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The influence of initial water curing on the strength development of ordinary portland and pozzolanic cement concretes

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Abstract

The effect of initial water-curing period on the strength properties of concretes was investigated. Three types of cement, one ordinary Portland cement (OPC) and two natural pozzolanic cements (blended and trass cements), were used in the concrete mixtures. Six different curing regimes were applied to the specimens, the first of which was continuous water storing, and the second continuous air storing. In the remaining four regimes, the specimens were stored under varying initial water-curing periods of 3, 7, 14, and 28 days, respectively. The compressive strength tests were carried out on the cubic specimens at the ages of 7, 14, 28, 90, and 180 days. The variation of compressive strength with time was evaluated by using a semilogarithmic function and the strength-gaining rates were calculated by using this equation for different curing conditions. It was found that poor curing conditions are more adversely effective on the strength of concretes made by pozzolanic cements than that of OPC, and it is necessary to apply water curing to the former concretes at least for the initial 7 days to expose the pozzolanic activity. However, when the pozzolanic cement concretes have sufficient initial curing, they can reach the strength of OPC concretes in reasonable periods of time.

Keywords: Curing; Compressive strength; Pozzolan; Portland cement; Blended cement

1. Introduction

Curing of concrete is important with respect to both strength and durability properties. In the definition of strength grade of concrete, a standard 28-day period is required under the water curing. Normally, strength gaining continues beyond 28 days when there exist adequate moisture and temperature conditions. In the standards, the minimum curing periods under certain weather conditions are given; for example, the ACI Recommended Practice for Curing Concrete (ACI 308) requires 7 days of moist curing for most structural concrete.

In the classical example about the curing effect in concrete [1], shown in many concrete textbooks, the difference between the moist-cured and air-cured concretes of Type I cement can be up to 58% at 6-month age. However, increasing the duration time of initial moist curing decreases this difference. Aitcin et al. [2] found 17–22% reduction in compressive strengths of concretes between moist-cured and air-cured specimens. It is mentioned [3] that the compressive strength of moist-cured specimens increased continuously with age over a 20-year period. In contrast, air-cured specimens stored in 50% RH reached a maximum compressive strength between 28 days and 5 years, and the 5-year strength was approximately the same as 28-day strength.

On the other hand, CO_2 emission has been a serious problem in the world due to the greenhouse effect and after the Rio de Janeiro Earth Summit in 1992 and following the Kyoto Protocol in 1997, many countries agreed to reduce the emission of CO_2. This necessitates a reduction of clinker production in the cement industry that is only possible by using supplementary materials, such as blast furnace slag, fly ash, natural pozzolan, silica fume, burnt shale, limestone powder, etc. [4]. Obviously, there are other advantages of using pozzolans in concrete, especially with respect to durability properties. Turkey is one of the natural-pozzolan-rich countries in the world, and two types of natural pozzolanic cements are used,

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blended cement (BC) and trass cement (TS). The natural pozzolan (trass) contents can be up to 19% and 40%, for the former and latter cements, respectively, in accordance with Turkish Standards TS 10156 and TS 26. However, the effect of lack of initial water curing on the concrete properties prepared with supplementary materials is worse than those of the ordinary portland cement (OPC) concretes [5]. A compressive strength loss of 38% for 25% slag, and about 50% loss for 25% fly ash, 50% slag, or high-volume fly ash concretes were reported [5], respectively, while it was only about 28% for control concrete (with ASTM Type I Cement) and silica fume concrete, measured between moist-curing and room-curing conditions. The loss in strength from continuously fog curing to 6-day fog curing followed by air curing was reported [6] as 13.5% for the concrete made with Type I cement, and 19.4% for the concrete made with cement and fly ash. Similarly, the strengths of fly ash concretes were mentioned [7] to be more sensitive to poor curing than that of the OPC concretes, and this sensitivity increases with increasing fly ash content.

The effect of accelerated curing on the early strength of concretes prepared by OPC and TC was investigated [8], and it was found that the early strength of the OPC concrete was higher than that of the TC concrete, but the difference between the strengths of these concretes reduced when the curing temperature was increased.

In this study, the effect of initial water-curing conditions on the compressive strengths of cubic specimens prepared by using an OPC and two natural pozzolanic cements (BC and TC) has been investigated at different ages.

Table 1
Physical properties and chemical analysis of cements

	Cement type			
	OPC 42.5	BC 32.5	TC 32.5	
Physical properties				
Density	3.10	2.94	2.83	
Specific surface				
Blaine (m^2/kg)	320	365	380	
Time of setting				
Initial (h:min)	3:30	3:40	3:50	
Final (h:min)	4:10	5:00	4:30	
Mechanical properties				
Compressive strength				
7-day (MPa)	46.5	28.9	20.4	
28-day (MPa)	57.4	43.4	33.3	
Chemical composition	Clinker	OPC	BC	TC
CaO	62.9			
SiO_2	21.0			
Al_2O_3	4.6			
Fe_2O_3	4.4			
MgO	1.2			
SO_3		2.4	2.8	2.5
CaO (Free)		0.9	0.8	0.9
Insoluble residue		0.3	15.6	29.5
Loss on ignition		1.7	3.5	3.6

Table 2
Aggregate densities and grading

Density of aggregate, kg/dm^3								
Crushed stone 2	Crushed stone 1	Crushed stone sand	Natural sand					
2700	2725	2710	2610					
	Cumulative percentage passing (%)							
Sieve size (mm)	31.5	16	8	4	2	1	0.5	0.25
Aggregate mixture	100	85	54	40	29	25	14	3

2. Experimental

2.1. Materials

2.1.1. Cement

OPC 42.5, BC 32.5, and TC 32.5 were used. The physical properties and chemical compositions of cements are given in Table 1.

2.1.2. Aggregates

Two sizes of limestone-based crushed stone (Crushed stone 1 and 2) were used as coarse aggregate, and a natural sand and a crushed stone sand (based on limestone) were used as fine aggregate. The volume fractions of aggregates in the aggregate mixture were as follows:

Crushed stone 2 (max. size 31.5 mm): 35%,
Crushed stone 1 (max. size 16 mm): 30%,
Crushed stone sand (max. size 4 mm): 15%,
Natural sand (max. size 2 mm): 20%.

The densities of aggregates and the grading of the aggregate mixture are shown in Table 2.

2.1.3. Admixture

A water reducer (ASTM C494 Type A) was used at a dosage of 0.5 wt.% of cement content.

Table 3
Mixing proportions of concretes

Mix no.	Cement type	Quantities in kg/m^3					
		Cement	Water	Crushed stone 2	Crushed stone 1	Crushed sand	Natural sand
1	OPC 42.5	260	200	666	577	287	369
2	BC 32.5	335	213	626	542	270	347
3	TC 32.5	450	233	564	489	312	312

Table 4
Curing regimes

Curing no.	Curing condition
1	Continuous water curing: immersion in lime-saturated water at 22∓1 °C
2	Continuous air curing: in the laboratory at 22∓2 °C and 70∓5% RH
3	Initial 3-day water curing + air curing (as in No. 2)
4	Initial 7-day water curing + air curing (as in No. 2)
5	Initial 14-day water curing + air curing (as in No. 2)
6	Initial 28-day water curing + air curing (as in No. 2)

2.2. Mix design

All three concretes were designed to have equal strengths at 28-day age, under standard water-curing condition. A strength grade of C 25 was chosen. The slump of fresh concretes was kept constant in the range of 12∓2 cm. A prestudy was carried out to determine the water/cement ratios of the concretes for each cement type. The minimum cement content given in Turkish Standard TS 11222, "Concrete, Ready Mixed Concrete," was used in the OPC 42.5 concrete. The mixing proportions of the concretes are shown in Table 3.

2.3. Testing procedure

Concrete batches were mixed in a 50 dm^3 pan mixer for 3 min. For compression testing, $150 \times 150 \times 150$-$mm^3$ specimens were used. The specimens were demoulded on the next day after production and the curing regimes, similar those used previously [1] and given in Table 4, were applied. Three specimens were tested for each curing condition for each concrete type.

3. Results and discussion

The concrete mixtures were designed to have similar strengths at 28-day age under water-curing condition. Achieving C 25 grade concrete was maintained by only a 260 kg/m^3 cement dosage for OPC 42.5, but for TC 32.5 the dosage was increased to a higher value of 450 kg/m^3 compared with the former dosage, indicating the difference in the effectiveness of the cements at the age of 28 days. The effectiveness of the blended cement, BC 32.5, remained between those of OPC and TC, as expected, because the former cement has a pozzolan content less than the latter.

The development of compressive strength is illustrated in Figs. 1–3 for OPC, BC, and TC concretes, respectively. Each curve in the figures represents a different curing condition given in Table 4. In Figs. 1–3, it is common that the air-cured specimens gained the lowest strengths for the three cement types for all ages tested, as expected. In general, the curves of concretes with increasing initial water-curing period take place in order over the air-cured ones, with two exceptions. For BC concrete 14-day, and for OPC concrete 28-day initially water-cured specimens exposed higher strengths at the ages of 28 days and 90 days, respectively, than the corresponding continuously water-cured specimens. The higher strength of partly dried specimens with respect to continuously wet ones was attributed to the increase in the secondary forces between the surfaces of the cement gel [9,10] and also the reduction in the disjoining pressure due to the drying.

The average distance between the strength curves of continuously water-cured and air-cured specimens is smaller for the OPC concrete than those of the BC and TC concretes. This shows that pozzolanic cement concretes are more sensitive to the inadequate curing than OPC concretes, as indicated previously [5]. However, the strength difference obtained in this study for the OPC concrete between the water-cured and air-cured specimens is smaller than those reported earlier [1] for the same type of cement. In the earlier study, about a 58% drop in strength was obtained between the two extreme curing conditions at 6-month age, whereas it

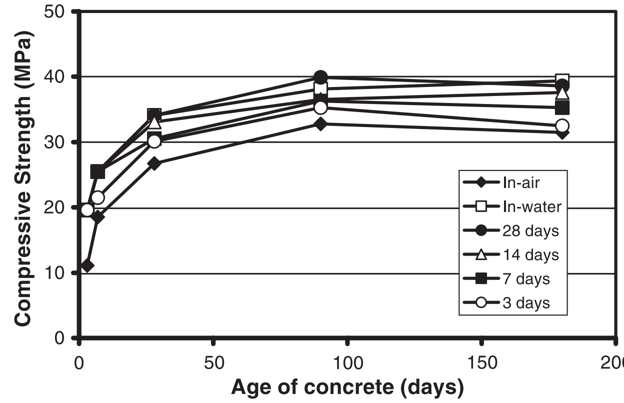

Fig. 1. Strength development for the OPC concrete.

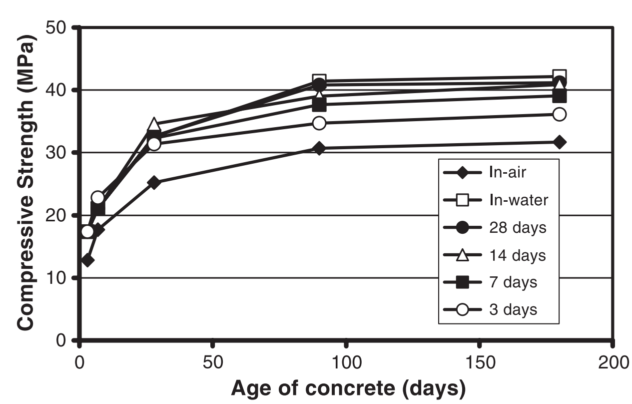

Fig. 2. Strength development for the BC concrete.

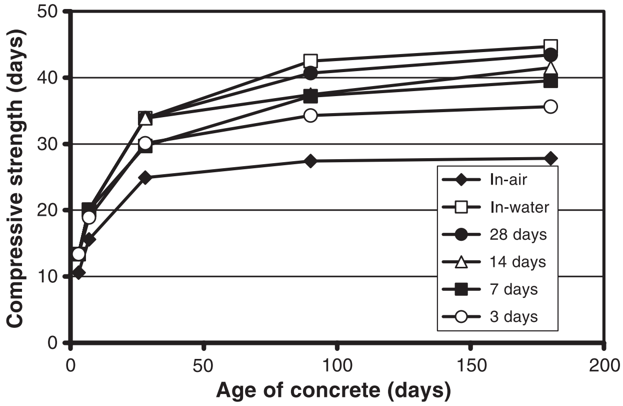

Fig. 3. Strength development for the TC concrete.

was found only 20% in this study. The difference between the strength losses of the two studies can be due partly to the coarser character of the cement used in the former study, and to the high level of RH in air-curing condition of this study (average 70%) compared with that of the previous study (50%). Increasing the fineness of cement causes gaining of high early strength while the concrete is still in partly wet condition. The ratio of 7-day to 28-day strengths is 0.75 in this study, whereas it was only 0.55 in the former one under the moist-curing condition. Because of this, for the concrete with finer cement, a smaller share remains to develop in the later ages compared with the one with coarser cement.

The strength of OPC concretes under interrupted curing dropped at the age of 180 days with respect to 90 days with one exception—14-day initially water-cured specimens showed slight increase in this period. This loss of strength experienced at later ages was explained [5,6] as the result of drying shrinkage cracking that occurred in the specimens. This behavior was not experienced for the pozzolanic cement concretes. It seems that pozzolanic activity suppressed the adverse effect of shrinkage cracking on the strength of concrete at later ages for the latter concretes.

3.1. Strength development analysis

For the analysis of strength development the following equation was used [11,12]:

$$f_c = a \log t + b \tag{1}$$

where f_c is the compressive strength of concrete at time t (in days), a and b are constants, and the former shows the strength-gaining rate. The plots of compressive strengths with the logarithm of time for the two extreme curing conditions are shown in Fig. 4. The curves for the other curing conditions remain in the area between these curves. The constants a and b obtained by using the least squares method are given in Table 5. For regression analysis, two ranges of time were used, 3–90 and 3–180 days. The correlation coefficients obtained are quite high, but slightly lower for the latter interval, i.e., 3–180 days for BC and TC concretes. However, for the OPC concrete the coefficients drop more than the former concretes, because strength losses are obtained after 90 days in this concrete (except continuously water-cured and 14-day water-cured specimens).

The variation of constant a, which represents the strength-gaining rate of concrete, is shown in Fig. 5 for different initial water-curing conditions. It seems that the constant a is insensitive to the curing regimes for the OPC concrete; however, it increases with the increasing water-curing time for BC and TC concretes, confirming that the cements with pozzolans are more affected by the curing conditions than OPCs, as stated before [5].

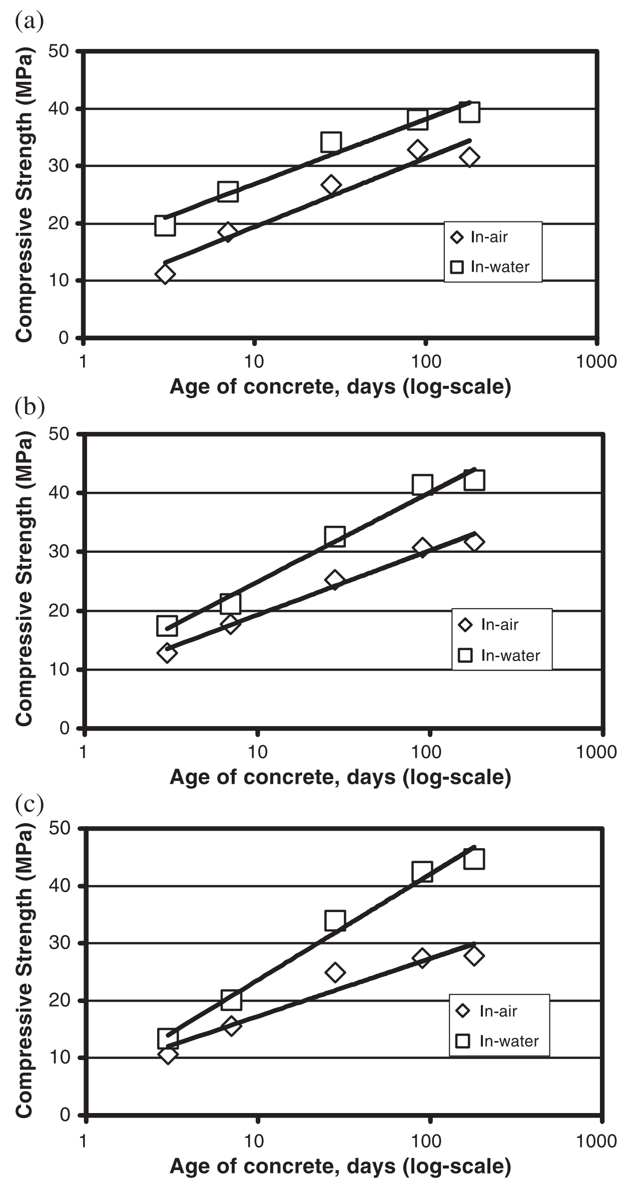

Fig. 4. Comparison of strength development: (a) OPC, (b) BC, (c) TC concretes.

Table 5
Regression analysis results

Cement type	OPC						BC						TC					
Regression interval	3–90 days			3–180 days			3–90 days			3–180 days			3–90 days			3–180 days		
Regression constants	a	b	r	a	b	r	a	b	r	a	b	r	a	b	r	a	b	r
Curing condition																		
Continuous air	14.45	5.21	0.995	11.99	7.39	0.968	12.14	7.27	0.999	10.99	8.28	0.992	11.84	5.64	0.981	10.06	7.21	0.965
3-day water	11.20	13.40	0.991	8.79	15.53	0.945	11.98	12.43	0.988	10.67	13.59	0.981	14.69	6.82	0.989	12.99	8.33	0.981
7-day water	10.83	15.18	0.993	9.15	16.67	0.972	14.43	10.09	0.993	13.05	11.31	0.988	16.05	6.15	0.999	14.94	7.13	0.996
14-day water	11.50	15.10	0.987	10.16	16.28	0.979	15.69	9.49	0.984	14.14	10.87	0.981	17.05	6.07	0.981	15.87	7.11	0.983
28-day water	13.76	13.52	0.998	11.44	15.58	0.971	16.37	8.65	0.996	14.66	10.15	0.988	19.04	4.54	0.995	17.45	5.95	0.991
Continuous water	12.67	14.36	0.991	11.29	15.58	0.983	16.73	8.37	0.996	15.21	9.71	0.990	20.14	3.70	0.998	18.41	5.22	0.993

Fig. 5 also exhibits that under varying water-curing periods, the strength-gaining rates are the highest for TC concretes, and BC concretes follow them while they are the lowest for OPC ones, indicating the effect of pozzolanic activity on strength gaining. However, under the air-curing condition, TC and BC concretes show lower rates than OPC concrete. This reflects that pozzolanic cement concretes are more adversely affected by the poor curing conditions than OPC concrete, and the latter is more tolerable to these conditions. The early-age strengths are lower for the pozzolanic cement concretes; nevertheless their strength-gaining rates are higher, and hence, under the moist-curing conditions, the gap between the strengths of the OPC concrete and BC and TC concretes are close at moderate ages. The time in which BC and TC concretes reach the strength level of continuously water-cured specimens prepared by OPC are shown in Table 6. These times were calculated by finding the intersection points of the equations, drawn by using the data up to 180 days, and are given in Table 4. Table 6 indicates that for both BC and TC concretes, 3-day water curing or curing only in air is not enough to reach the strength of OPC concrete cured continuously in water. Table 6 also shows that the longer the initial water-curing period, the shorter the time to reach the strength level mentioned above. It can be concluded that at least 7-day initial water curing is necessary to expose sufficient pozzolanic activity for BC and TC.

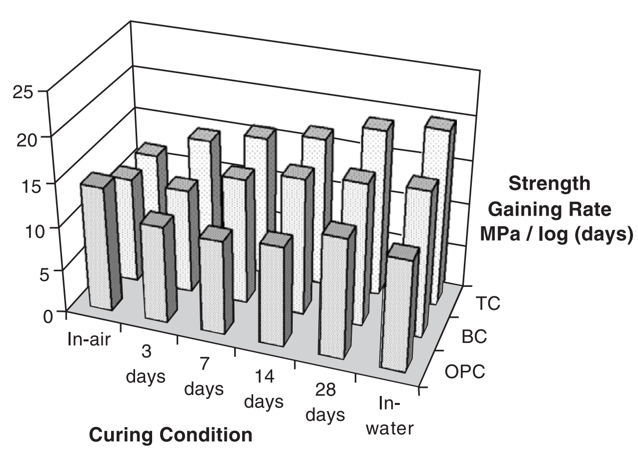

Fig. 5. Comparison of strength-gaining rates.

A comparison is also made between the pairs of the concretes with different cement types at each curing condition. The periods of time to reach the equal strength levels were calculated by using the regression constants of 3- to 90-day data for the comparison of BC–OPC and TC–OPC concretes, and 3- to 180-day data for TC–KC, respectively, and are given in Table 7. This table shows that although BC and TC concretes have lower early strengths than the OPC concrete, they can reach the strength level of the latter at most at 74 and 76 days, respectively, for all curing conditions, except the air curing. For the air-curing condition, the OPC concrete has higher strength-gaining rate than the pozzolanic cement concretes; however, the latter concretes can attain the strength of the former concrete due to the strength loss obtained in the former after 90 days. BC and TC concretes reached the strength level of OPC concrete in 142 days (assuming a linear reduction in strength of OPC concrete between 90 and 180 days) and 259 days (assuming the strength of OPC concrete remains constant after 180 days), respectively.

On the other hand, the TC concrete can reach the strength of the BC concrete in about 1 month for the 28-day or longer water-cured specimens. However, under the shorter curing periods it takes longer times, and the shorter the moist curing time, the longer the period to reach the

Table 6
Time to reach the strength of the OPC concrete cured in continuous moist condition

Curing condition	Time to reach the strength of OPC concrete (days)	
	BC concrete	TC concrete
Continuous in air	Impossible	Impossible
3-day water + air	Impossible	18,612
7-day water + air	269	207
14-day water + air	45	59
28-day water + air	41	37
Continuous in water	31	28

Table 7
Comparison of concretes with respect to the time to reach the equal-strength levels (under the same curing conditions)

Curing condition	Time to reach the equal strengths (days)		
	BC–PC[a]	TC–PC	TC–BC
Continuous in air	142	259	Impossible
3-day water + air	18	76	185
7-day water + air	26	54	163
14-day water + air	22	42	148
28-day water + air	74	50	32
Continuous in water	30	27	25

[a] The first concrete in the comparison has a lower early strength than the second one.

corresponding strength level. Besides, for the air-cured specimens, the TC concrete can never reach the strength level of BC.

4. Conclusions

The following conclusions can be drawn from this study.

1. The curing conditions affect the strengths of both the OPC concrete and pozzolanic cement concretes. However, poor curing affects the strength properties of pozzolanic cement concretes more adversely that those of the OPC.
2. For pozzolanic cement concretes, at least an initial 7-day water curing is necessary to expose the pozzolanic activity. Pozzolanic cement (BC and TC) concretes, water-cured for at least 14 days, can reach the strength level of the OPC concrete cured continuously in water in periods shorter than 2 months. However, the former concretes, when initially moist cured for 3 days or shorter periods, can never attain the strength of the latter concrete, which was stored continuously in water.
3. The strength-gaining rates of the OPC concrete under varying initial water-curing periods are lower than those of the BC and TC concretes. However, it is opposite for the air-curing condition, i.e., the OPC concrete has a higher rate than the pozzolanic cement concretes.
4. The OPC concretes, except 14-day or continuously water-cured ones, show strength losses between 90 and 180 days. On the other hand, the pozzolanic cement concretes continue increasing strength beyond 90 days, which can be attributed to the suppressing effect of the pozzolanic activity over the shrinkage cracking.

Acknowledgements

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References

[1] W.H. Price, Factors influencing concrete strength, J. Am. Concr. Inst. 22 (6) (1951) 417–432.
[2] P.C. Aitcin, B. Miao, W.D. Cook, D. Mitchell, Effect of size and curing on cylinder compressive strength of normal and high strength concretes, ACI Mater. J. 91 (4) (1994) 349–354.
[3] S.L. Wood, Evaluation of the long-term properties of concrete, ACI Mater. J. 88 (6) (1991) 630–643.
[4] European Standard, EN 197-1, Composition, specification and conformity criteria for common cements, European Committee for Standardization, 2000.
[5] A.A. Ramezanianpour, V.M. Malhotra, Effect of curing on the compressive strength, resistance to chloride-ion penetration and porosity of concretes incorporating slag, fly ash, or silica fume, Cem. Concr. Compos. 17 (2) (1995) 125–133.
[6] M.N. Haque, M.K. Gopalan, D.W.S. Ho, Estimation of in situ strength of concrete, Cem. Concr. Res. 21 (6) (1991) 1103–1110.
[7] M.D.A. Thomas, J.D. Matthews, C.A. Haynes, The effect of curing on the strength and permeability of PFA concrete, in: V.M. Malhotra (Ed.), Proceedings Third CANMET/ACI International Conference on the Use of Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, ACI SP-114, American Concrete Institute, Detroit, 1989, pp. 191–217.
[8] M.H. Ozkul, Efficiency of accelerated curing in concrete, Cem. Concr. Res. 31 (9) (2001) 1351–1357.
[9] S. Popovics, Effect of curing method and final moisture condition on compressive strength of concrete, ACI J. 83 (4) (1986) 650–657.
[10] K. Tan, O.E. Gjorv, Performance of concrete under different curing conditions, Cem. Concr. Res. 26 (3) (1996) 355–361.
[11] B. Postacioglu, Concrete, vol. 1, Teknik Kitaplar, Istanbul, 1987.
[12] A.M. Neville, Properties of Concrete, 3rd ed., Longman Scientific & Technical, Harlow, Essex, 1993.