# Using the Maturity Method in Concrete Produced with Setting Agents

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**Abstract:** The maturity function provides a reliable approach in the determination of the in situ strength of concrete at later ages. This study was aimed at determining the strength–maturity relationship on concrete specimens which were prepared using different admixtures and cured under different temperatures. For this reason, three sets of concrete specimens, having dimensions of $15 \times 15 \times 15$ cm, were produced using the set accelerating admixture, set retarding admixture, and no admixture content at a constant consistency and 0.59 water-to-cement ratio. All hardened concrete specimens were cured at 0, 20, and 40°C temperatures under 100% humidity for 1, 3, 7, and 28 days. The compression tests were applied on specimens at the end of the curing time. Equations for the relationship between maturity and strength were worked out for the admixtures used in the study.

**DOI:** 10.1061/(ASCE)0899-1561(2007)19:7(569)

**CE Database subject headings:** Concrete structures; Compressive strength; Concrete; Admixtures; Temperature effects.

## Introduction

The bending strength of concrete is the most important factor in the determination of mold replacing in concrete and shows a parallelism with the compressive strength of the concrete just like all other properties. The quality of the casted concrete must be determined for production quality control during mold removal of concrete. Compressive strength of the concrete determined by using various methods is important in estimating the stripping time in construction (Topçu 2006a,b). Temperature and time are the most important factors in determining the strength development of the concrete. The maturity method is a technique in which time and temperature effects must be taken into consideration in strength development (Topçu and Karakurt 2002; Topçu and Toprak 2005). If the same specimens are kept under various curing conditions, strength estimations can be made on a strength–maturity relationship using the temperature history of concrete.

## Maturity Concept

With the aim of cutting down on financial costs and decreasing the construction time, various methods have been developed to accelerate the strength gain of concrete. Factors such as material properties, concrete composition, concrete placement and compaction factor, geometric dimensions of structural members, curing cycle, and curing conditions affect early age strength development along with heat-treatment applications. The maturity method is a technique which accounts for the combined effects of time and temperature on the strength development of concrete (Topçu and Karakurt 2005; Topçu and Toprak 2007).

Knowing the temperature history of the placed concrete that will be used in the structure is necessary in order to be able to utilize the maturity method. At any given age from the time of mixing, the strength of the concrete depends on the concrete thermal history. The age alone is thus not sufficient to estimate the strength. The concept of maturity was introduced to describe the level of development of the hydration process of concrete. For a compressive strength, as expressed in the Nurse–Saul maturity law (Waller et al. 2004). Saul (1951) suggested that specimens of the same concrete will have equal strength if they have equal maturity, irrespective of their actual time–temperature histories. The temperature history of the concrete in place is observed continuously and defined from this information. For this reason the most well-known Nurse–Saul maturity function, which is used in the determination of the maturity index, is given as (Mc Intosh 1949; Schutter 2004; Topçu and Akman 2005)

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

where $M$=maturity index (°C h or °C day); $T$=average concrete temperature in time interval $\Delta t$ (°C); $T_0$=initial temperature (used as −10°C); $t$=time (day or hour); and $\Delta t$=time interval (day or hour) are represented.

One of the most common equations related to the maturity–strength relationship is the logarithmic equation proposed by Plowman shown as Eq. (2). In this equation, $a$ and $b$ are the constants found by regression analyses with respect to characteristic properties of the concrete. $M$=maturity degree of the concrete found by Eq. (1) and $f_c$=estimated compressive strength value found with respect to this maturity degree (Akman 1983):

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Note. Associate Editor: Kamran M. Nemati. Discussion open until December 1, 2007. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on February 22, 2006; approved on December 28, 2006. This paper is part of the ***Journal of Materials in Civil Engineering***, Vol. 19, No. 7, July 1, 2007. ©ASCE, ISSN 0899-1561/2007/7-569–574/$25.00.

**Table 1.** Cement Properties Used in Experiments

| Chemical composition | (%) | Physical and mechanical properties | |
|---|---|---|---|
| CaO | 63.97 | Blain fineness ($cm^2/g$) | 3345 |
| $Al_2O_3$ | 5.58 | Specific gravity | 3.15 |
| $Fe_2O_3$ | 3.69 | Initial setting (hour:minute) | 3:00 |
| $SiO_2$ | 20.96 | Final setting (hour:minute) | 4:00 |
| MgO | 1.69 | Le Chatalier soundness (mm) | 3 |
| $Fe_2O_5$ | — | 2-day compressive strength (MPa) | 21.9 |
| $K_2O$ | — | 7-day compressive strength (MPa) | 38.3 |
| $Na_2O$ | — | 28-day compressive strength (MPa) | 45.1 |
| $SO_3$ | 2.84 | | |
| Cl | 0.008 | | |
| $TiO_2$ | — | | |
| Excess heating loss | 1.15 | | |
| Unassigned | 0.05 | | |

$$f_c = a + b\log(M) \quad \text{(MPa)} \tag{2}$$

Carino and Tank (1992) developed the constant rate model by making various studies related to maturity. In their experimental studies, they kept seven different concrete mixtures prepared by using admixtures and three different types of cement (ASTM Types I, II, and III) in curing temperatures of 10, 23, and 40°C. Using various chemical and mineral admixtures of 0.45 and 0.60 water-to-cement (w/c) ratios produced concretes. Also, they investigated concepts such as ultimate strength and initial age and examined temperature and admixtures effects on these concepts. Ramakrishnan and Mac Donald (1979) developed the following equation for the strength–maturity relationship in their studies. The study used 34 different types of mixtures:

$$f_c = -38.59 + 18.05\log(M) \quad \text{(MPa)} \tag{3}$$

Karakurt (2002) investigated the strength–maturity relationships in concretes produced with Types I and II cements at a constant w/c ratio and mix composition by considering the standard of ASTM C 1074 (ASTM 1987). For this purpose, concrete specimens were produced with CEM I 42.5R and CEM II 32.5/B-M type cements. Karakurt (2002) investigated the strength–maturity relationships of specimens by linear and logarithmic regression equations with respect to the analyzed data of the Nurse–Saul function. He also observed that there was a decrease at the ultimate strengths of the concrete in high maturity values. A formula was suggested for estimating the strength development of concretes produced with Type I Portland cement with the maturity method as

$$f_c = -17.77 + 9.22\ln(M) \quad \text{(MPa)} \tag{4}$$

## Practical Application of the Method

In practice, the maturity method involves three phases (Waller et al. 2004).

**Table 2.** Properties of Admixtures Used in Experiments

| | Admixture type | |
|---|---|---|
| Property | SA | SR |
| Description | Set accelerating admixture | Set retarding admixture |
| Standard | ASTM C 494-81 Type C | ASTM C 494-81 Type B |
| Content | Nonchloride | Modified phosphate |
| Color | Brown liquid | Yellow liquid |
| Density | $1.25\pm0.03$ kg/dm$^3$ | $1.25\pm0.02$ kg/dm$^3$ |
| pH | $6.5\pm0.5$ | $8\pm1$ |
| Dosage | 1% by weight of cement | 0.2–2% by weight of cement |
| Shell life | 24 month | 12 month |

1. Calibration phase: This consists of measuring the evolution of the compressive strength of the concrete at the beginning of the project when subjected to different temperature conditions, which are as close as possible to the expected extreme concrete temperatures on the construction. This phase also leads to the development of the concrete calibration curve for the curve giving the evolution of the concrete compressive strength versus time at 20°C, deduced from the previous results.
2. Validation phase: This occurs during the first weeks of the construction; it makes it possible to check that the variations in the characteristics of the concrete constituents do not have too much influence on the concrete characteristics obtained in the calibration phase. At the end of this phase, the "calibration curve" becomes the "reference curve" and can be used on the construction field.
3. On-site application phase: This continues throughout the project and includes regular checking of the characteristics.

The limits of the theory mentioned earlier may lead to a relatively high safety margin in the calibration phase, which results in a high "safety cost" for the user. Thus, the narrower the temperature and the strength tested ranges in this phase, the more accurate the strength estimation and the lower the safety cost. The use of the maturity method is perfectly suitable to predict on-site concrete strength evolution with a reasonable accuracy.

## Experimental Study

The aim of the experimental study was to determine the admixture effect on the strength–maturity relationship of concrete. For this purpose CEM I 42.5R type portland cement (C) was preferred to produce concrete specimens and its properties are given in Table 1. Concrete mixtures prepared with Sakarya River sand (S), crushed Stone I (CS I) with a diameter range of 8–16 mm, and crushed Stone II (CS II) with a diameter range of 16–32 mm as aggregates were used.

Three different types of concrete mixtures were produced with set accelerating (SA) admixture, set retarding (SR) admixture, and no admixture (NA) inclusion in the same concrete composi-

**Table 3.** Sieve Analysis of Aggregates Used in Experiments

| Aggregate | Sieve size (mm) | 31.5 | 16 | 8 | 4 | 2 | 1 | 0.5 | 0.25 |
|---|---|---|---|---|---|---|---|---|---|
| S | Passing (%) | 100 | 100 | 100 | 98.6 | 76.8 | 57.0 | 42.2 | 16.2 |
| CS I | | 100 | 96.6 | 0 | 0 | 0 | 0 | 0 | 0 |
| CS II | | 100 | 12.0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Table 4.** Material Contents Used in Concrete Production for 1 $m^3$

| Material contents | δ ($kg/dm^3$) | NA | | SA | | VSR | |
|---|---|---|---|---|---|---|---|
| | | Volume ($dm^3$) | Weight (kg) | Volume ($dm^3$) | Weight (kg) | Volume ($dm^3$) | Weight (kg) |
| C | 3.150 | 111 | 350 | 111 | 350 | 111 | 350 |
| SA | 1.250 | — | — | — | — | 5.60 | 7 |
| SR | 1.200 | — | — | 5.83 | 7 | — | — |
| S | 2.630 | 290 | 756 | 290 | 762 | 290 | 762 |
| CS I (8–16) | 2.690 | 202 | 544 | 202 | 544 | 202 | 544 |
| CS II (16–32) | 2.700 | 182 | 491 | 182 | 491 | 182 | 491 |
| W | 1.000 | 205 | 205 | 205 | 205 | 205 | 205 |
| Mixture | 2.352 | 1,000 | 2,352 | 1,000 | 2,352 | 1,000 | 2,352 |

tion. SA increases the rate of hydration of the $C_3A$ compound in cement. Thus the cement matrix of concrete sets as rapidly as possible. The SR mechanism is based on the adsorption of retarding admixture on the surface of the cement particles. It slows down the rate of early hydration of $C_3S$. Later, as a result of the reaction between the admixture salts and $C_3A$ from the cement, the salts are removed from the liquid phase system, thus eliminating further retardation (Erdoğan 1997). Technical features of the concrete admixtures used in the experimental study are given in Table 2.

Particle size of the aggregate is defined with respect to the sieve group in TS 706 Turkish code. This composition is used in the ratios of 43% of S with ranges of 0–4 mm; 30% of CS I; and 27% of CS II in the form of the range between reference curves of A32 and B32 suggested in TS 707 Turkish code (Kirca et al. 2002). The sieve analyses results are given as a percentage (%) in Table 3.

A total of 108 concrete specimens of $15\times15\times15$ cm, with 10 cm in constant slump value and 0.59 in w/c ratio, were produced by using SA and SR admixtures or with no admixture inclusion. Absolute volume method "concrete mixture account bases in TS 802, Turkish code" is used to account for the concrete compositions. Mix designs of the concrete specimens for 1 $m^3$ are given in Table 4. Constant mix ratios were preferred for all mix designs in order to obtain the effect of concrete admixture on the maturity–strength relationship.

In this study, cubic concrete specimens produced by using SA and SR admixtures and NA were kept in lime saturated water under the temperatures of 0, 20, and 40°C, until the end of the considered curing time. After the curing period, the cubic concrete specimens were subjected to compressive strength tests to determine their strength–maturity relation at the ages of 1, 3, 7, and 28 days (Akar 2002).

## Evaluation of Experimental Results

Compressive strengths of the cubic specimens were determined at the end of the curing cycle. Thus, the effects of curing temperature and admixture type on properties of hardened concrete were calculated. According to the Nurse–Saul function, the maturity index calculated and compressive strength–maturity index relation was determined according to logarithmic regression analysis. According to this analyses, the following equation has been proposed for ultimate strength determination of concrete produced with different types of admixtures

$$f_c = c \ln M + b \tag{5}$$

where $f_c$=ultimate compressive strength of concrete; $M$ =maturity index calculated with Eq. (1); and $b$ and $c$ =regression coefficients determined from the regression analyses. The $b$ and $c$ coefficients vary due to the type of admixture used in concrete. This approach is significant for various admixture behaviors on the maturity–strength relation. The test results of the specimens are given in Table 5.

Compressive strength development of the concretes under different curing time and temperatures by using the SA and SR admixtures versus the reference concrete having the same conditions without using admixtures is given in Fig. 1.

The SA and SR effects on the strength development at initial ages are dominant, but these effects decrease due to the curing time. It has been seen from Fig. 1 SA and SR admixtures have less effect on strength gaining of concrete at 40°C temperature. Finally, it can be concluded that these types of admixtures do not have any beneficial effect on concrete strength gaining for high temperature environments. This event is based on the crossover effect that exists and which relates the long-term ultimate strength

**Table 5.** Compressive Strength Test Results of Concrete Specimens (MPa)

| Admixture | Time (day) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | | | 3 | | | 7 | | | 28 | | |
| | 0°C | 20°C | 40°C | 0°C | 20°C | 40°C | 0°C | 20°C | 40°C | 0°C | 20°C | 40°C |
| SA | 3.58 | 7.40 | 18.76 | 22.83 | 24.42 | 31.02 | 24.42 | 29.42 | 31.38 | 34.07 | 32.82 | 32.38 |
| NA | 2.37 | 4.59 | 16.51 | 15.82 | 18.38 | 29.91 | 22.49 | 27.22 | 30.33 | 34.49 | 33.07 | 32.47 |
| SR | 0.31 | 1.34 | 7.67 | 2.40 | 5.62 | 28.82 | 9.58 | 24.53 | 29.22 | 37.93 | 35.58 | 33.44 |

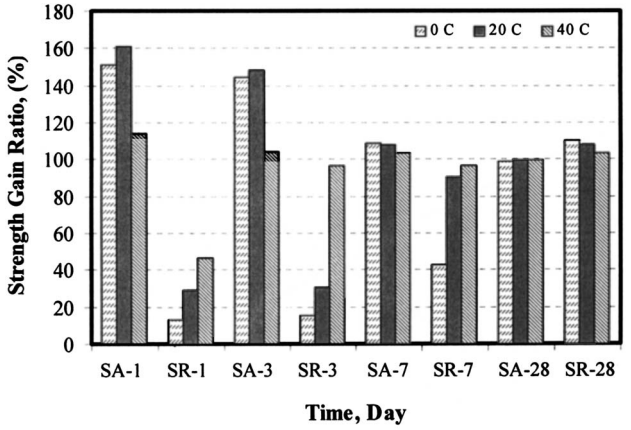



**Fig. 1.** Effects of temperature and admixture at different curing times to relative strength

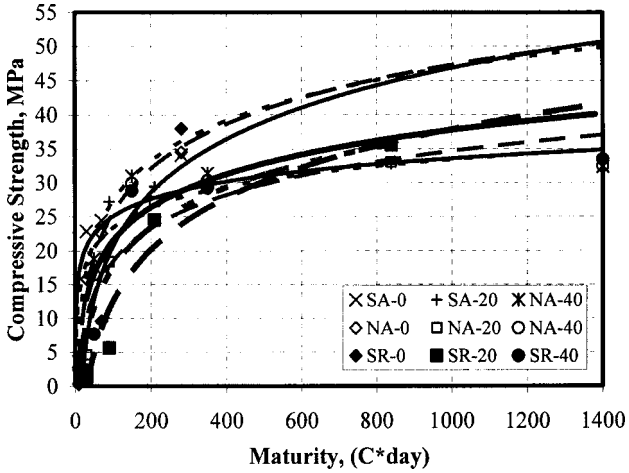



**Fig. 3.** Compressive strength–maturity logarithmic relationship

of the concrete to the temperature during the curing period. As seen from the test results, the same mixtures gain strength quickly at high curing temperatures, but at later ages, the strength curves cross over leaving the concrete that was cured at the highest temperature with the lowest ultimate strength. This is important because most design strength criteria assume concrete strength gain to continue after the standard 28 days.

It is seen that the slope of all trends are negative in Fig. 2. This state shows that high temperatures affect the ultimate strength of concrete negatively. From Fig. 2, it has been seen that ultimate strength of the concrete prepared with an admixture can be achieved by the one without an admixture by increasing the cure temperature. For lower curing temperatures, ultimate strength varies at a wide range with respect to different types of admixtures. It can be concluded that hydration products form a structure in the form of a shell surrounding especially the cement gains hence preventing them from hydrating by decreasing total hydration or ion diffusion occurring in this structure, and finally the long-term ultimate strength decreases due to this event (Akar 2002). Especially this effect increases in SA used in concrete specimens. With the aim of determining the strength development of concrete produced by using the SA and SR admixtures or without admixture, the strength–maturity relationships are investigated logarithmically for three different types of cure temperatures of 0, 20, and 40°C, and the results are given in Fig. 3 and Table 6.

From Fig. 3, it can be observed that the concrete strength takes values close to each other for constant maturity values. Consequently, it can be concluded that the strength–maturity relationships vary clearly with respect to cure temperature and admixture type. If correlation coefficients were examined in Table 6, the correlation coefficients decrease in all conditions by increasing initial cure temperature. 3, 7, and 28 day strength estimations are made by using the maturity–strength relationship proposed for the temperature of 20°C, and the results are compared to the results of Ramakrishnan and Mac Donald (1979) and Karakurt (2002) in Table 7. The maturity term in the equations proposed is accounted for by the Nurse–Saul equation (°C day). In this study, aimed at converting cylindrical specimen strength to cubic one, the multiplier coefficient (1.25) is added to the equations of Ramakrishnan and Mac Donald (1979) and Karakurt (2002) for considering cubic compressive strength.

According to these results, the error portions in the estimation of the maturity-strength by the proposed equations are lower than the ones made by the equations of Ramakrishnan and Mac Donald (1979) and Karakurt (2002). This condition is based on ignoring the characteristic properties of the concrete by equations. Especially, it is observed that the error portions in the estimation of specimens prepared by using admixtures affecting setting time at early ages are higher compared to the ones without admixture. The most reliable results are obtained from 28 day specimens in the strength estimation made using experimental data.

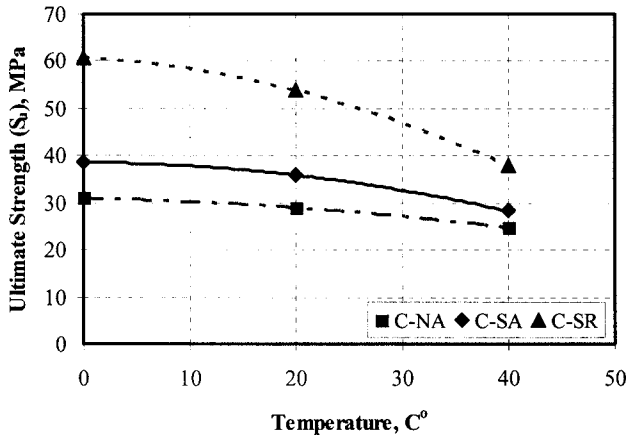



**Fig. 2.** Relationship of ultimate strength and curing temperature with admixtures

## Conclusions

It is seen from the test results that when using the Nurse–Saul equation for estimating the compressive strength of concrete, the correlation coefficients of the results are lower for high curing temperatures. To account for the maturity index period, the concrete rapidly gains strength after its setting time, using the Arrhenius function which takes into consideration the effects of temperature on decreasing error margins at early ages. With the proposed equations, it is seen that the 28 day strength of specimens in the concrete used the SA and RA admixtures can be estimated with a 10% error margin.

**Table 6.** Strength-Maturity Logarithmic Relationship $y=c \ln M+b$

| Curing temperature (°C) | SA | | | NA | | | SR | | |
|---|---|---|---|---|---|---|---|---|---|
| | $c$ | $b$ | $R^2$ | $c$ | $b$ | $R^2$ | $c$ | $b$ | $R^2$ |
| 0 | 8.56 | −12.14 | 0.889 | 9.48 | −18.15 | 0.990 | 11.40 | −31.87 | 0.851 |
| 20 | 7.10 | −11.25 | 0.760 | 8.53 | −21.82 | 0.939 | 11.05 | −38.43 | 0.933 |
| 40 | 3.72 | 7.93 | 0.657 | 4.38 | 3.21 | 0.714 | 7.06 | −14.11 | 0.733 |

**Table 7.** Control of the Concrete Strength with Maturity Method

| Admixture | Day | $f_c$ (MPa) | Eq. (3) | Error (%) | Eq. (4) | Error (%) | Eq. (5) | Error (%) |
|---|---|---|---|---|---|---|---|---|
| SA | 3 | 5.62 | 27.00 | 79.17 | 29.66 | 81.05 | 11.29 | 50.22 |
| | 7 | 24.53 | 35.30 | 30.50 | 39.43 | 37.78 | 20.66 | 18.77 |
| | 28 | 35.58 | 48.88 | 27.22 | 55.41 | 35.79 | 35.97 | 1.10 |
| NA | 3 | 18.38 | 27.00 | 31.92 | 29.66 | 38.04 | 16.58 | 10.82 |
| | 7 | 27.22 | 35.30 | 22.88 | 39.43 | 30.96 | 23.81 | 14.31 |
| | 28 | 33.07 | 48.88 | 32.35 | 55.41 | 40.33 | 35.64 | 7.23 |
| SR | 3 | 27.22 | 27.00 | 0.84 | 29.66 | 8.23 | 20.70 | 31.51 |
| | 7 | 29.42 | 35.30 | 16.65 | 39.43 | 25.38 | 26.71 | 10.14 |
| | 28 | 32.82 | 48.88 | 32.86 | 55.41 | 40.77 | 36.56 | 10.21 |

For in situ applications, the use of the Nurse-Saul function is simpler and thus preferred to the use of the Arrhenius based function. To estimate in-place strength, the maturity of the structural elements is acquired as per the procedures described earlier and the correlation relationship is used to convert the test results to a compressive strength value. The writers recommend linear analysis for early ages (1–3 days) and logarithmic analysis for later ages (7–28) if Nurse–Saul function is used for concrete strength estimation. As in-place concrete strength predictions from the two functions are compared, they do not differ more than 10%.

If accelerated curing is applied to the concrete at high temperatures, the curing process should be reduced; because the strength of the concretes could be lower than the ones produced under normal conditions due to the crossover effect.

## Notation

*The following symbols are used in this paper:*

$C$ = CEM I 42.5 R cement;
$C_3A$ = tricalcium aluminate;
$C_3S$ = tricalcium silicate;
CSI = crushed Stone I;
CSII = crushed Stone II;
$E$ = determined activation energy;
$f_c$ = compressive strength of concrete;
$M$ = maturity index;
NA = not including admixture;
$R$ = general gas constant;
$S$ = concrete strength in $t$ age;
$S_u$ = limit strength;
SA = set accelerating admixture;
SR = set retarding admixture;
$T$ = average concrete temperature;
$T_0$ = initial temperature;
$t_e$ = equivalent age related to temperature;
$W$ = water;
w/c = water-to-cement ratio;
$\Delta t$ = time interval;
$\delta$ = density; and
(S) = river sand.

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