98	11.77	7-day	37.1	28.4
C_4AF	11.53	10.84	28-day	47.4	35.1

Thermocouples for “Maturity Meter M-3056”, which measures temperature history, were placed in center of the cylindrical specimens the size of ϕ15×30 cm and were cured in water tank heated at a desirable temperature. The conditions of 40 ºC and 23 ºC were obtained for the water tank, while 0 ºC was obtained through a freezer. At the end of curing time, specimens were initially tested by the ultrasound pulse velocity test. Afterwards, the compressive strength test was carried out on the cylindrical specimens. Next, maturity Eq. (1), compressive strength maturity relationship was determined for three possible conditions that should effect on concrete during construction. While determining the maturity of concrete specimens, the datum temperature (T_0) is considered as –10 °C for Type I cement. On the other hand, ASTM C 1074 proposes that datum temperatures, which are defined as the degree at which the strength gaining stops, should be taken as 0 °C for the concretes without admixture [8]. The relationship between compressive strength-maturity and dynamic modulus of elasticity-maturity was also determined.

4. Test Results

According to the compressive strength test results, when exposing the specimens to a high temperature it can be seen in Figure 1. that early-age strength is high; however, long-term strengths of the specimens are lower than concretes produced under normal conditions. In Figure 1, the specimens produced with CEM I 42.5 R and CEM II/B-M 32.5 type cements, are cured at 0, 23, 40 °C.

When analyzing the results of compressive strength tests, it can be seen that they didn’t show a constant variation in the strength gaining duration. So, there exist some strength differences given in Table 2 between the concrete specimens’ strengths produced by CEM II/B-M 32.5 and the ones produced with CEM I 42.5 R for diverse maturity values.

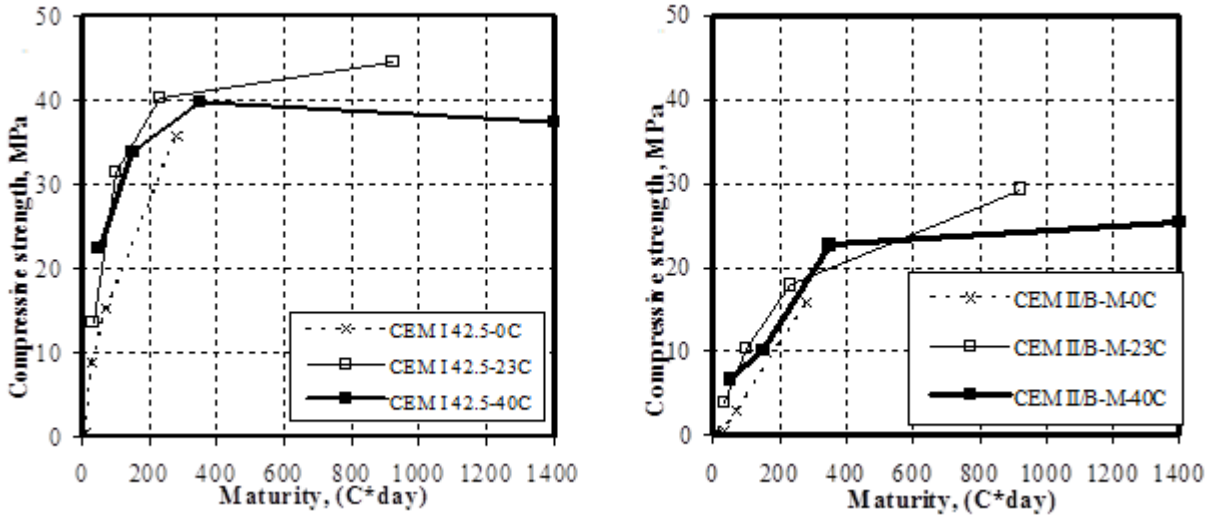


Figure 1. Relation between compressive strength and maturity

When comparing the compressive strength tests depending on the maturity values of the specimens kept in the same curing conditions with the compressive strength results done in other curing conditions, it can be seen that the compressive strength of the specimens produced through CEM II/B-M 32.5 is lower than the ones produced by CEM I 42.5 R cement types. If we examine the results, as the temperature increase in the curing, the difference between the strengths for concretes decrease. It can be seen in Table 2-3 that the concrete specimens produced by CEM I 42.5 R and CEM II/B-M 32.5 cement types are cured at 0, 23, 40 °C. When analyzing the results of the dynamic E-Moduli estimated in the process of strength gaining of the concrete, it is observed that they showed no regular variation. When comparing the dynamic e-modulus results for those cements, there is a decreasing 16% and 36% for concretes produced with CEM II/B-M 32.5 and CEM I 42.5 R. Analyzing the results, as the temperature of the curing surrounding increases, the differences of the dynamic E-moduli between the concretes produced with those cement types decrease (Figure 2).

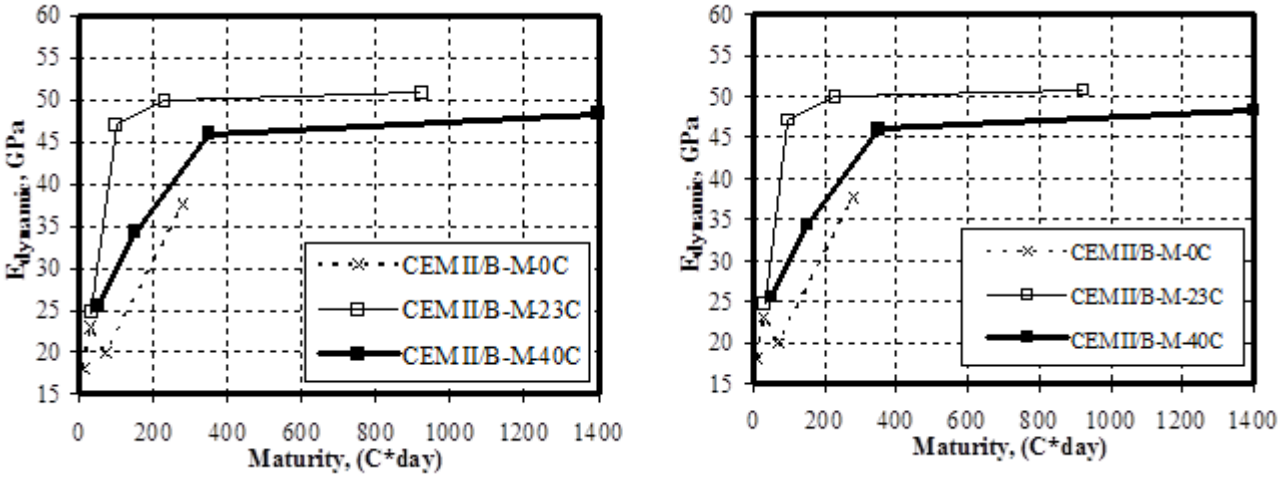


Figure 2. Relation between dynamic modulus of elasticity and maturity

Table 2. Errors in Strength of Concrete Produced with CEM I 42.5 vs. CEM II/B-M 32.5

Maturity (°Cxday)	Errors (%)	Maturity (°Cxday)	Errors (%)	Maturity (°Cxday)	Errors (%)
10	22.36	33	71.95	50	70.51
30	93.63	99	67.23	150	70.12
70	81.04	231	55.56	350	42.99
280	56.04	924	34.36	1400	24.52

Table 3. Errors in Dynamic E-Moduli of Concrete Produced with CEM I 42.5 vs. CEM II/B-M 32.5

Maturity (°Cxday)	Errors (%)	Maturity (°Cxday)	Errors (%)	Maturity (°Cxday)	Errors (%)
10	17.24	33	35.90	50	44.01
30	34.59	99	15.35	150	34.58
70	50.98	231	9.68	350	15.78
280	23.63	924	6.46	1400	18.04

In the light of the data obtained from the compressive strength test, we determined the relationship between the strength of the concrete and maturity according to Eq (1). As a result of the analysis done, two equations were suggested; CEM II/B-M 32.5 Eq. (4) and CEM I 42.5 R Eq. (5). In these equations, M is the maturity of the concrete mixture calculated with the Eq. (1) and with (°C×day) type. The correlation coefficients of these equations are 0.94 for CEM II/B-M with the suggested Eq. (4) and 0.87 for CEM I 42.5 with the suggested Eq. (5).

$$f_c = -19.07 + 6.55 \ln M \quad (4)$$

$$f_c = -17.77 + 9.22 \ln M \quad (5)$$

The strength-maturity relations are given in Fig. 3. as a function of temperature and time for two different cement types. In this way, the approximate in-situ strength can be predicted if time and temperature that was exposed is known.

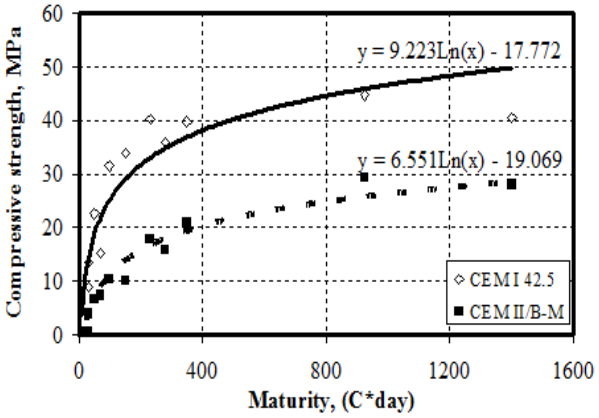


Figure 3. Development of compressive strength of concretes made for different cements

5. Conclusions

Using two different types of cements (CEM II/B-M 32.5 and CEM I 42.5), we suggest the following conclusions as a result of the experiments with concrete specimens with constant mixture ratios and kept under three different curing conditions (0 ºC, 23 ºC and 40 ºC).

- The compressive strengths of the concrete specimens produced by CEM II/B-M 32.5 are lower than the ones produced by CEM I 42.5 R in the rate of 57 %. This decreasing is not a regular variation in the strength gaining process.
- In the strength gaining process; the difference between the compressive strengths produced with those two different cements get lower when the curing temperature increases from 0 °C to 40 °C.
- The dynamic E-Moduli of the concrete specimens produced by CEM II/B-M 32.5 are lower than the ones produced by CEM I 42.5 R in the ratio of 26 %. This decreasing is not a regular variation in the strength gaining process. As in the compressive strengths, this decreasing did not show a regular change in the dynamic E-Moduli.
- In cold weather concreting if finer type of the cement is used, the development of the compressive strength occurs faster due to the fast hydration.
- If accelerated curing is applied to the concrete at high temperatures, the curing process should be less; because, the strength of the concretes could be lower than the ones produced under normal conditions due to the crossover effect.
- The relationships between different types of cements with different properties and maturity correlations should be investigated more extensively.
- This technique can be useful for huge concrete structures such as bridge decks and dam structures for the monitoring of the concrete strength development.

References

[1]. Akman S, Materials of Construction, *ITU Library*, 1408, Turkey, (1990).

[2]. Schutter, G. D., "Applicability of Degree of Hydration Concept and Maturity Method for Thermo-Visco-Elastic Behaviour of Early Age Concrete", ***Cement and Concrete Composites***, 26:437-443 (2004).

[3]. Topçu, İ. B., "Determination of Stripping Time for Mortars*, ICCE/9, 9th Annual International Conference on Composite Eng.*, San Diego, California. (2002).

[4]. Price, W. F. and Haynes, J. P., "In-Situ Strength Testing of High Strength Concrete", ***Magazine of Concrete Research***, 48:189-197 (1996).

[5]. Dilly, R. L. and Ledbetter, W. B., "Concrete Strength Based on Maturity and Pullout", ***Journal of Structural Engineering***, 110:354-365 (1984).

[6]. Mc Intosh, J. D., "Electrical Curing of Concrete", ***Magazine of Concrete Research***, 2:79-88 (1949).

[7]. Saul, A. G. A., "Principles Underlying the Steam Curing of Concrete at Atmospheric Pressure", Magazine of Concrete Research, 2:27-140 (1951).

[8]. ASTM C 1074, "Standard Practice for Estimating Concrete Strength by the Maturity Method, Annual Book of ASTM Standards, 04. 02, ASTM, Philadelphia, USA. (1987).

[9]. Delatte, N. J., Williamson, M. S. and Fowler, W. F., "Bond Strength Development with Maturity of High-Early-Strength Bonded Concrete Overlays", ACI Materials of Journal, 97:201-207 (2000).

[10]. Hansen, F. and Pedersen, J., "Maturity Computer for Controlled Curing and Hardening of Concrete", ***Nordisk Betong***, 1:19-34 (1977).

[11]. Tank, R. C. and Carino, N. J., "Rate Constant Functions for Strength Development of Concrete, ***ACI Mat. of Jour***., 88:74-83 (1991).

[12]. Carino, N. J. and Lew, H. S., "The Maturity Method: from Theory to Application", *Structures Congress & Exposition*, May 21-23 2001, Washington D C, American Society of Civil Engineers Reston, Virginia, USA (2001).

[13]. Oluokun, F. A., Burdette, E. G., Deatherage, J. H., "Early-Age Concrete Strength Prediction by Maturity-Another Look", ***ACI Materials of Journal***, 87:565-572 (1990).

[14]. Karakurt, C., "Maturity concept for different cement concretes", M.Sc. Thesis, Osmangazi University, Eskisehir, Turkey, (2002).

[15]. ASTM C 192, "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory", Annual Book of ASTM Standards,15. 09, ASTM, Philadelphia, USA, (1990).

[16]. Yikici, T. A., Chen, H. L., "Use of Maturity Method to Estimate Compressive Strength of Mass Concrete", ***Construction and Building Materials***, 95:802-812 (2015).