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Accelerated Strength and Testing of Concrete Using Blended Cement

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Accelerated strength testing using the boiling water procedure of ASTM C 684 was performed to evaluate this test method for use in the routine quality control of concrete made of local materials with particular emphasis on the use of blended cements, and in the prediction of potential quality and strength of concrete at later ages. Large number of groups of standard concrete specimens are sampled; in each group one cube represented the accelerated strength and is tested at 28.5 h while the other one is normally cured and tested at 28 days. Test results were recorded and statistically evaluated. A computer program was developed to carry out the numerical statistical computations and regression analysis. Correlation between the 28-day compressive strength and the corresponding accelerated strength was established considering the utilization of local materials and practices. The outcome of this study in the form of prediction models confirm that accelerated strength testing could be accepted in lieu of the standard 28-day testing. The conclusions derived may provide experimental evidence in favor of implementing the standard boiling water method for use in relation to quality control and prediction of concrete strength at later ages. ADVANCED CEMENT BASED MATERIALS 1997, 5, 49–56. *© 1997 Elsevier Science Ltd.*

KEY WORDS: Accelerated strength; accelerated testing; concrete; blended cement

The rapid growth and the quickening pace of construction have been recognized in the last decade. The conventional 28-day compression strength test exhibited deficiencies for acceptance of concrete since the quantities of concrete became so large and the speed of construction became so fast that a judgment on the adequacy of controlling the quality of concrete would be needed much sooner than even a 7-day test could provide. Hence, a new attitude developed the trend with the merits of knowing the potential strength of concrete at the earliest possible time after the concrete has been placed, while there is still room for adjustments or remedial measures.

A perusal of research publications indicates a serious search for accelerated tests throughout the past 60 years [1]. In 1971, ASTM published Designation C684 standardizing three procedures of accelerated curing [2].

Upon realization of peace in the Middle East, a large number of firms, as well as business people, started to invest their capitals in the region. As a result, the concrete mixing plants appeared on the scene throughout Jordan. The efficient manufacturing of concrete, which resulted in using ready-mixed concrete, became an important factor in the construction of large projects. The primary objective remains to finish such huge projects in the shortest possible time. However, the unfavorable limitations of the 28-day compression strength test could delay the progress of accelerated construction. All of this gave birth to the idea of trying to adopt a reliable method for accelerated strength testing of concrete in a major project which is King Abdullah Hospital—a $70 million project in which the reinforced concrete values to about $20 million. Due to the fact that blended cement is used in more than one third of the total concrete utilized in this Project (about 100,000 *meter*^{3}). As an extension to a previous study [4] which focused on concrete mixes with pozzolanic-Portland cement only, the objective of this study is to integrate and complement the past research work and to employ the results to this project and other similar projects. Based on a critical review of the ASTM procedures, the Boiling Water Method was adopted and used throughout the testing program [2]. The procedure of this method is implemented by the following steps:

- Cast specimens in conventional molds and store them covered at 21 ± 6 C°.
- At age 23 h ± 15 minutes, immerse them in boiling water.
- Remove them from bath after 3.5 h ± 15 minutes, demold and leave them to cool.
- Test specimens at age 28.5 h ± 15 minutes.

It should be mentioned that this method was found better than either the warm water method or the auto-

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TABLE 1. Specifications of the White Cement

Specifications	White Cement Typical Average	White Cement Min/Max	Jordan Standards	BS 12/78
1. Physical specifications				
Fineness (Blaine)	3700	3600 min	⩾3000	⩾2250
Setting time (VICAT):				
Initial	3 h	1 h min	>1	>1
Final	4 h	10 h max	<10	<10
Soundness (Lechatelier)	1 mm	10 max	<10	<10
Compressive strength:				
3 days	24 N/mm^2	23 min	16.0	23
7 days	30 N/mm^2	25 min	24.0	—
28 days	60 N/mm^2	41 min	32.5	41
Whiteness (MgO)	82%	80% min	—	—
2. Chemical specifications				
Free lime	0.67%	1.5% max	—	
Ins. R.	0.51%	1.0% max	1.0	
MgO	0.11%	2.0% max	2.0	
SO_3	2.9%	4.0% max	4.0	
Loss O.I	3.5%	4.0% max	—	
Fe_2O_3	0.35%	0.5% max	—	

geneous method because it satisfies the following requirements:

- The equipment is inexpensive and easy to handle in the laboratory as well as at the job site; this rules out the autogenous method.
- Test results should be consistent when performed at different places and on different occasions. The different types of cement are more sensitive to the warm water method than to the other two methods.
- Prediction of 28-day strength from accelerated tests should not be influenced by the use of concrete admixtures which affect the setting time of concrete. The selected method starts only after nearly 24 h after casting, by which most of retardation effects have disappeared.

This work aims at producing a database on accelerated strength testing of concrete made of local aggregates and pozzolanic-Portland cement and/or blended cements manufactured in Jordan. This pilot study resulted in deriving correlation models for prediction of concrete strength at an early time and improvements in the quality control of the manufactured concrete.

TABLE 2. Specific gravity and absorption

Description	Crushed Limestone Course	Crushed Limestone Medium	Wadi Sand
Bulk specific gravity (*Dry*)	2.47	2.56	2.63
Bulk specific gravity (*Saturated surface dry*)	2.53	2.60	2.66
Apparent specific gravity	2.63	2.66	2.70
Absorption	2.60	1.47	1.01

Experimental

Materials

Pozzolanic-Portland Cement. Bulk cement conforming to Jordanian Specification No. 219-1981, manufactured and supplied by the Jordan Cement Factories at Fehais, has been used in the Project. The retained quantity of cement on sieve size 0.09 *millimeter* should not exceed 10% by weight. The primary setting time should not be less than 45 minutes and the final setting time should not exceed 10 h. The strength is measured by testing three cubes of cement mortar to achieve a nominal compressive value of 16 MPa after (72 ± 1) h or 24 MPa after (168 ± 2) h. The lime saturation factor (LSF) ranges from 0.66 to 1.02. The specific gravity is 3.08 and the bulk specific gravity ranges from 1.2 to 1.3 depending on the degree of compacting and humidity conditions. This cement contained 15% natural pozzolan which was added during the production process in which the manufactured cement was produced to achieve a Blaine Specific Surface of 3000 $centimeter^2/gram$.

White Cement. The white cement in 50 kg sacks conforming to Jordanian Specifications, manufactured and supplied by the Arab Company for White Cement Industry, has been used in the Project. The specifications of white cement are listed in Table 1.

TABLE 3. Designed concrete mixes

Class of Concrete	28-day Cube Crushing Strength		Nominal Cement Content	Pozzolanic-Portland Cement	White Cement	Water/Cement Ratio
	kg/cm^2	MPa	kg/m^3	kg/m^3	kg/m^3	
A	400	39.22	400	220.0	180.0	0.52
B	300	29.42	350	192.5	157.5	0.56
C	250	24.51	300	165.0	135.5	0.62
D	200	19.61	250	137.5	135.5	0.68

AGGREGATES. Aggregate constituents were the crushed limestone aggregate; coarse and medium, and a natural valley sand as fine aggregate. The specific gravity and absorption were determined according to ASTM C127 for coarse and medium aggregates and according to ASTM C128 for the sand. A summary of test results is shown in Table 2. Abrasion resistance using Los Angeles machine according to ASTM C131 was 32 for coarse and medium aggregates, respectively. The blend of all aggregate produced a gradation curve that conformed successfully to the Jordanian Specification No. 96 which is in compliance with ASTM C136.

ADMIXTURES. Only a workability agent was used to facilitate pumping of the produced wet concrete. The brand is Cormix SP4; a superplasticiser admixture, complying with ASTM C494 and BS 5075 Part I: 1982 and BS 5075 Part III: 1985. The dose was about 2.22 liters per meter^3 of concrete.

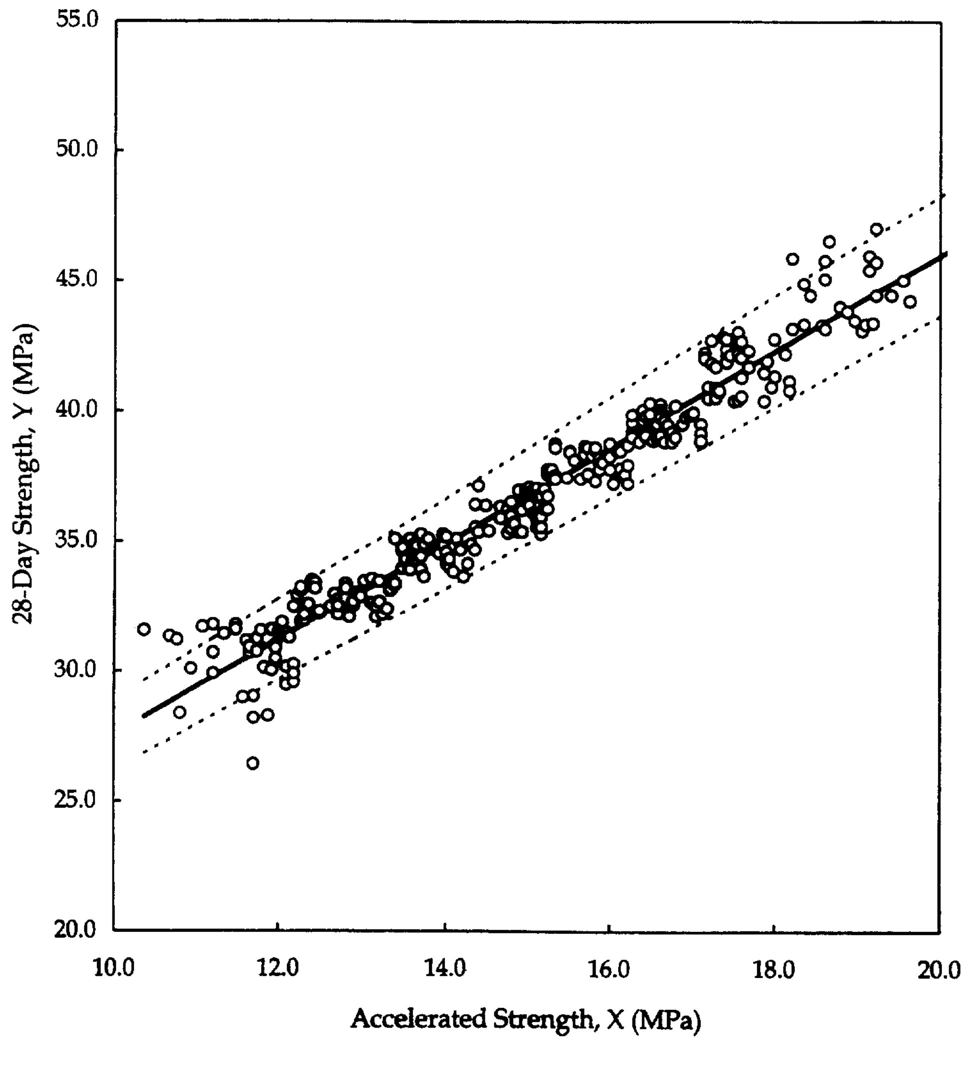

FIGURE 1. Linear function model: $Y = 9.16 + 1.84\ X$. Dashed lines show 95% confidence level.

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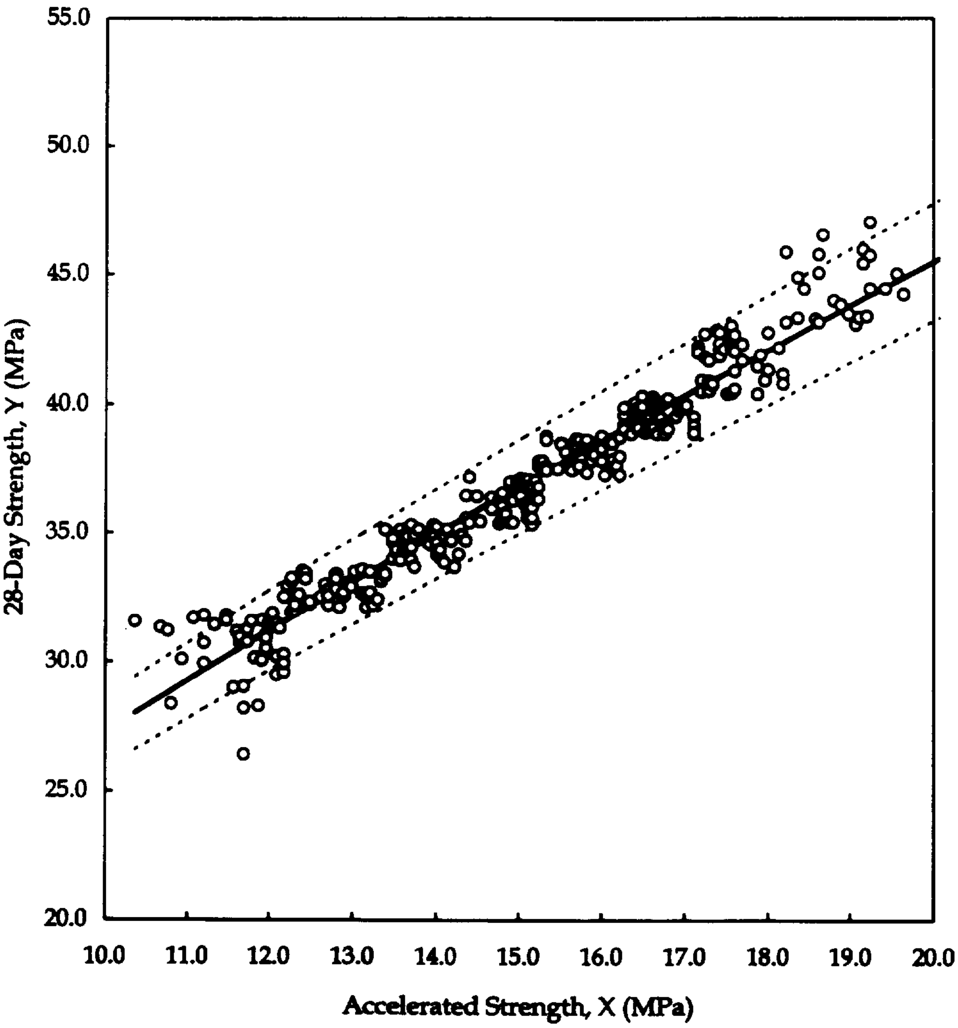

FIGURE 2. Power function model: $Y = 4.99\ X^{0.73763}$. Dashed lines show 95% confidence level.

Design of Concrete Mixes

The concrete mixes were designed to meet the outlined four Classes of concrete to be used in the project which are shown in Table 3. The nominal 28-day compressive strength was based on testing standard concrete cubes.

The plasticiser admixture was also added by a dose of 2.22 L/meter^3. Slump tests were frequently taken and its range was between 80 and 110 millimeter depending on the Class of concrete.

Sampling

The concrete needed for making specimens was obtained from the discharge flow of the concrete truck mixer to the pump. Samples of wet concrete were taken each day of concreting. Each sample consisted of two cube specimens; one of them was accelerated-cured and tested at 28.5 h, while the other cube was normally cured and tested at 28 days. ASTM Standards [5,6] were applied regarding sampling, curing, and testing.

Test Results

Each sample was represented by a group of two specimens. Groups were assigned serial numbers starting from 1 and ending in 305. The test results were recorded, documented, and further plotted as a scattergram as shown in Figure 1.

Analysis of Results

Statistical Evaluation

The following symbols were used:

n = Number of tests
μ = Mean
σ = Variance; σ = Standard deviation
r = Coefficient of correlation
ρ = Coefficient of variation = σ/μ
X = Denotes accelerated strength test

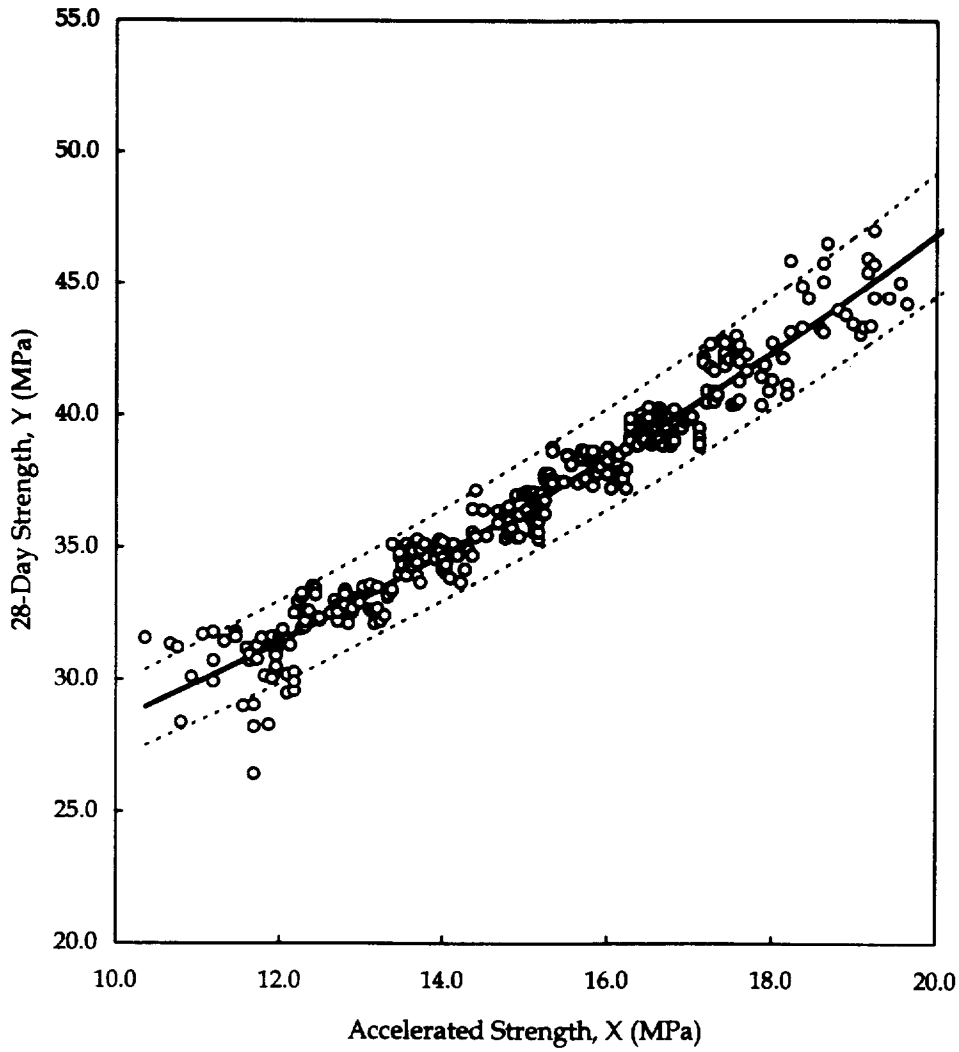

FIGURE 3. Exponential function model: $Y = 17.24\ \mathrm{Exp}(0.049967\ X)$. Dashed lines show 95% confidence level.

Y = Denotes 28-day strength test

(a) Accelerated strength results.

$n = 305$; $\mu = 15.08$ MPa; $\sigma = 2.24$ MPa; $\rho = 0.148$

(b) 28-day strength results

$n = 305$; $\mu = 36.86$ MPa; $\sigma = 4.23$ MPa; $\rho = 0.115$

The above-mentioned statistics were computed considering the population of data to follow a normal distribution. It should be noted that the coefficient of variation for the accelerated strength is relatively higher than that of the 28-day strength. This difference could be related to the fact that the accelerated strength is influenced by some retardation effects in the short period of time in contrast with the late 28-day strength where such effects are diminished. Moreover, this work was not controlled within the typical laboratory conditions.

Prediction Models

The coefficient of correlation, r, between the accelerated strength and the normal 28-day strength results was found to be equal to 0.9458. Based on this factor a linear regression seems very reliable [11]. However, excluding the *Ratio Model*, three regression models have been obtained based on the best curve fitting by utilizing a computer program developed for this purpose.

(1) Ratio Model

This model is based on the ratio values of 28-day strength to the corresponding accelerated strength and can be expressed by the following equation:

$$Y = (2.46 \pm 0.12)\ X \qquad (1)$$

The upper bound of the estimated value of anticipated 28-day compressive strength of concrete = 2.58 times that of the accelerated strength at age of 28.5 h; the lower bound is equal to 2.34 times that of the acceler-

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TABLE 4. Predicted 28-day strength of concrete for accelerated strength of 15.0 MPa

Prediction Model	Ref.	Minimum Strength MPa	Mean Strength MPa	Maximum Strength MPa
$Y = (2.46 \pm 0.12)\ X$		35.10	36.90	38.70
$Y = (2.42 \pm 0.22)\ X$	[3]	(33.00)	(36.30)	(39.60)
$Y = 9.16 + 1.84\ X$		35.84	36.76	37.68
$Y = 10.31 + 1.40\ X$	[3]	(30.53)	(31.31)	(32.09)
$Y = 4.99\ X^{0.73763}$		35.86	36.78	37.70
$Y = 6.34\ X^{0.58584}$	[3]	(30.21)	(30.98)	(31.75)
$Y = 17.24\ \mathrm{Exp}\ (0.049967\ X)$		35.57	36.48	37.39
$Y = 13.93\ \mathrm{Exp}\ (0.055096\ X)$	[3]	(31.04)	(31.83)	(32.63)

ated strength test result. The advantage of this model is in obtaining a quick unforgettable prediction of the anticipated 28-day strength of concrete without using any curves such as those produced by the other models.

(2) Linear Function Model

It is expressed by the following regression equation:

$$Y = \alpha + \beta X \tag{2}$$

where α and β are constants to be evaluated by regression analysis. Using the computer program, eq 2 can be written as:

$$Y = 9.16 + 1.84\ X \tag{3}$$

This equation is plotted on the scattergram of the data points as shown in Figure 1. The band width is also shown for a 95% confidence level.

(3) Power Function Model

The predicted nominal 28-days strength of concrete can be estimated from the accelerated strength test by:

$$Y = 4.99\ X^{0.73763} \tag{4}$$

This equation is plotted on the scattergram of the data points as shown in Figure 2. The band width is also shown for a 95% confidence level.

(4) Exponential Function Model

The anticipated 28-day strength value can be estimated by:

$$Y = 17.24\ \mathrm{Exponential}\ (0.049967\ X) \tag{5}$$

This equation is plotted on the scattergram of the data points as shown in Figure 3. The band width is also shown for a 95% confidence level.

Discussion of Results

Considering the test result of accelerated strength is equal to 15.0 MPa, then the predicted 28-day strength in terms of the mean as well as the minimum and the maximum values are shown in Table 4. It should be noted that the upper and lower bounds were based on the standard deviation for the ratio model and on 95% confidence for the other models. Values in parentheses are obtained using similar models where White cement was not used in the concrete mixes [3]. One can observe that prediction of 28-day strength is dependent of the type of cement used in the concrete mixes.

The 28-day strength of concrete can be predicted by using any of the abovementioned models. However, the linear function model is chosen to ease comparison with available models obtained by other researchers. The reliability of the test results is evaluated by comparing the function models with available results found in the literature. Of particular concern is the linear function model which is appropriate for this study.

TABLE 5. Comparison of selected regression linear models

Study	Number of Tests n	Standard Deviation σ	Coefficient of Correlation, r	Derived Equation
Lapinas [7]	312	1.82	0.93	$Y = 14.32 + 1.16\ X$
Ramakrishnan [8]				$Y = 8.08 + 1.55\ X$
Rodway [9]	219	3.66	0.80	$Y = 13.81 + 1.48\ X$
Naser [10]	63		0.964	$Y = 10.48 + 1.42\ X$
Resheidat [3]	380	3.14	0.958	$Y = 10.31 + 1.40\ X$
Authors	305	4.28	0.946	$Y = 9.16 + 1.84\ X$

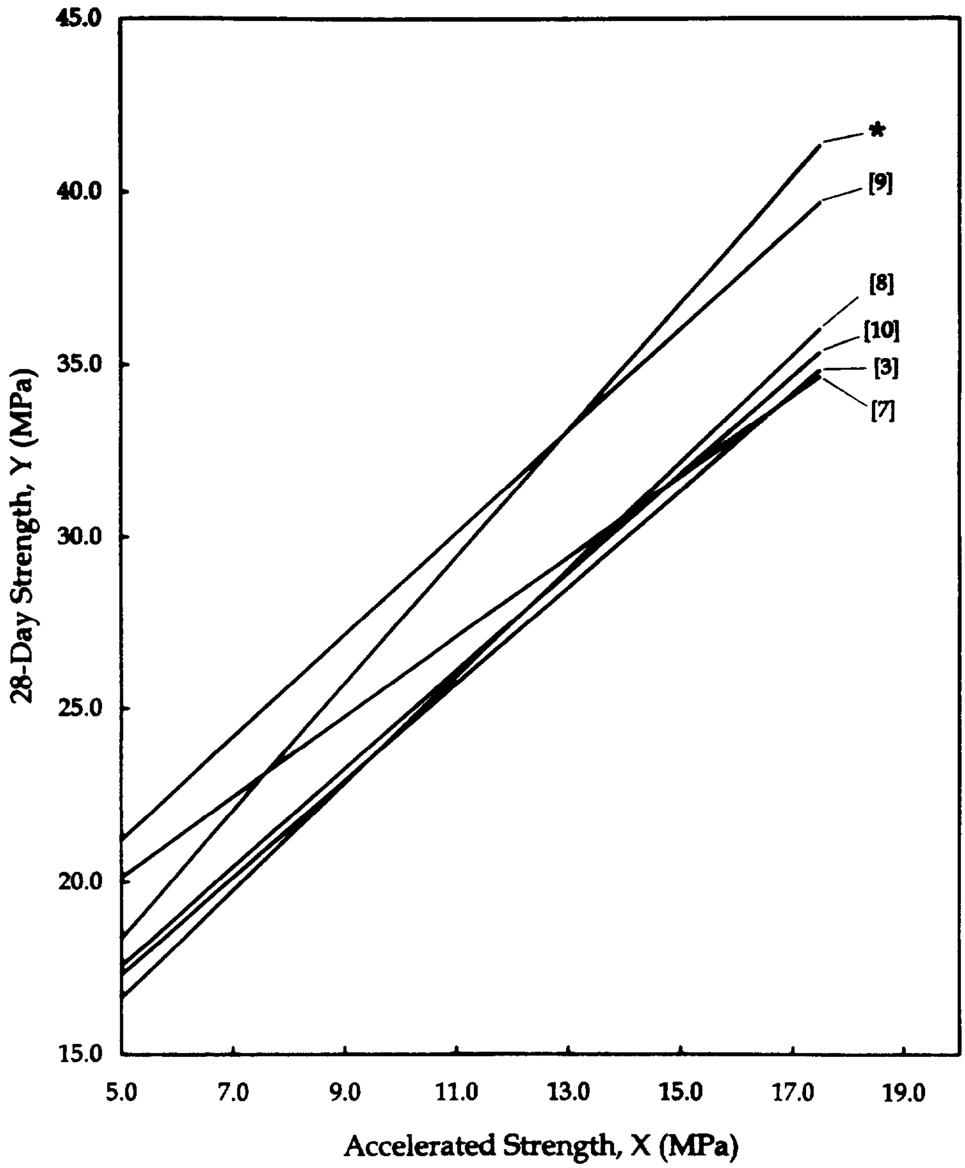

FIGURE 4. Comparison of linear function models: Resheidat [3], Lapinas [7], Ramakrishnan and Dietz [8], Rodway and Lenz [9], Nasser [10], authors (*).

It is a fact that differences do occur due to the use of local materials and workmanship. Despite that, discussion is directed to compare the prediction of 28-day strength independent of the influence of such differences. The linear regression model as expressed by eq 2 is compared with similar functions obtained by several experimental investigations [7,8,9,10] as shown in Table 5 and Fig. 4.

It can be observed that closest agreement is found with the work of Rodway and Lenz [9]. However, the pattern of the proposed model is similar to other models excluding the model of Lapinas [7]. Prediction of 28-day strength utilizing other models underestimates the concrete strength. This will justify the need for having a prediction model for concrete using blended cements. It is concluded that the type of materials and mix proportions influence the constants α and β of eq 2. This conclusion outlines the need for carrying out a preliminary study on the accelerated strength of concrete for about 30 specimens prior to the use of accelerated strength testing in quality control or prediction of 28-day strength.

Conclusions

The following conclusions may be drawn from this study:

1. The accelerated strength testing of concrete using the Boiling Water Method was found to be an adequate and reliable measure of controlling the

quality of concrete as well as prediction of its 28-day strength.

2. Statistical Ratio model can be used for quick prediction without using curves or charts.
3. Regression models, namely: linear, power, and exponential models give nearly the same predicted values.
4. High values of coefficients of variation for both test results (normal and accelerated) were observed. This is natural since the concrete specimens were taken directly from the concrete used for the project and not prepared in the laboratory. The test results are more realistic than in-lab controlled tests.
5. The proposed prediction models reflect the actual forecasting of 28-day concrete strength. Prediction by any other models may be very conservative.

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