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The effect of excessive steam curing on Portland composite cement concrete

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Abstract

Steam curing at atmospheric pressure is an important technique for obtaining high early strength values in precast concrete production. Cement type, as well as curing period and temperature, is an important parameter in the steam-curing process. PC42.5 is the type of cement that is most commonly used in Turkish precast concrete plants. Its behavior is well known. Nowadays, the production of composite cements is becoming more popular every other day due to its advantages. The object of this study was to determine the properties of this relatively new binder comparatively with conventional PC42.5 under steam curing. For this purpose, 15-cm concrete cubes were prepared with a water/cement ratio (W/C) of 0.44 and were subjected to steam curing for five different curing periods of 4, 8, 16, 24 and 36 h under curing temperatures of 65 and 85 °C. Cement dosage was kept constant (400 kg/m^3) for all specimens. The variation of compressive strength values and maturity for each condition has been presented comparatively within this study. Test results indicated that Portland composite cement (PKC/A42.5) can be used in place of PC42.5 for steam curing at atmospheric pressure in precast concrete production. However, in case of early high strength demand for early demolding purposes, curing temperature should be increased to 85 °C for PKC/A42.5 cement concretes.

Keywords: Concrete; Curing; Compressive strength; Maturity

1. Introduction

Atmospheric steam curing is a heat treatment which has been used for many years to accelerate the strength development of concrete products. Because the hydration rate of cement increases with the increase in temperature, the gain of strength can be speeded up by curing concrete in steam. When steam is generated in atmospheric pressure, the temperature is below 100 °C; the process can be regarded as a special case of moist curing in which the vapour-saturated atmospheres ensures a supply of water [1,2].

Maximum curing temperatures may be anywhere in the range of 40 to 100 °C. However, the optimum temperature has been found in the range of 65 to 85 °C. The curing temperature will be a compromise between rate of strength gain and ultimate strength, because the higher the curing temperature, the lower the ultimate strength [3].

The role of cement type as a binder has a great importance in heat treatment applications. The primary factors determining the behavior of cements subjected to heat treatment are fineness and composition of cements, the type and amount of additives used in blended cements and curing cycle parameters. For compressive strength development of concrete, duration of steam curing is also an important parameter as well as temperature [4]. The treatment period and temperature is adjusted according to the targeted 1-day strength level. It is obvious that heat treatment application at a lower temperature is more economical and energy saving [5].

The length of the total curing period must allow for controlled heating application and cooling of the concrete

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Table 1
Chemical analysis and physical and mechanical properties of cements

Chemical composition (%)	Cement type	
	PC42.5	PKC/A42.5
SiO_2	19.70	23.99
Al_2O_3	4.97	6.43
Fe_2O_3	3.58	3.49
CaO	64.25	56.79
MgO	0.91	0.69
Na_2O	0.17	0.26
K_2O	0.77	1.06
SO_3	2.65	2.18
Cl	0.011	0.017
Loss on ignition	1.78	2.16
Insoluble residue	0.38	6.20
Lime (CaO), free	1.07	1.60
Complex compounds (%)		
C_3S	61.41	–
C_2S	10.14	–
C_3A	7.11	–
C_4AF	10.88	–
Mechanical properties		
2-day (MPa)	26.0	24.2
7-day (MPa)	42.0	39.7
28-day (MPa)	52.0	51.7
Physical properties		
Specific surface (cm^2/g)	3600	3561
Initial time of sett. (h:min)	2:15	2:25
Final time of sett. (h:min)	3:25	3:50
Specific gravity	3.15	3.04

[3]. Practical curing cycles are chosen as a compromise between the early and late strength requirements but are governed also by the time available (e.g., length of work shifts). Economic considerations determine whether the curing should be suited to a given concrete mix or, alternatively, whether the mix ought to be chosen so as to fit a convenient cycle of steam curing. Whereas, details of a satisfactory cycle would consist of the following: a preheating (delay) period of 2 to 5 h, heating at the rate of 22 to 44 °C/h up to a maximum temperature of 50 to 82 °C, then storage at maximum temperature, and finally a cooling period, the total cycle (exclusive of the delay period) should be completed preferably not more than 18 h [6]. Erdem et al. [7] concluded that in the delay in the commencement of steam-curing operation by a period equal to the initial setting time of cement, higher strengths were obtained when the delay period was equal to the setting time.

Table 2
Specific gravity and absorption of aggregates

Aggregate type (mm)	Specific gravity		Absorption (%)
	Dry	SSD*	
Coarse aggregate (5–25 mm)	2.69	2.70	0.70
Fine aggregate (sand 0–3 mm)	2.47	2.53	2.20
Fine aggregate (0–5 mm)	2.58	2.62	1.40

* SSD: saturated surface dry.

Table 3
Concrete mix proportions (kg/m^3)

Materials	Mix with PC42.5, weight (kg/m^3)	Mix with PKC/A42.5, weight (kg/m^3)
Cement	400	400
Water	176	176
Coarse aggregate (15–25 mm SSD)	425	423
Coarse aggregate (5–15 mm SSD)	497	495
Fine aggregate (0–5 mm SSD)	449	446
Fine aggregate (0–3 mm sand SSD)	433	431
Admixture	6.4	6.4
Total	2386	2377

The hydration rate of cement is greatly affected by a number of factors besides temperature, so the gain in strength of concrete is also largely controlled by these factors. However, it is clear that the effect of the humidity during curing is a major consideration that cannot be ignored. To estimate the strength of concrete without the necessity of carrying out physical tests, the concept of “concrete maturity” has been established [3]. The maturity concept was proposed in the late 1940s and early 1950s as a technique to account for the combined effects of time and temperature on the strength development of a concrete mixture [8]. In this approach, a maturity function is used to convert the measured temperature history of the concrete to a numerical index, indicative of the extent of the strength development. Concrete strength may be estimated based upon the measured maturity index and “strength–maturity relationship” for that particular concrete mixture during the curing period [9].

The maturity concept proposed by Saul [10] stated that samples of concrete from the same mixture will have equal strength if they have equal maturity values, although their temperature histories may differ.

Saul introduced the term “maturity”, defining it as the product of age and average temperature above freezing. He found the strength development of a given mix to be a function of the maturity, provided that the temperature did not reach 50 °C until 1.5 to 2 h or 100 °C until 5 to 6 h after the time of mixing. On the basis of these findings, Saul [10] proposed a “law” of strength gain with maturity. A characteristic relation between strength and maturity exists

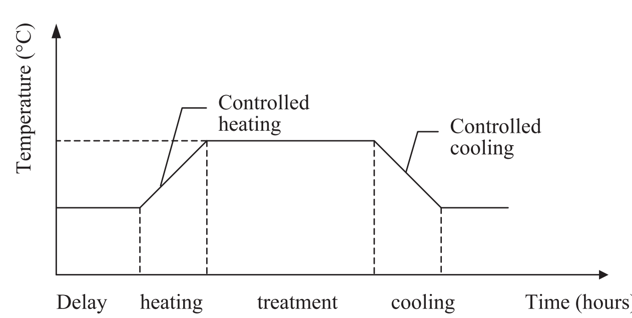

Fig. 1. Schematic representation of the heat treatment procedure.

Table 4
Details of steam-curing treatment

Delay period		Temperature rise period		Treatment period		Cooling period		Total cycle
Temp.(°C)	Time (h)	Temp. (°C)	Time (h)	Temp. (°C)	Time (h)	Temp. (°C)	Time (h)	Time (h:min)
27	3	27–65	2.25	65	4	65–32	3	12:15
27	3	27–65	2.25	65	8	65–32	3	16:15
27	3	27–65	2.25	65	16	65–32	3	24:15
27	3	27–65	2.25	65	24	65–32	3	32:15
27	3	27–65	2.25	65	36	65–32	3	44:15
29	3	27–85	3	85	4	85–34	4.67	14:40
29	3	27–85	3	85	8	85–34	4.67	18:40
29	3	27–85	3	85	16	85–34	4.67	26:40
29	3	27–85	3	85	24	85–34	4.67	34:40
29	3	27–85	3	85	36	85–34	4.67	46:40

for every type of concrete, as this relation is dependent on the concrete composition.

Classical maturity formulas do not incorporate the effect of relative humidity on the strength development of concrete. However, the validity of this approach under low relative humid conditions has been criticized. According to Baradan and Un [11], under 70% relative humid environment, there has been no considerable increase in maturity of concretes in different curing conditions regardless of curing temperature and time.

In this paper, the effect of excessive steam-curing applications on the strength and maturity of concretes incorporating composite cements, which are more commonly produced recently in Turkey, has been investigated.

2. Experimental study

An experimental program has been conducted to investigate the effect of cement type and excessive steam-curing applications on the compressive strength development of concrete.

2.1. Materials

2.1.1. Cement

A Portland cement similar to ASTM Type III cement (PC42.5) and a Portland composite cement (PKC/A42.5) were used in the experimental program. Cements in conformity with Turkish Standards (TS19 and TS12143) were manufactured by Cimentas Cement Plant, Izmir, Turkey. The chemical analysis and physical properties of cements that are presented in Table 1 were supplied by the manufacturer. The Portland composite cement was a blended cement incorporating 12.4% of trass+fly ash (C type).

2.1.2. Aggregate

Crushed limestone and natural river sand was used as coarse and fine aggregates. Maximum aggregate size was 25 mm. The physical properties of aggregates are given in Table 2. The gradation of the aggregates in concrete mix was ideal according to relevant Turkish standard. The other properties of aggregates were also suitable for use in production of concretes.

2.1.3. Water

The type of water used in the experiments was ordinary drinkable tap water.

2.1.4. Superplasticizer

A high-range water-reducing admixture complying with the ASTM C 494 (Type A) specification was used in concrete mixes.

2.2. Mixing, curing and preparation of specimens

Concrete mixes have been designed with the same consistencies (6–8 cm slump), same water/cement ratios (W/C=0.44) and same type of aggregates but with different

Table 5
Compressive strength of standard moist and steam-cured specimens

Cement type	Compressive strength (MPa)									
	Control curing, time (days)				Curing temp. (°C)	Steam curing, treatment time (h)				
	3	7	28	56		4	8	16	24	36
PC42.5	38.2	44.5	49.8	52.4	65	36.3	38.6	39.7	46.7	43.0
					85	39.4	42.6	43.6	41.1	41.2
PKC/A42.5	36.2	40.9	49.0	52.2	65	29.8	33.3	34.1	37.6	42.4
					85	33.5	37.8	38.1	39.6	38.7

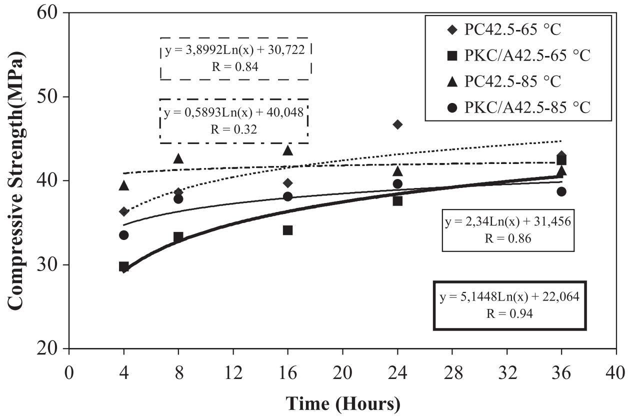

Fig. 2. Compressive strength with respect to treatment temperature and cement type at the corresponding time.

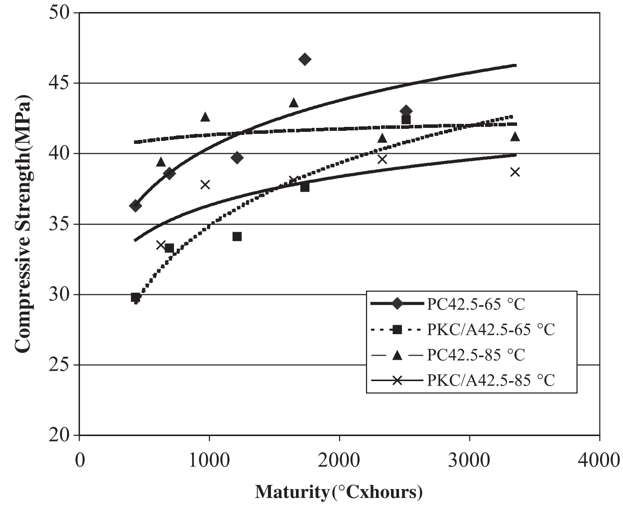

Fig. 3. Maturity factor and compressive strength relationship.

types of cement. Cement dosage was kept constant for all specimens. Concrete mix proportions are given in Table 3. Slight difference between concrete mixes were originated from their different specific weights. A total of 12 series of concrete batches was prepared, including 2 control mixes. Control concrete samples were moist cured by immersing them in lime-saturated water until the testing ages of 3, 7, 28 and 56 days. Steam curing at atmospheric pressure was applied immediately after casting for five different curing periods (exclusive of the delay period): 12, 16, 24, 32 and 44 h. The delay periods were kept constant (3 h) for all specimens. The maximum temperatures during curing were 65 and 85 °C. A steaming cycle consists of a gradual increase to the maximum temperature of 65 and 85 °C for a period of 2 and 3 h, respectively (which corresponds to a temperature of 18±1 °C/h). The schematic representation of the heat treatment procedure is shown in Fig. 1.

This was followed by steaming period (which includes treatment) 4, 8, 16, 24 and 36 h at each maximum temperature. The period of steam curing at maximum temperature was followed by cooling periods. The details of steam treatment are presented in Table 4. After the cooling period, testing procedure was carried out according to relevant Turkish standards.

3. Results and discussions

Test results of the effect of moist and steam curing on the compressive strength of concrete are presented in Table 5.

There are several important points worth noting in Table 5. Test results indicate that higher steam-curing strengths were obtained at 24 h and 65 °C, 16 h and 85 °C for PC42.5 cement, 36 h and 65 °C, 24 h and 85 °C for PKC/A42.5 cement, respectively. For the PC42.5 cement, early compressive strength was found to decrease when a heat treatment cycle with a 24 h, 65 °C and 16 h, 85 °C treatment duration is applied. The decrease in strength is believed to be a result of a less uniform distribution of hydration products in the paste due to the rapid initial hydration. This may be reflected in changes in pore-size

Table 6
Compressive strength (indicated as % of control) development of PC42.5 and PKC/A42.5 under different curing periods

Cement type	Treatment time (h)	Compressive strengths (% of control)							
		Treatment temperature and age							
		65 °C				85 °C			
		3 days	7 days	28 days	56 days	3 days	7 days	28 days	56 days
PC 42.5	4	95	82	73	69	103	88	79	75
	8	101	87	78	74	112	95	85	81
	16	104	89	80	76	114	98	88	83
	24	122	105	94	89	108	92	82	78
	36	113	97	86	82	108	92	82	78
PKC/A42.5	4	82	73	61	57	92	82	68	64
	8	92	81	68	64	104	92	77	72
	16	94	83	70	65	105	93	78	73
	24	104	92	77	72	109	97	81	76
	36	117	104	87	81	106	94	79	74

Table 7
Steam-curing compressive strength (f)–maturity (M) relation

Cement type	Temperature (°C)	Logarithmic regression eq.	Coefficient of correlation
PC42.5	20	f=4.6852LnM+5.1156	0.989
	65	f=4.8475LnM+6.9282	0.840
	85	f=0.6264LnM+36.995	0.262
PKC/A42.5	20	f=5.5405LnM −4.039	0.995
	65	f=6.4843LnM−9.9497	0.955
	85	f=2.9465LnM+15.976	0.836

distribution, particularly of the large capillary pores greater than 0.01 μm in diameter [3]. Therefore, a treatment duration, 65 °C duration temperature and 24 h, was found to be optimum for the PC42.5 cement concrete. Compressive strength values of PKC/A42.5 cement control specimens were less than PC42.5 concrete specimens at every test age. This result may be attributed to the mineralogical composition of the cement, rather than their similar physical properties, such as fineness.

For PC42.5 cement type, 24-h curing at 65 °C, (32 h total cycle) was more benefical than 16-h curing at 85 °C (24 h total cycle). The performance of PKC/A42.5 was also acceptable for curing periods exceeding 24 h at 65 °C of curing temperature. Based on test data, the optimum curing temperature may be chosen as 65 °C for both cement types. This result is in conformity with the Kjellsen and Detwiller [12] conclusions that composite cements incorporating slag, fly ash or a natural pozzolan perform well under heat treatment and they do not exhibit a loss in the curing temperature of 65 °C within a 36-h steam-curing period.

Fig. 2 illustrates the variation of compressive strength of the heat-treated specimens with respect to treatment temperature and cement type. The relationship between compressive strength and heat treatment, from a practical point of view, can be expressed in logarithmic form. These results show that heat treatment with higher temperatures and excessive curing cycle does not have a positive effect on strength. On the contrary, the strength decreases at temperatures of 85 °C and excessive curing cycle for PC42.5 cement. Thus, the higher the maximum curing temperature, the shorter the curing time. However, this higher rate of hydration will lead to a lower ultimate strength.

Table 8
Comparison of moist curing compressive strength of PC42.5 and maturity estimated values

Concrete age (days)	Maturity (°C×h)	Comp. strength tested (MPa)	Comp. strength maturity (MPa)	Deviations	
				MPa	(%)
3	1440	38.2	42.2	4.0	10.4
7	3360	44.5	46.2	1.7	3.8
28	13,440	49.8	53.0	3.2	6.4
56	26,880	52.2	56.4	4.2	8.0

Equation: f=4.8475LnM+6.9282.

Table 9
Comparison of moist curing compressive strength of PKC/A42.5 and maturity estimated values

Concrete age (days)	Maturity (°C×h)	Comp. strength tested (MPa)	Comp. strength maturity (MPa)	Deviations	
				MPa	(%)
3	1440	36.2	37.2	1.0	2.7
7	3360	40.9	42.7	1.8	4.4
28	13,440	49.0	51.7	2.7	5.5
56	26,880	52.2	56.1	3.9	7.4

Equation: f=6.4843LnM−9.9497.

Moreover, during the heating stage, the differences in the thermal expansion coefficient of the concrete ingredients can lead to microcracking and increased porosity [7]. However, because the steam curing of the concretes begins after a delay period almost equal to its setting time, no such deleterious effect occurs.

Compressive strength (indicated as % of control) rates of PC42.5 and PKC/A42.5 under different curing periods are tabulated in Table 6. As it was seen from Table 6, steam-curing concrete was 22% higher than the control moist curing concrete's 3-day compressive strength for PC42.5 cement at 24-h soaking time and 65 °C. By the application of 65 °C–36-h curing, PC42.5 reached 113% of the 3-day normal cured compressive strength. Approximately 28% and 26% reductions in compressive strength were encountered at the age of 28 days for both curing of 24 and 16 h at 65 °C, respectively. It was also clear that steam-curing concrete was 17% higher than the control moist curing concrete's 3-day compressive strength for PKC/A42.5 cement at 36-h soaking time and 65 °C. When the steam-curing temperature was increased to 85 from 65 °C, similar behaviors were observed.

A general evaluation associated with Table 6 is that early compressive strength increases with a heat treatment cycle with durations of 24 and 16 h for PC42.5 cement at 65 and 85 °C, respectively. On the other hand, for both PC42.5 and PKC/A42.5 cement, when the steam curing was prolonged

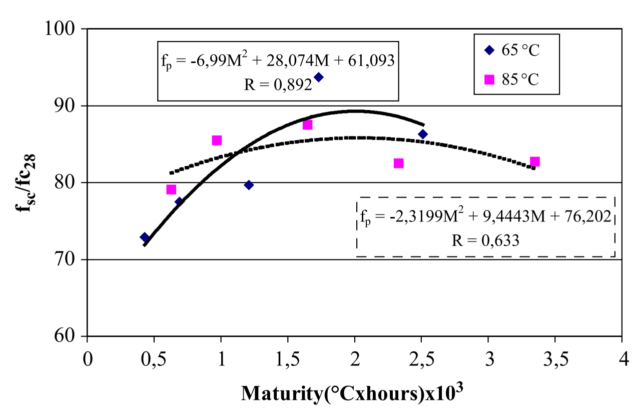

Fig. 4. Proportions of f_{sc}/f_{c28} at 65 and 85 °C with respect to maturity for PC42.5.

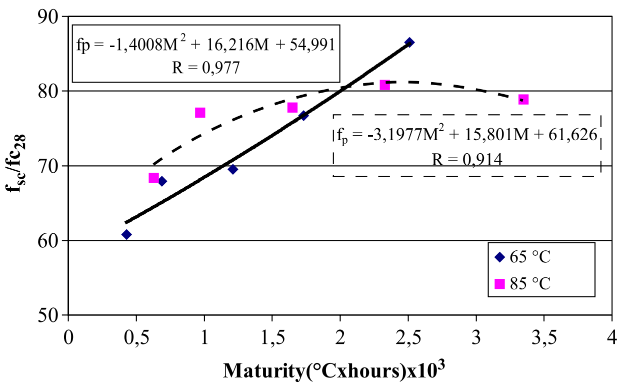

Fig. 5. Proportions of f_{sc}/f_{c28} at 65 and 85 °C with respect to maturity for PKC/A42.5.

from these times, the increases in strength at 7, 28 and 56 days were much less than those at 3 days.

A comparison of all the steam-curing cycle between PC42.5 and PKC/A42.5 cement shows that, at every test age, strength gains of PC42.5 due to steam curing are higher than PKC/A42.5. However, its strength losses at later ages are almost equal with PKC/A42.5.

3.1. Estimating concrete strength by the maturity method and comparison with test results

The test results were used to establish a relationship between strength and maturity for two types of cements under different curing cycles. The concept of concrete maturity may be defined as some function of the product of curing time t and curing temperature T. In this study, maturity was calculated by using the $M=\Sigma(T\times t)$ equation.

Fig. 3 indicates strength–maturity relations that were found to be logarithmic equations. The equations obtained after regression analyses are given in Table 7.

The coefficient of logarithmic regressions was maximum 0.955 for PKC/A42.5 at 65 °C. The tested moist curing compressive strength values are compared by maturity function approach for two types of cement in Tables 8 and 9, respectively.

As can be seen from Tables 8 and 9, deviations varied from 2.7% to 10.4% by using maturity function approach.

Figs. 4 and 5 illustrate variation of steam-curing compressive strength development for different curing conditions to the control 28-day compressive strength with respect to maturity for PC42.5 and PKC/A42.5, respectively. The coefficient of correlation, R, between the proportions of strength and maturity was found from 0.633 to 0.977. Based on these factors, a polynomial regression seems very reliable. It should be noted that the optimum maturity value can be derived based on the curve fitting.

Optimum ratios of steam-curing strengths to the 28-day control strength were found as 89.28%, 89.31% and 85.81%, 80.74% at 65 and 85 °C for PC42.5 and PKC/A42.5, respectively. On the other hand, the optimum values of maturity were obtained as 2010, 2788 and 2035, 2471 °C×hours at 65 and 85 °C for both cement types, respectively. The upper optimum ratios of steam-curing strengths to the 28-day control strength are very close for the PC42.5 and PKC/A42.5 at 65 °C. However, the maturity value of PKC/A42.5 is 1.38 times that of the PC42.5. This will justify the need for having more steam curing for concrete incorporating composite cements. The intersection points of the curve fitting were obtained from the equations as 1138 °C×hours−83.99% and 1751 °C×hours−79.09% for PC42.5 and PKC/A42.5, respectively.

4. Conclusions

The results obtained from experimental studies can be summarized as follows:

(1) All concrete specimens incorporating PC42.5 cement have developed higher compressive strength values at 85 °C than 3-day-old control concretes, at all curing periods.
(2) The optimum performance can be obtained by steam curing at 65 °C for 31 h for Portland cement (PC42.5) concrete specimens. The same performance can be achieved by curing at 85 °C for a period of 29-h steam curing for Portland composite cement (PKC/A42.5) concrete specimens.
(3) However, in case of early high strength value demand for early demolding purposes, curing temperature should be increased to 85 °C for Portland composite cement concretes.
(4) In case of exceeding a maturity degree of 2000 °C×hours, besides a waste of energy, a negative effect in mechanical properties can be observed in both types of concretes regardless of cement type.

References

[1] J.A. Hanson, Optimum steam curing procedure in precasting plants, ACI J. Proc. 60 (1963) 75–100.
[2] A.M. Neville, Properties of Concrete, Pitman Publishing, London, 1997.
[3] S. Mindess, J.F. Young, Concrete, Prentice Hall, 1981.
[4] E. Oztekin, Determination of heat treatment cycle for cements (in Turkish), Turkish cement manufacturers' association, Cem. Bull. 206 (3) (1984) 24–26.
[5] S. Erdogdu, S. Kurbetci, Optimum heat treatment cycle for cements of different type and composition, Cem. Concr. Res. 28 (1998) 1595–1604.
[6] ACI 517.2 R-87, Accelerated Curing of Concrete at Atmospheric Pressure-State of the Art, ACI Manual of Concrete, 1992, Revised.
[7] T.K. Erdem, L. Turanli, T.Y. Erdogan, Setting time: an important criterion to determine the length of the delay period before steam curing of concrete, Cem. Concr. Res. 33 (2003) 741–745.
[8] R.C. Tank, N.J. Carino, Rate constant functions for strength development of concrete, ACI J. 88 (1991) 74–83.

[9] N.J. Carino, R.C. Tank, Maturity functions for concretes made with various cement and admixtures, ACI J. (1991) 188–196.
[10] A.G.A. Saul, Principles underlying the steam curing of concrete at atmospheric pressure, Mag. Concr. Res. 2 (1951) 127–140.
[11] B. Baradan, H. Un, Mechanical Properties Development of Mortars by Using Different Types of Cement Under Different Climate and Curing Conditions, Final Report, Turkish Cement Manufacturers' Association, 2002, in Turkish.
[12] K.O. Kjellsen, R.J. Detwiller, Later-age strength prediction by a modified maturity model, ACI J. (1993).