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Efficiency of accelerated curing in concrete

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Abstract

The relation between 28-day strength of normal cured concrete and accelerated strength is investigated by using an ordinary portland cement and a trass cement under two different accelerated curing conditions, warm water and boiling water. Linear regression analysis was applied on the test results and evaluated by using the efficiency concept, i.e., the ratio of accelerated strength and 28-day normal cured strength. It is concluded that the ordinary portland cement gives higher efficiency than that of the trass cement. The difference due to the cement type is less in the boiling water method than that in the warm water method. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Efficiency; Acceleration; Thermal treatment; Pozzolan; Portland cement

1. Introduction

For quality control purposes, the standard compressive strength tests, which are based on keeping the concrete immersed in water or in a “fog room” at 20°C temperature for 28 days, have been carried out. The weak point of this method is the necessity of delaying the determination of test results for 28 days. This period is too long in today’s concreting technology, and, therefore, more rapid methods of determining the potential strength of concrete have been investigated. In the maturity concept of concrete, both the duration time and temperature of curing are important factors, and for this reason, increasing the temperature of concrete gives the opportunity of determining the strength at early ages, which is the basic approach of accelerated test methods.

There are three standardised accelerated curing methods, such as “warm water”, “boiling water” and “autogenous curing” (ASTM C 684 and Turkish Standard TS 3323). The methods, given in British Standard BS 1881: Part 112, suggest curing temperatures of 35°C, 55°C and 82°C, respectively. Some modified curing methods [1,2] and K-5 method [3] (ASTM C 684, Procedure D) have also been developed.

In predicting the 28-day strength by using the accelerated test strength results, a regression analysis is applied and the effects of various factors, such as cement type [2,4–6], pozzolan addition [2,7,8], maximum size of aggregate [9], chemical admixture addition [2] and water/cement ratio [10], on regression relation were investigated. In the presented study, two standardised accelerated curing methods, warm water and boiling water, were used in predicting the 28-day strength of concretes. The most widely used pozzolan in Turkey is the natural pozzolan, and it is added in with the cement clinker during the grinding stage. According to the Turkish Standard TS 3120, up to 40% natural pozzolan can be added to the clinker in the production of Trass Cement, TC 32.5. For this reason, the effect of ordinary portland cement and trass cement on early strength prediction was investigated in this study by using the efficiency factor, i.e., the ratio of the accelerated early strength and 28-day standard cured strength.

2. Experimental

2.1. Materials

Two types of cements, Ordinary Portland Cement (OPC 42.5) and Trass Cement (TC 32.5), which were supplied from the same factory, were used in the experiments. The chemical compositions and physical properties of cements are given in Table 1.

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Table 1
Physical properties and chemical analysis of cements

Cement type	OPC 42.5	TC 32.5
Physical properties		
Density (g/cm^3)	3.17	2.86
Specific surface		
Blaine (m^2/kg)	322	385
Time of setting		
Initial (h:min)	3:15	2:45
Final (h:min)	4:00	3:45
Mechanical properties		
Compressive strength		
2 Days (MPa)	34.8	17.1
7 Days (MPa)	48.3	28.4
28 Days (MPa)	60.6	41.9
Chemical composition		
Oxide (%)		
CaO	63.8	46.7
SiO_2	22.2	17.3
Al_2O_3	3.6	7.0
Fe_2O_3	4.4	4.0
MgO	2.1	1.5
SO_3	2.2	2.2
CaO (free)	0.8	0.6
Insoluble residue (%)	0.5	19.9
Loss on ignition (%)	1.1	3.1

A water reducer admixture, based on lignosulphonate and complying ASTM C 496, Type A, was used, 0.5% by weight of cement.

Crushed limestone in two sizes (4–10 and 10–25 mm) as coarse aggregate, and sea sand (0–2 mm) and crushed limestone sand (0–4 mm) as fine aggregate, were used. Maximum aggregate size was 25 mm.

2.2. Mixing proportions

The cement contents were 300 and 350 kg/m^3 for the warm water method, and 300, 350 and 400 kg/m^3 for the boiling water method, respectively. Water/cement ratio varied between 0.40 and 0.65 for the cement dosages of 300 and 350 kg/m^3, and between 0.30 and 0.55 for that of 400 kg/m^3 at 0.05 increments, respectively.

In all mixtures, aggregate proportions were kept constant at sand/crushed stone sand/crushed stone 1/crushed stone 2 as 1:0.83:0.83:1.50. The consistency of mixtures changed from zero slump to collapse type, i.e., high slump according to the water/cement ratio.

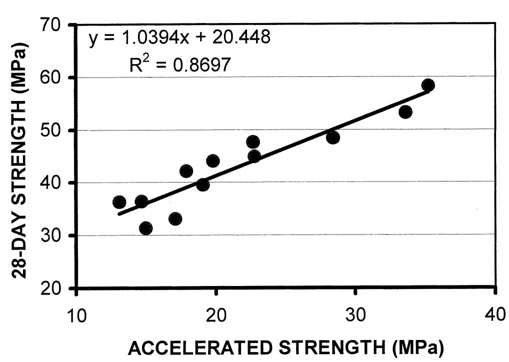
2.3. Test procedure

Two methods were applied for accelerated curing, the warm water method (ASTM C 684, Method A and also TS 3323) and the boiling water method (ASTM C 684, Method B and also TS 3323). The maximum curing temperatures were 35°C and about 100°C for the former and latter methods, respectively. One hundred and fifty cubic millimeter specimens were used for compression testing. The specimens were kept at 23°C ± 1°C immersed in water for standard curing. Three specimens were used for each curing condition.

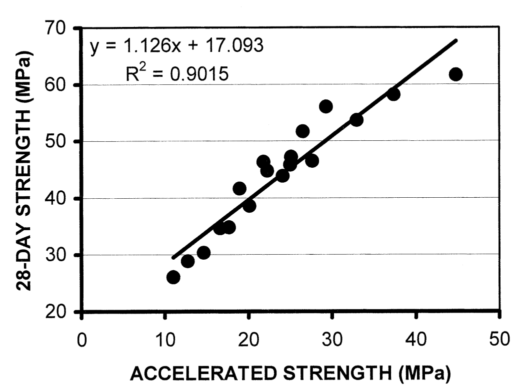
3. Results and analysis

3.1. Results

Relationships between 28-day compressive strength of standard cured specimens and accelerated cured strength for the warm water and boiling water methods are given in Figs. 1 and 2. Fig. 1 shows the concretes prepared by ordinary portland cement (OPC 42.5) and Fig. 2 shows those prepared by trass cement (TC 32.5). The linear regression curves obtained by using the least square method are superimposed on each data set. The regression analysis results are shown in Table 2 for each curing method and cement type. The slopes of the lines are steeper for concretes of TC 32.5 than those of OPC 42.5 for both curing methods, as can be seen in Fig. 3 and Table 2. However, the intercept constants of the former concretes are smaller than those of the latter. These results show that the cement type affects the

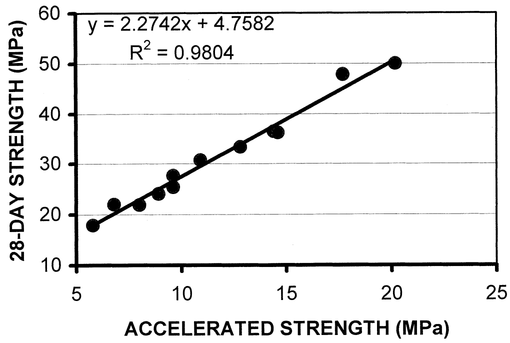


(a)



(b)

Fig. 1. Relationship between accelerated strength and 28-day strength of normal cured concrete (cement type: OPC 42.5). (a) Warm water method; (b) boiling water method.



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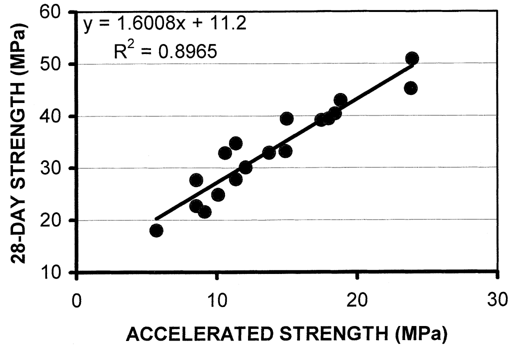


(b)

Fig. 2. Relationship between accelerated strength and 28-day strength of normal cured concrete (cement type: TC 32.5). (a) Warm water method; (b) boiling water method.

strength prediction equation. Similar to that reported [2,5,7] earlier, cement type and the addition of pozzolan to the concretes change the constants of regression relation.

3.2. Analysis

In evaluating test results, a linear regression analysis is usually applied between the 28-day strength of normal cured concrete (f_{c28}) and the accelerated strength (f_{ca}), and the constants of a and b of the following equation are found, as shown in Fig. 4:

$$f_{c28} = af_{ca} + b \tag{1}$$

Eq. (1) can be written in the following form:

$$\frac{f_{ca}}{f_{c28}} = \frac{1}{a} - \frac{b}{a}\frac{1}{f_{c28}} \tag{2}$$

The left side of Eq. (2) is defined as the efficiency of accelerated curing, i.e., the ratio of the accelerated strength and 28-day normal cured strength. The plotting of efficiency (f_{ca}/f_{c28}) with $1/f_{c28}$ is shown in Fig. 5. It gives a line with a slope of $(-b/a)$ and an intercept of $1/a$.

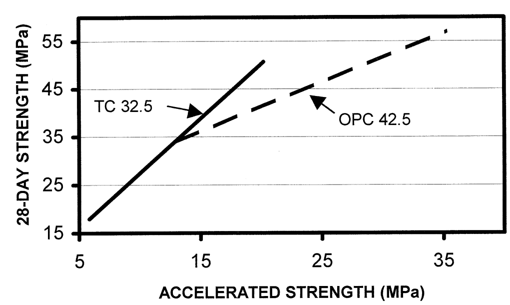
Fig. 4 shows that when f_{ca} increases, f_{c28} also increases, and for this reason, a is always positive. Having negative values of b means that f_{c28} is negative for accelerated

Table 2
Results of regression analysis

Curing method	Cement type	Regression constants [MPa]			Intersection point [MPa]
		a	b	b/a	
Warm water	OPC 42.5	1.039	20.45	19.08	
	TC 32.5	2.274	4.76	2.09	28.25
Boiling water	OPC 42.5	1.126	17.09	15.18	
	TC 32.5	1.601	11.20	6.99	31.05

strength close to zero, which is impossible, hence, b should be positive also. When $b=0$, efficiency, i.e., f_{ca}/f_{c28}, becomes constant for all strengths. Generally, b is positive and, hence, b/a becomes positive. From Fig. 5a, for positive b/a, the efficiency increases when $1/f_{c28}$ decreases, which corresponds to increasing of f_{c28}. This shows that, for increasing strengths, which is possible by decreasing w/c ratios, efficiency also increases. This is in line with the results of Al-Rawi and Al-Murshidi [10] who concluded that for all sizes of aggregates, the ratio of accelerated strength to 28-day strength decreases with the increasing w/c ratio.

Eq. (1) is compared with a similar relation of $f_{c28} = a'f_{ca} + b'$ in Fig. 4, and in the form of Eq. (2) in Fig. 5. Since $b/a > b'/a'$ in Fig. 5a, the efficiency is higher for Eq. (1) than that of the equation with superscript constants for



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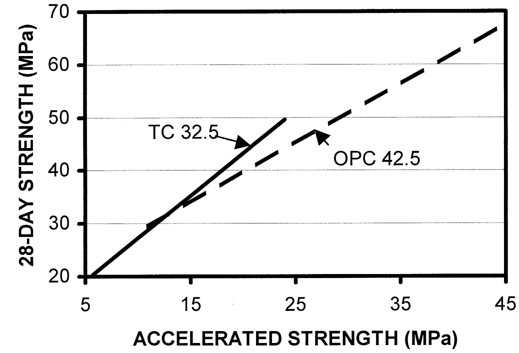

(b)

Fig. 3. Linear regression curves for both cement type concretes. (a) For warm water method; (b) for boiling water method (borrowed from Figs. 1 and 2).

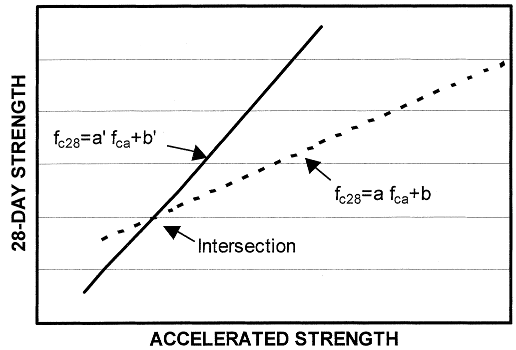

Fig. 4. Comparison of regression lines.

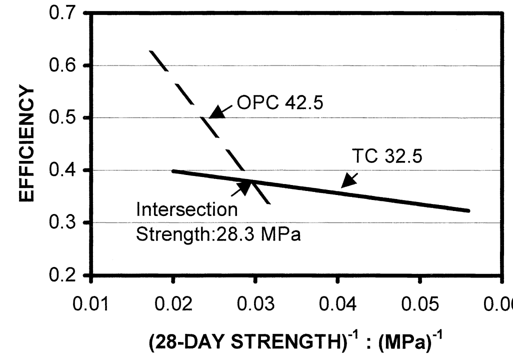

Fig. 6. Comparison of efficiencies for warm water method.

f_{c28} greater than the corresponding intersection point. However, when the intersection point is negative, as shown in Fig. 5b, the lower the value of (b/a), the higher the efficiency for all strength levels, opposite to the previous situation.

Changes in efficiency (f_{c28}/f_{ca}) with $1/f_{c28}$ for ordinary portland cement and trass cement are shown in Figs. 6 and 7 for the warm water and boiling water methods, respectively. These figures show that efficiency is higher for concretes of OPC 42.5 than those of TC 32.5 for the strengths greater than the intersection points, i.e., 28.3 MPa for the warm water and 31.1 MPa for the boiling water methods, which correspond approximately to the minimum strength level of OPC 42.5 concrete data.

Figs. 6 and 7 also exhibit that the rate of change in the efficiency with strength is higher for OPC 42.5 concretes than those of TC 32.5 for both curing methods, as the slopes of lines are compared. On the other hand, the comparison of the accelerating methods shows that the ratios of (b/a) for OPC and TC concretes are $19.08/2.09 = 9.42$ for the warm water and $15.18/6.99 = 2.17$ for the boiling water method. The low ratio for the boiling water method compared with that of the warm water can be due to the higher curing temperature of the former method, i.e., 100°C, while it is only 35°C for the latter. It seems that high curing temperature is more effective to activate the pozzolanic reaction and, therefore, the accelerated strengths approach to each other for both cement types in the boiling water method. It was explained that the water in the warm water method acts as an insulator to conserve the heat of hydration of cement and does not contribute to the accelerated maturity [11]. For this reason, the warm water method for low-heat cements, such as pozzolan cement, is not as effective as for rapid hardening cements, such as Type III cement. On the other hand, in the boiling water method, the level of temperature provides thermal acceleration for both cement types [12]. Lea [13] developed a method to assess the pozzolanic activity in which the concretes prepared by the mixture of

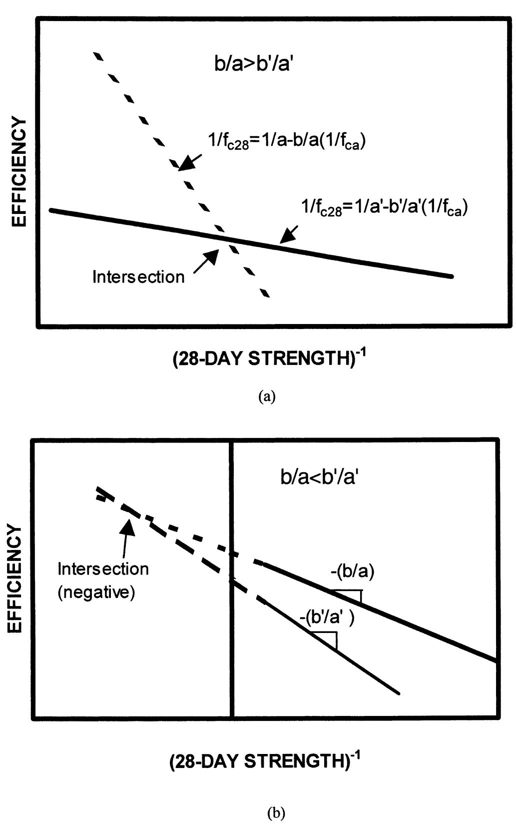

Fig. 5. Comparison of efficiencies. (a) Positive intersection; (b) negative intersection.

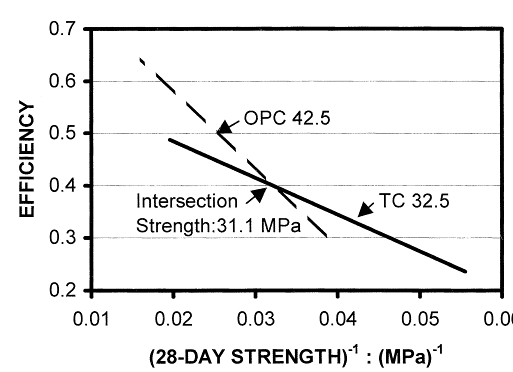

Fig. 7. Comparison of efficiencies for boiling water method.

a pozzolan and a portland cement. The concretes were cured at the temperatures of 18°C and 50°C for comparison. The cement–pozzolan mixture exhibited considerably greater strength increase than plain cement mixture between these temperatures, indicating that higher curing temperature is more effective for the pozzolan containing mixtures. Similarly, it was reported [14] that the accelerated curing temperature has a more favorable effect in the case of low initial reactivity cements.

Klieger [15] has also extensively investigated the effect of curing temperature on concrete strength. The efficiency factors calculated from the data of his study are 0.274 and 0.375 at the curing temperatures of 32°C and 49°C, respectively, for the concrete made with Type I cement, and 0.505 and 0.601 at the same curing temperatures but for the concrete with Type III cement. The ratios of the efficiencies of the latter concrete and those of the former are found as 1.843 and 1.603 at the curing temperatures of 32°C and 49°C, respectively. This shows that the difference between the efficiencies of concretes prepared by Type I and Type III cements diminishes when the curing temperature increases.

The results of the regression analysis applied on test data obtained by eight different laboratories under the ASTM's cooperative test program [4] are given in Table 3. Although there were some discrepancies between the test data and the

Table 3
Regression analysis of test results found in the literature

Curing method	Lab	Cement type	Pozzolan addition	Regression constants [MPa]			Intersection point [MPa]	Reference
				a	b	b/a		
Warm water	1	Type I	–	1.120	13.55	12.10		[4]
	1	Type III	–	0.960	15.65	16.30	28.3	
	4	Type I	–	1.515	19.10	12.61		
	4	Type III	–	1.095	18.96	17.32	18.6	
	5	Type I	–	1.375	15.27	11.11		
	5	Type III	–	0.905	17.86	19.73	22.8	
	6	Type I	–	1.525	14.17	9.29		
	6	Type III	–	1.290	14.31	11.09	15.1	
	8	Type I	–	1.985	9.10	4.58		
	8	Type III	–	1.285	15.44	12.02	27.1	
	9	Type I	–	1.320	16.31	12.36		
	9	Type III	–	0.540	23.48	43.48	28.4	
	10	Type I	–	1.440	19.13	13.28		
	10	Type III	–	0.770	24.20	31.43	30.0	
	11	Type I	–	1.475	14.34	9.72		
	11	Type III	–	1.090	13.76	12.62	12.1	
Boiling water	1	Type I	–	1.060	12.82	12.09		
	1	Type III	–	0.910	16.55	18.19	39.2	
	4	Type I	–	1.290	17.79	13.79		
	4	Type III	–	1.145	13.96	12.19	< 0	
	5	Type I	–	1.225	9.86	8.05		
	5	Type III	–	0.840	14.96	17.81	26.1	
	6	Type I	–	1.280	11.58	9.05		
	6	Type III	–	1.050	13.13	12.50	20.2	
	8	Type I	–	1.280	15.62	12.20		
	8	Type III	–	1.220	14.86	12.18	< 0	
	9	Type I	–	1.015	16.89	16.64		
	9	Type III	–	0.780	19.55	25.06	28.4	
	10	Type I	–	1.195	19.48	16.30		
	10	Type III	–	1.000	17.79	17.79	9.1	
	11	Type I	–	1.515	9.51	6.28		
	11	Type III	–	1.095	13.41	12.25	23.6	
Warm water	–	Type II	–	1.116	17.86	16.00		[7]
	–	Type II	Pozzolan	1.810	11.70	6.46	27.7	
76°C	–	PC 325	–	1.950	4.00	2.05		[2]
	–	PC 425	–	1.190	11.60	9.75	23.5 (with PC 325)	
	–	Poz. C 325	–	2.210	1.56	0.71	22.3 (with PC 325)	
	–	PC 325 (70%)	Fly ash (30%)	2.010	2.36	1.17	10.4 (with PC 325)	
	–	PC 425 (f_c < 35)	–	1.520	7.32	4.82		
	–	PC 425 (f_c > 35)	–	0.915	18.88	20.63	36.4 (with f_c < 35)	
K5	–	Type I	–	1.051	14.30	13.61		[3]
	–	Type I	Fly ash	1.454	9.66	6.65	26.4 (with Type I)	
	–	Type III	–	0.967	13.30	13.75	1.8 (with Type I)	
	–	Type III	Fly ash	1.446	8.17	5.65	23.7 (with Type III)	

regression evaluation results, the latter was accepted as correct. The result of Lab 12 was discarded because a different cement type (Type II) was used instead of Type I cement. The regression constants *a* and *b*, as well as the intersection points, show great variance between the laboratories although the same cement types and accelerating methods were used. This was attributed [4] to each laboratory using locally available aggregate and cement. It was reported [12] that the correlation of accelerated strength and 28-day standard strength can be different for different brands of the same type of portland cement possibly due to the differences in the alkali contents of various brands. The high variance in the cement chemistry of the same cement type was also reported [16]. However, Table 3 shows that, in spite of the considerable variance between the laboratories, the values of the slope (b/a) of Eq. (2) for concretes of Type III cement are greater than that of Type I cement for all the laboratories in the warm water method, hence, the efficiencies of the former concretes are higher than those of the latter for the 28-day strengths greater than the corresponding intersection points. Similarly, in the boiling water method at six laboratories, the concretes of Type III cement have (b/a) value greater than that of Type I, which shows that the former concretes have higher efficiencies for strengths over the intersection points. The remaining two laboratories exhibited (b/a) for Type I cement concrete greater than that of Type III cement. However, the intersection points were negative for these concretes. As shown in Fig. 4b, the latter concretes have higher efficiencies than the former for all strength levels, as in the previous six laboratories. On the other hand, the difference between the (b/a) slopes of the Type III and Type I cement concretes was reduced for the boiling water method with respect to the warm water method, confirming that under high temperature, low early strength cement shows higher early activation.

Table 3 also contains the results of Lamond [7], in which the warm water method was applied. The data were reevaluated and the results of Type II cement concretes were separated and compared with those of the pozzolan added concretes made with the same type cement. Pozzolan addition reduced the (b/a) slope as expected causing lower efficiencies.

Sievero [2] used an accelerating curing method with a maximum temperature of 76°C. Three types of cement, Portland 325, Portland 425 and Pozzolan 325 with 30% fly ash addition as substitution of Portland 325, were tested. The (b/a) values given in Table 3 show that the highest value belongs to the Portland 425 concrete, indicating that the efficiency is highest for this concrete and the concretes of Portland 325 and Pozzolan 325 follow it in order. However, the 30% fly-ash-substituted Portland 325 concrete has a slope between those of Portland 325 and Pozzolana 325 concretes. The test data were also grouped according to the w/c ratios (and, hence, according to the 28-day strengths), and it was found that for concretes with $f_{c28} > 35$ MPa, the (b/a) value was greater than that of $f_{c28} < 35$ MPa, as shown in Table 3. It seems that high-strength concretes behave as high early cement concretes as it was mentioned [12] that for concretes with low w/c ratio, early strength development increases.

Nasser and Beaton [3] have used the K-5 method, in which the curing temperature was raised to 149°C under a pressure of 10.3 MPa. The test data were reevaluated by grouping the concretes with respect to the cement type and pozzolan addition. The concretes prepared by lightweight aggregate were excluded from the analysis, and the constants of linear regression are given in Table 3. Test results show that the efficiencies of concretes prepared by Type III cement are higher than that of Type I cement for all strength levels. In addition, the fly ash addition reduced the efficiencies of both cement type concretes for strengths greater than the intersection points.

4. Conclusions

Test results show that both cement type and curing method affect the relation between the 28-day strength and accelerated strength. The accelerated strength development efficiency is higher for concretes of ordinary portland cement than that of trass cement in general. However, the difference between the efficiencies of concretes prepared by these two cements becomes smaller for increasing curing temperature, comparing the warm water and boiling water methods. It is concluded that the efficiencies of the concretes prepared by low early strength cements increase when the curing temperature is increased. Test results found in the international literature support the findings of this study.

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