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Fine aggregate and curing temperature effect on concrete maturity

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Abstract

Removal of formwork can be made in a short time by early-strength gain of concrete with heat treatment. The effects of accelerated curing temperature and fine aggregate on early strength as well as the relationships between early strength–28-day strength and strength maturity have been examined. Cube concrete specimens produced with a 10-cm constant slump value, 0.59 w/c ratio, and with two different types of fine aggregate were subjected to three-phase cure processes. These cure processes include a 1-h preheating process after having replaced concrete in the mould, the cure application process, and finally the last waiting period for 2 h that is aimed at minimizing the effects of thermal stresses. Each of the specimen groups was cured at different temperatures for different periods (6 or 18 h). At the end of curing and on the 28th day, cube compressive strengths were determined. Therefore, it was seen that it is possible to estimate 28-day strength beforehand with reasonable accuracy.

Keywords: Concrete; Heat treatment; Early strength; Maturity

1. Introduction

With the aim of satisfying increasing accommodation demands economically and in a short period of time, various methods have been developed to accelerate the strength gain of concrete. Factors such as material properties, concrete composition, concrete replacement and compaction factor, and geometric dimensions of building element, cure cycle, and curing conditions affect early-strength gain along with the heat-treatment applications [1]. Various types of fine aggregate are being used in concrete mixtures. The type of fine aggregate used changes the geometric properties of cement paste, and affects not only the shell formation during heat treatments but also the properties of concrete. The quality of poured concrete must be determined to control the production quality during the time required to remove the formwork. Compressive strength is parallel with all the other properties of concrete; therefore, it is an important criterion that must be followed while removing the formwork from the concrete [2]. In fact, the concrete strength is determined with the help of coring from the buildings. However, taking coring specimens is very difficult when the concrete is of early age. Therefore, to determine the removal time of the formwork, some ideas about concrete strength can be obtained by using various methods, such as ultrasound velocity or Schmidt rebound hummer [3,4].

The maturity method, which can determine the strength of concrete, replaced in-place relating with heat and time, and the accelerated cure methods, which are based on the determination of 28-day strength by finding the relationship between the early strength that is gained by the concrete generally through heating in order to accelerate the hardening of the concrete, and 28-day strength, are alternative methods.

In this study, early strength has been provided for specimens by the curing method in cabinet, and the effects of the curing temperature and the fine aggregate type on early strength has been investigated. It is aimed that the concrete subjected to the heat treatment will be tested by the accelerated cure and the maturity methods with the early strength–28-day strength relationships provided by regression analysis of the experimental results.

2. Estimation of concrete strength with the maturity method

The maturity method is a method in which time and temperature effects must be taken into consideration in

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Table 1
Properties of cement used in experiments

Chemical composition (%)	
CaO	63.97
Al_2O_3	5.58
Fe_2O_3	3.69
SiO_2	20.96
MgO	1.69
Fe_2O_5	–
K_2O	–
Na_2O	–
SO_3	2.84
Cl	0.008
TiO_2	–
Excess heating loss	1.15
Unassigned	0.05
Physical properties	
Blain fineness (cm^2/g)	3345
Specific gravity	3.15
Initial setting	2 h 5 min
Final setting	3 h
Lechatalier soundness (mm)	3
Compressive strength (MPa)	
2-day	21.9
7-day	38.3
28-day	45.1

Table 2
Sieve analysis of aggregates used in experiments

Aggregate	Sieve size	31.5	16	8	4	2	1	0.5	0.25
RS	Passing	100	100	100	98.6	76.8	57.0	42.2	16.2
CS	(%)	100	100	100	98.0	71.0	56.0	42.0	26.0
CS I		100	96.6	0	0	0	0	0	0
CS II		100	12.0	0	0	0	0	0	0

Table 3
Material contents used in concrete production of 1 m^3

MC	RS			CS		
	δ_u (g/cm^3)	V (dm^3)	W (kg)	δ_u (g/cm^3)	V (dm^3)	W (kg)
C	3.150	111	350	3.150	122	384
S	2.630	287	756	2.700	274	741
CS I (8–16)	2.690	201	540	2.690	192	515
CS II (16–32)	2.700	181	488	2.700	172	465
Water	1.000	205	205	1.000	225	225
Air	0.000	15.0	0.00	0.000	15.0	0.00
Mixture	2.339	1000	2339	2.330	1000	2330

strength development. If the same specimens are kept under various cured conditions, strength estimations can be done with strength–maturity relationships about the temperature history of concrete and specimens. It is necessary to know the relationships of the concretes that are to be used in buildings in which the maturity method will be used.

The temperature history of the concrete in place is observed continuously, and maturity is defined with this information. By observing strength–maturity relationship in place, the strength of a building can be estimated. The Nurse–Saul maturity function, which is frequently used in the determination of the maturity index, is given below as [5]:

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

In this function, M is the maturity index (°C-h or °C-day), T is the average concrete temperature at time interval Δt (°C), T_0 is the datum temperature (− 10 °C), t is the time (days or hours), and Δt is the time interval (days or hours).

One of the most common equations about the strength–maturity relationship is the logarithmic equation below suggested by Plowman [6].

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

In this equation, M is the maturity index (°C-h or °C-day), and a and b are coefficients peculiar to the concrete mixture.

Volz et al. [7] show the importance of cure conditions in the first 7 h (early age) following concrete moulding in the relationship of maturity and strength in their studies. They conclude that Eq. (1) becomes inefficient because it ignores the first hours. Then, they try to determine the concept of early age regarding the Nurse–Saul equation. Therefore, concrete specimens produced from the same mixture were kept at − 1 °C (30 °F), 21 °C (70 °F), and 43 °C (100 °F). Some of the specimens were kept in temperatures as above, and the others were kept at 21 °C (70 °F) after 6, 18, 30, and 48 h, respectively, and were tested in compression on the 1st, 3rd, 5th, 7th, and 28th days.

From the results obtained, it was observed that the maturity–strength relationship, which was acquired after keeping the specimens at a normal temperature after 6, 18, 30, and 40 h, or at the first temperature, did not change

Table 4
Experimental results of cube compressive strength (MPa) made on specimens

Specimen	AC											
	6-h						18-h					
	20 °C	40 °C	60 °C	20 °C	40 °C	60 °C	20 °C	40 °C	60 °C	20 °C	40 °C	60 °C
	9-h			28-day			21-h			28-day		
RS	3.7	10.1	13.6	48.2	42.4	35.3	8.4	21.1	23.3	46.9	36.7	32.5
CS	5.5	11.7	14.3	42.2	37.2	33.2	10.7	22.6	23.9	41.5	34.8	28.6

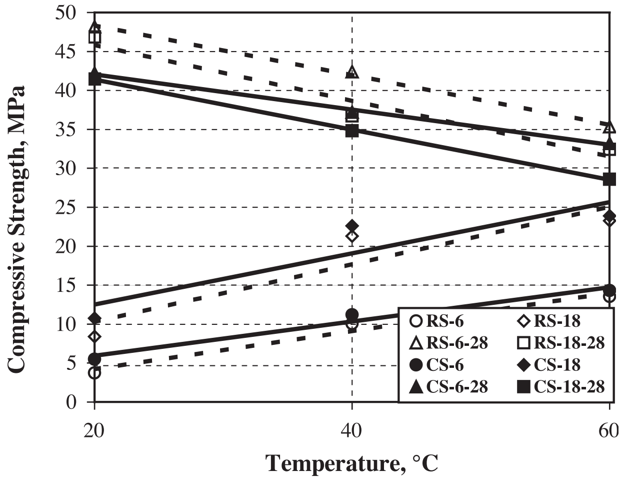

Fig. 1. Compressive strength–curing temperature relationship.

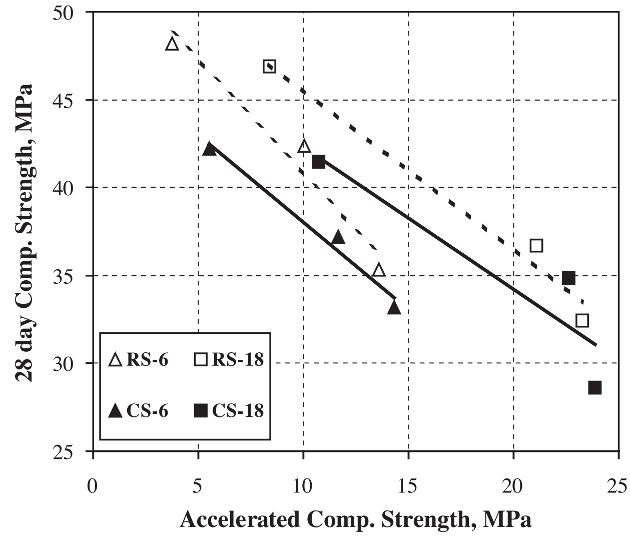

Fig. 2. Twenty-eight-day strength–accelerated strength relationship.

permanently. Volz et al. explain that the curves form unity in themselves depending on the initial temperature, and that the initial curing temperature that lasts 6 h can affect the movement of the maturity strength curve, and finally that late temperature variations do not change the curve. Olukun et al. [8] explain that compressive strength of the concrete at early ages can be estimated by maturity beforehand [Eq. (3)]. In this equation, f_c represents strength resulting in maturity, f_{28} is the 28-day compressive strength, m is maturity/10,000, and γ is an equation constant for the estimation of strength with maturity in ages of 1 day and less. In this equation, the maturity term is the maturity of the concrete mixture determined by the Nurse–Saul equation in the type of °C-day.

$$f_c = f_{28} + (1 - e^{-\gamma m}) \quad (3)$$

3. Experimental study

Because the gain of high early strength is desired in concrete mixtures prepared for experiment, PC 42.5 (Type III) Portland cement (C) is preferred; its properties are given in Table 1. Two different mixtures are constituted by using two different fine aggregates, such as river sand (RS) from Sakarya river and crushed stone sand (CS) with the root of limestone, in experiments. Composition rates and coarse aggregate are the same for each mixture. Grading composition is defined with respect to the sieve group by DIN 4226 standard. This composition is used in the rates of 43% of sand (S) at the ranges of 0–4 mm; 30% of crushed stone (CS I) at the ranges of 8–16 mm; and 27% of crushed stone (CS II) at the ranges of 16–32 mm in the form of the range between the reference curves of A32 and B32 suggested in EN 932-2 standard [9]. The rates of aggregate passing through a sieve are given as percentages in Table 2. Seventy-two 15-cm-cube specimens, having a w/c ratio of 0.59 and 10 cm slump value, were produced by using RS and CS as fine aggregate. For designing concrete mixtures, the absolute volume method that is specified in the TS EN 206-1 standard was used. In Table 3, δ_u is the density of the components, V is volume, W is mass, and MC is material contents/unit of concrete (m^3).

When the ratio of early strength that is gained with accelerated cure (AC) to the ratio of 28-day strength is higher, early strength–28-day strength relationship reaches a most reliable level [10]. In our study, the cube concrete specimens produced with two different types of fine aggregate gained early strength by application of two different cure cycles, 1-h preheating cure process, 6- or 18-h cure process at 20, 40, and 60 °C in cabinet, and 2-h last-waiting cure treatment. During these cure applications, moisture is kept over 50%. After the accelerated cure applications, 28-day specimens were kept in a curing tank at 20 °C until the time of the experiment. At the end of the cure applications

Table 5
Linear relationship of compressive strength–curing temperature, $y = ax + b$

AC	RS			CS		
	a	b	R^2	a	b	R^2
6-h cure in	0.246	−0.723	0.974	0.220	1.54	0.972
cabinet	−0.321	54.797	0.997	−0.226	46.58	0.996
18-h cure in	0.372	2.787	0.847	0.329	5.943	0.821
cabinet	−0.361	53.097	0.947	−0.321	47.8	0.999

Table 6
Linear relationship of early-age strength–28-day strength, $\sigma_{28} = a\sigma_a + b$

Specimen	6-h cure in cabinet			18-h cure in cabinet		
	a	b	R^2	a	b	R^2
RS	−1.258	53.432	0.952	−0.911	54.706	0.976
CS	−0.992	47.941	0.975	−0.809	50.398	0.835

Table 7
Estimates of concrete strength with $\sigma_a - \sigma_{28}$ relationship

Specimen	AC	σ_{28} (MPa)	Ref. [9], 20 °C	Error (%)	σ_{28} (MPa)	Ref. [9], 40 °C	Error (%)	σ_{28} (MPa)	Ref. [9], 60 °C	Error (%)
RS	6-h cure	48.2	48.78	1.1	42.39	40.79	3.9	35.3	36.32	2.8
CS		42.2	42.49	0.7	37.19	36.38	2.2	33.2	33.76	1.7
RS	18-h cure	46.9	47.05	0.3	36.71	35.48	3.5	32.5	33.48	2.9
CS		41.5	41.74	0.6	34.82	32.09	8.5	28.6	31.06	7.9

to the specimens, the cube compressive strength was obtained on the 28th day of cure treatment.

4. Results and the implementation of experiments

As a result of the accelerated cure applications of specimens produced by using two different aggregates RS and CS, cube compressive strengths were determined on the 28th day. Aggregate type and curing temperature effects on the early-strength gain of the concrete were investigated by implementing the experimental results. It was aimed to determine whether the early strength–28-day strength and the strength–maturity relationship would control the concrete strength [9]. Experimental results are given in Table 4 for each of the curing groups with the average of the three specimens used.

To determine the effects of accelerated curing temperature on early and 28-day strength, changes in cube compressive strength of specimens subjected to curing in cabinet were examined linearly on the 28th day and at the end of the curing applications at different temperatures and in two different curing periods. The results are given in Fig. 1 and Table 5. Fig. 1 shows that the increase in curing temperature accelerates the early-strength gain of the concrete but affects the 28-day concrete strengths negatively. As explained in the literature, this is because the hydration product at high temperatures forms a shell structure focusing around the cement grains, and ion diffusion of this structure decreases; consequently, the strength of cement at older ages decreases with the decrease in total hydration [11]. From Table 5, it can be seen that the correlation coefficients of specimens subjected to curing in cabinet for 18 h are lower than the correlation coefficients of those that had been exposed to cure application for 6 h. This is because early strength–curing temperature relationship loses linearity due to the decrease in humidity rate of the concrete in a short time.

To determine the 28-day potential strength of the concrete that was subjected to heat treatment in the cabinet, the relationship between the early strength gained through two different accelerated cure applications and the strength of 28-day specimens that were kept in the curing tank at 20 °C until the experiment time after curing are investigated linearly in Fig. 2, and the obtained regression equations and the estimations made about the concrete subjected to different accelerated cures with equations are given in Tables 6 and 7.

In Fig. 2, the slope of the curves is seen as negative in all conditions. According to this, when the 28-day strength decreases, the accelerated strength values of the two mixtures increase. This state is clear in concretes produced with CS. When accelerated strength values of the two mixtures increase, the 28-day strength decreases. This case is clearer for concretes produced with CS. From Table 6, it is seen that correlation coefficients are higher in the specimens produced with CS subjected to 6-h curing, and those produced with RS and 18-h curing. Thus, it can be concluded that it is suitable to use a softer cycle that is less than 18-h curing to determine the early strength of concrete produced by CS. When the strength estimations are compared with real cube compressive strength, the range of 2–9% error portion estimates the 28-day strength of the concrete subjected to the process.

To determine the development of strength of concrete with maturity, maturity–strength relationships were examined logarithmically in concretes produced with two different

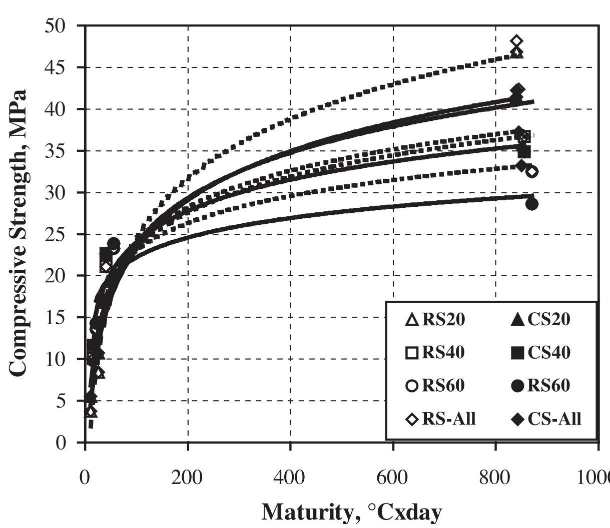

Fig. 3. Compressive strength–maturity logarithmic relationship.

Table 8
Strength–maturity logarithmic relationships at different initial curing temperatures, $y = c\ln M + b$

Initial cure temperature (°C)	RS			CS		
	c	b	R^2	c	b	R^2
20	10.320	− 23.064	0.993	8.486	− 15.90	0.997
40	6.338	− 5.396	0.961	5.396	− 0.813	0.931
60	4.709	1.350	0.922	3.390	6.611	0.802
All temperatures	7.813	− 12.069	0.893	6.304	− 5.875	0.879

Table 9
Control of concrete strength with the maturity method

Specimen	Specimen age	f_c (MPa)	Ref. [8]	Error (%)	Ref. [9], all T	Error (%)	Ref. [9], 40 °C	Error (%)
RS	9-h	10.05	10.19	1.4	9.09	10.6	12.28	18
	21-h	21.09	20.62	2.3	15.7	34.3	18.18	16
	28-day	36.71	–	–	40.7	9.8	37.39	1.8
CS	9-h	11.65	11.62	0.2	11.2	3.9	14.23	18
	21-h	22.63	22.40	1	16.5	27.1	19.26	17
	28-day	34.82	–	–	36.7	5.1	35.62	2.2

types of fine aggregate at different initial temperatures. The common formula used for all of the initial temperatures is from Plowman's Eq. (2), and the results are displayed in Fig. 3 and Table 8.

In Table 8, by using maturity–strength relationships suggested for RS and CS mixtures subjected to accelerated cure at 40 °C, and the common formula suggested for all of the cure temperatures, strength of concrete about maturity is estimated at the end of 9- and 21-h cycles and on the 28th day. The results are compared in Table 9, using Eq. (3) as proposed by Oluokun et al. [8], to estimate maturity and strength at critical early ages based on 28-day strength of concrete. For comparing the estimations of strength, the strengths of the specimens in the 9th and 21st h and on the 28th day were used. Twenty-eight-day specimens were kept at 20 °C after being exposed to cure application for 21 h until the experiment. Maturity in the equations suggested here was based on the Nurse–Saul equation (°C-day). At the end of the regression analysis, values of γ constants in Oluokun et al.'s equation were 200 in the concrete produced with RS and 250 in the ones produced with CS.

According to these results, maturity estimations made at the age of 1 day and earlier using the equation suggested by Oluokun et al. for the concrete with applied heat treatment are nearly the same with the real strength. When the table is investigated, error ratio strength estimations at early ages are quite high with the equations given in Table 8 based on Eq. (2). In the 28-day estimation, the error ratio of the equation for cure application at 40 °C is low, whereas the error ratio of common equations is high for cure applications at different initial temperatures. Thus, when cure temperature changes in a wide range, there should not be so much difference between the initial cure temperatures and the average temperature of the in-place concrete. It is possible to make more accurate estimates considering mixture properties in Oluokun et al.'s study. It is seen that it will be possible with Eq. (3) suggested by Oluokun et al. to estimate within an approximately 2% error ratio the 28-day strength of the specimens subjected to heat treatment at early ages.

5. Results and suggestions

Increase in cure temperatures improves the strength of concrete at early ages; however, it affects the 28-day results negatively, and these effects are clearer on the specimens produced with CS. It is possible to estimate 28-day strength of concretes with applied heat treatment over a short period, such as 9 or 21 h. The 28-day strength of concretes with heat treatment using early strength–28-day strength relationships suggested by Oluokun et al.'s equation and in Table 6 can be estimated. It is easy to determine the influence of the concrete temperature at early ages on the strength of concrete at older ages with the equations, which consider the different initial temperatures.

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