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Interrelations Between Cement and Concrete Properties, Part 3

Compressive Strengths of Portland Cement Test Mortars and Steam-Cured Mortars

R. L. Blaine, H. T. Arni, and M. R. DeFore

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Contents

Section 7. Compressive Strength of Test Mortars

R. L. Blaine, H. T. Arni, and M. R. DeFore

The relationships between cement characteristics and compressive strength of 1:2.75 (cement to graded Ottawa sand) mortars of standard consistency at ages of 24 hours to 10 years, and made with 199 cements of different types, were studied by fitting multivariable regression equations with the aid of a digital computer. The dominant variables associated with the differences of compressive strength, strength gain, and strength ratios were different at the various test ages, and after different curing conditions. The additional use of certain trace elements with commonly determined independent variables resulted in a significantly better fit between the equations and the observed data. Interactions between the fineness values and other independent variables were noted. Certain parallelisms and differences were noted with respect to variables associated with compressive strength differences at various ages and the heat of hydration of the cements at these ages.

Key Words: Chemical composition, fineness, heat of hydration, strength gain of portland cements, trace elements.

CONTENTS

1. Introduction

Compressive strength tests of 1:2.75 (cement to graded Ottawa sand) mortar cubes are required in Federal [1][1] and ASTM [2] specifications for portland cements. These plastic mortar tests were adopted in 1936 after considerable study, as a means for evaluating the strength producing properties of different portland cements. Although the test-mortar cannot be used to predict the strength characteristics of any and all concretes, it is considered indicative, to a limited extent, of the relative concrete strengths which may be obtained if other potential variables are held constant.

These specification tests are usually made at early ages, for example, 1 and 3 days, 3 and 7days, or occasionally at 7 and 28 days. The values obtained, together with knowledge of the chemical composition of the cements, are used, to some extent, to predict the potential strength, or the strength at later ages of mortars or concretes made from these cements. Lack of complete information on the variables associated with gain in com-

[1] Figures in brackets indicate the literature references at the end of this section, p.65.

pressive strength with time of hydration results in difficulties in predicting the potential compressive strength. Tests have been reported on the strengths and strength-gain characteristics of laboratory prepared major compounds potentially present in cement, both separately, [3, 4] and in various combinations. Tests have also been made of the effect of some of the minor constituents [5].

Numerous authors [2] have published the results of strength tests, and the increase of strength with age of both mortars and concretes [6]. Statistical techniques have been used to derive factors for the contributions of the major components. However, it has been reported that results obtained from different sets of data vary widely. Some of the limitations and uncertainties of the statistical approach to the study of factors contributing to the strengths of cements have also been discussed [7]. Mentioned among these limitations of previous studies was the lack of information on the kind and amount of the minor constituents and trace elements. The present statistical analysis includes the study of the effects of the trace elements as well as other components among the variables associated with compressive strength values of mortar cubes at ages up to 10 years.

2. Materials

The portland cements used in this study have previously been described [8, 9, 10]. Briefly, they consisted of 199 commercially manufactured cements of the different types, and were obtained from different areas of the USA, with a few obtained from other countries. These cements were classified primarily on the basis of their chemical analyses and physical tests, and included 82 Type I, 68 Type II, 20 Type III, 3 Type IV, and 12 Type V cements. Also included were 14 air-entraining cements. The chemical analyses and other tests indicated a fairly broad range of properties.

3. Tests and Nomenclature

Mortars for two-inch plastic mortar cubes were proportioned, mixed, and compacted in accordance with Federal [11] and ASTM [12] specifications except that the amount of water required for a percentage flow of 110 ± 5 was used. Three 9-cube batches of the 1: 2.75 (cement to graded Ottawa sand) mortar were made with each of the cements. Although most of the cements were tested in the Washington laboratory, many were tested at the field stations in Allentown, Denver, San Francisco, and Seattle.

Three cubes were tested in compression at each age, and after each of the various storage conditions. After the first 22 to 24 hr in the molds in the moist cabinet at 95 to 100 percent relative humidity, most of the specimens were stored in water and tested at the ages of 24 hr, 3, 7, and 28 days, 1, 5, and 10 years. In this section of this series, these will be designated as ST01, ST03, ST07, ST28, ST1Y, ST5Y, and STXY respectively. Three specimens made with each cement were stored continuously in the moist cabinet at 95 to 100 percent relative humidity and tested at 1 year. These were designated as ST1M. The other 3 specimens were stored in water for 6 days, then in laboratory air at 50 ± 5 percent relative humidity for 49 weeks, then in water for 2 weeks and then tested in compression. These specimens were designated ST1A.

In addition to using the value of the strength at various ages and conditions as dependent variables, the following calculated variables were used: ratios between two strengths, strength gains expressed as the difference between two strengths, and strength gains expressed as the ratio of the difference between two strengths to the earlier strengths. The various measured and calculated dependent variables are identified by symbols as follows:

SR(1) for ST1Y/ST1M
SR(2) for ST1A/ST28
SG(1) for ST28–ST07
SGR(1) for (ST28–ST07)/ST07
SG(2) for ST1Y–ST07
SGR(2) for (ST1Y–ST07)/ST07
SG(3) for ST1Y–ST28
SGR(3) for (ST1Y–ST28)/ST28
SG(4) for STXY–ST28
SGR(4) for (STXY–ST28)/ST28

Other nomenclature used in this section is consistent with that used in previous sections of this series.[3]

4. Statistical Studies

The statistical techniques used to determine the independent variables associated with the strength values at the different ages, the increase in strength at the later ages, and the strength ratios at different ages have been described in a previous section in this series of articles [8]. These techniques included plots of the dependent and major

[2] Compressive strengths of portland cement mortars and concretes have been the subject of so many investigations during the past century that it would not be practical or possible to list them all.

[3] Among the abbreviations or symbols used are C_3A, C_3S, C_2S, and C_4AF for the calculated potential compounds, tricalcium aluminate, tricalcium silicate, dicalcium silicate, and tetracalcium aluminoferrite respectively. Also used are AE+NAE for air-entraining plus nonair-entraining cements, NAE for nonair-entraining cements, APF for air permeability fineness, WAGN for Wagner turbidimeter fineness, Loss for loss on ignitions, and Insol. for insoluble residue.

independent variables as well as the use of the "tic-tac-toe," and the Students "t" test, of the "hi-lo" and "middle-ends" comparisons to determine which of the minor constituents or trace elements were probable contributing factors to variations.[4]

Multiple regression equations were calculated by the least squares method and were considered of greatest significance in drawing conclusions. As in previous sections, comparisons were made of the degree of fit using only commonly determined variables, and these together with minor and trace elements. The level of significance of any reduction in the S.D. values resulting from the use of the additional variables in the equation was calculated for various pairs of equations or for the S.D. values of the property of the cements (as presented in footnotes in the tables) compared with the S.D. values of an equation fitted with independent variables. The reduction in variance for different pairs of equations and critical "F" values which must be exceeded for significance at the five- and one-percent probability levels are presented in a table summarizing these calculations. Equations were obtained using the major potential compounds as well as the major oxides. Equations were calculated for both the AE+NAE cements and for the NAE cements for all of the dependent variables.

After it had been determined which of the independent variables were significantly [5] associated with the dependent variable when used in an equation, the residuals of the equation were fitted by a least squares method to other single independent variables and the reduction in variance calculated. If any of the additional independent variables indicated a significant reduction in variance, they were tried in the equation and retained if the coef./s.d. ratio was greater than one.

Equations were also computed for the "odds" and "evens" in the array of cements. Comparisons were made of the coefficients of the variables in the two lots of cements and these were compared to the coefficients and coef./s.d. ratios computed for all the cements.

In calculating the equations, there was a choice in the fineness values of those determined by means of the air-permeability method and those determined by the Wagner turbidimeter method. Calculations were made using the fineness values as obtained by each of the methods. Although the results obtained by the two methods are closely related, the ratios of the values obtained by the two methods may differ appreciably. Variables associated with these differences are presented in the discussion.

No measurements were made of the quantity of air entrained in the 1:2.75 mortars. It was therefore necessary to use the air-content values in the 1:4 (cement to 20–30 Ottawa sand) mortars as an independent variable even though the relation between the entrained air in the 2 mortars is far from perfect.

Although compressive strength tests were made on all 199 cements, the calculations of the equations presented in this section were limited to those for which trace-element determinations had been made. The 3 white cements and the cement having a high autoclave expansion were excluded, as were also a few other cements that had large deviations from the calculated relationships for no apparent reason. The frequency distributions as well as the calculated contribution of the various independent variables included all the cements for which values were available.

Equations presented in this article were selected from a large number of trial equations indicating the relationship of various independent variables to the compressive strength values [6] at each of the test ages, to the strength gain at different ages, and to the strength ratios of specimens tested at different ages of after different curing conditions. The differences and trends indicated by these series of equations will be treated in the discussion in subsection 6. Some of the limitations on interpretations of multiple regression equations, as well as other statistical techniques used in this this series of articles, have been discussed in section 1, subsections 4.2, 4.3, and 5.[8].

5. Results of Tests

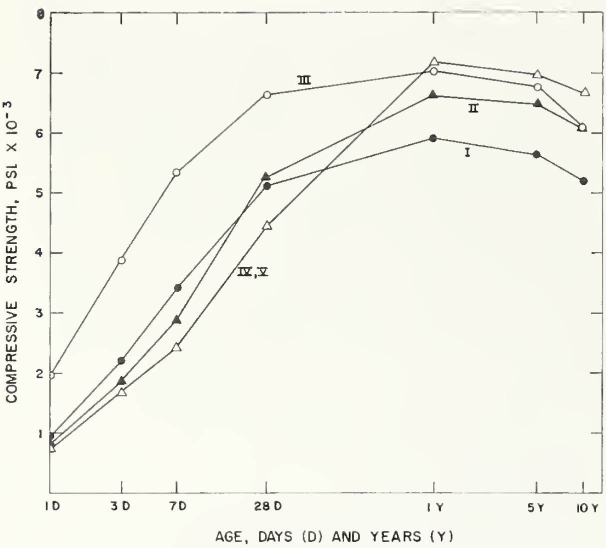
5.1. Compressive Strengths of Mortars of Different Types of Cement

Presented in figure 7–1 are plots on a semilog scale of the average compressive strength values of the mortars made from the different types of cement versus the age at which the specimens were tested. None of the AE cements were included in these averages. All of the specimens were stored in water after the first 24 hr in the molds in the moist cabinet. The average compressive strength values of the 1 year air-stored specimens, (ST1A), (not indicated in this figure) were about the same as the averages of the 28 day water stored specimens, (ST28). The 1 year moist-air-stored specimens (ST1M) had average compressive strength values close to those stored in water for

[4] Statistical terms and notations employed in this section are the same as those of previous sections in this series of articles. For example, S.D. refers to the estimated standard deviation calculated from the residuals of a fitted equation, or the estimated standard deviation about the average. Also, as in previous sections, s.d. refers to the estimated standard deviation of a coefficient of an independent variable used in a fitted equation, coef./s.d. the ratio of the estimated coefficient (of an independent variable used in an equation) to its estimated standard deviation and "F"=Fisher's ratio of variances.

[5] As previously indicated [8], a coef./s.d. ratio greater than one was considered to be of sufficient significance to warrant further investigation.

[6] The equations may be interpreted as indicating the independent variables associated with the compressive strength, per se, or, what appears more plausible, the independent variables associated with differences in compressive strengths of different cements. This interpretation assumes that portland cements have certain inherent strength-producing properties resulting from chemical, and manufacturing, as well as specification requirements.



● Type I, ▲ Type II, O Type III, and Δ Types IV, V

FIGURE 7–1. *Results of plotting average compressive strength at the various test ages of nonair-entraining cements of the different types.*

1 year (ST1Y). These strength ratios will be considered in a later subsection. The cements classified as Types IV and V had an average compressive strength lower than that for the other types at ages up to 28 days but had the highest average at 1, 5, and 10 years. The averages of those classified as Type I cements had the lowest average compressive strength after 1 year or longer. The averages of all of the types of cement appear somewhat lower at the 10 year test age than when tested at the age of 1 year. This decrease did not occur for every cement within each group.

5.2. Compressive Strength at 24 Hours

The frequency distributions of the 24-hr compressive strength values obtained with the cements are presented in table 7–1. Each of the types of cement, as classified,[7] had a range of strength

[7] As previously indicated, [8], the cements were classified primarily on the basis of the chemical analysis and physical tests such as air-entrainment, fineness, etc.

TABLE 7–1. *Frequency distribution of cements with respect to 1-day compressive strength in psi of 1:2.75 (cement to graded Ottawa sand) mortar cubes*

Type cement	Compressive strength, psi $\times 10^{-3}$											Total
	0 to 0.3	0.3 to 0.6	0.6 to 0.9	0.9 to 1.2	1.2 to 1.5	1.5 to 1.8	1.8 to 2.1	2.1 to 2.4	2.4 to 2.7	2.7 to 3.0	3.0 to 3.3	
	Number of cements											
I	1	2	37	35	5	2	---	---	---	---	---	82
IA	---	---	8	---	---	---	---	---	---	---	---	8
II	---	7	33	26	2	---	---	---	---	---	---	68
IIA	---	---	1	1	1	---	---	---	---	---	---	3
III	---	---	---	---	2	8	3	3	2	1	1	20
IIIA	---	---	---	---	---	2	---	---	1	---	---	3
IV & V	---	2	8	5	---	---	---	---	---	---	---	15
Total	1	11	87	67	10	12	3	3	3	1	1	199

TABLE 7–2. *Equations relating the 1-day compressive strengths in psi of AE+NAE cements to various independent variables*

Equat on	Note		Const.	C_3S	C_4AF	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	Loss	Insol.	APF	WAGN	Air 1:4 mortar	K_2O	SrO	Ni	P	S.D.
1	(1)	ST01	=−2029	+18.19						+224.7	−168.8	−228.2	+0.5509		−16.82	+349.1				185.9
		s.d.	= (133)	(2.33)						(54.1)	(29.6)	(109.1)	(0.0369)		(3.97)	(72.5)				
2	(1)	ST01	=−2073	+18.99						+258.7	−186.5	−162.7	+0.5413		−15.54	+374.8	−358.7	+5451	−282.1	179.5
		s.d.	= (132)	(2.27)						(54.1)	(29.0)	(106.9)	(0.0363)		(3.86)	(70.6)	(162.0)	(4308)	(128.7)	
2A	(2)	ST01(odd)	=−1922	+13.81						+244.4	−120.8	*−40.7	+0.5718		−17.43	+230.7	*−199.5	*+5162	−246.9	165.9
		s.d.	= (175)	(2.93)						(76.9)	(42.0)	(122.5)	(0.0504)		(6.02)	(89.3)	(224.3)	(5245)	(174.9)	
2B	(2)	ST01(even)	=−2106	+24.18						+237.9	−213.7	462.9	+0.5008		−16.56	+483.2	−248.3	*−1460	−341.9	184.1
		s.d.	= (201)	(3.55)						(75.2)	(42.2)	(205.0)	(0.0519)		(5.20)	(112.0)	(243.8)	(7351)	(185.1)	
3	(1)	ST01	=−2188	+19.21	−21.12					+287.9		−196.9		+0.9976	−16.02	+426.5				191.2
		s.d.	=(1812)	(2.40)	(6.92)					(51.7)		(111.8)		(0.0703)	(4.15)	(76.1)				
4	(1)	ST01	=−2164	+19.32	−24.92					+311.3		−155.8		+0.9838	−15.22	+459.5	−383.9	+5721	−284.0	184.9
		s.d.	= (1774)	(2.33)	(6.76)					(51.1)		(108.4)		(0.0687)	(4.01)	(74.3)	(164.7)	(4511)	(132.4)	
5	(1)	ST01	=−3878			+89.50	−99.77	−126.9	−58.52	+235.8	−150.4	−192.2	+0.5415		−18.00	+451.1				179.3
		s.d.	=(1333)			(14.88)	(25.40)	(29.8)	(22.23)	(57.3)	(31.0)	(108.9)	(0.0367)		(3.94)	(79.0)				
6	(1)	ST01	=−3758			+88.18	−103.6	−108.0	−69.17	+236.3	−169.6	−171.3	+0.5470		−16.76	+447.8	−304.5	+6807	−298.1	173.8
		s.d.	=(1297)			(14.57)	(24.7)	(29.7)	(21.78)	(56.0)	(30.6)	(105.8)	(0.0360)		(3.85)	(77.6)	(171.5)	(4211)	(125.4)	
6A	(2)	ST01 (odd)	=−4567			+79.83	−59.73	−66.0	−67.50	+220.5	−87.5	*−34.8	+0.5782		−18.98	+389.3	*−209.0	+7097	−293.7	156.8
		s.d.	=(1700)			(18.44)	(31.20)	(39.8)	(31.45)	(74.0)	(42.4)	(117.2)	(0.0489)		(5.82)	(104.5)	(229.8)	(5039)	(166.9)	
6B	(2)	ST01 (even)	=−1896			+91.88	−167.2	−164.7	−80.50	+189.8	−220.9	−506.3	+0.4983		−17.39	+463.8	*−167.8	*−1796	−357.7	183.6
		s.d.	= (2033)			(23.18)	(40.9)	(46.4)	(33.03)	(88.9)	(46.9)	(213.7)	(0.0543)		(5.34)	(119.0)	(265.9)	(7399)	(189.1)	
7	(1)	ST01	=−4471			+100.8	−118.9	−115.2	−72.41	+285.6		−156.0		+0.9844	−15.21	+487.8				190.8
		s.d.	= (1305)			(15.4)	(24.2)	(29.8)	(23.38)	(60.1)		(114.3)		(0.0744)	(4.19)	(82.4)				
8	(1)	ST01	=−4704			+100.4	−115.0	−80.1	−80.38	+282.7		−146.3		+1.0117	−13.48	+494.5	−442.9	+6069	−311.1	183.2
		s.d.	= (1257)			(15.0)	(23.3)	(30.3)	(22.61)	(58.0)		(109.9)		(0.0722)	(4.06)	(80.1)	(178.5)	(4480)	(132.0)	

*Coef./s.d. ratio less than 1. [1] 176 cements; Avg=974; S.D.=398.8. [2] 88 cements.

DEPENDENT VARIABLE COMPRESSIVE STRENGTH	INDEPENDENT VARIABLES																		
AGE	NOTE *	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TOTAL ALKALI	C_3A	C_3S	C_2S	C_4AF	$\frac{A}{F}$	$\frac{S}{A+F}$	AIR P. FINE	WAGN. FINE	AIR 1:4 MORT
1 DAY ** (ST01)	(1)	9/3	7/5	8/4	10/2	6/6	10/2	10/2	6/6	6/6	8/4	10/2	10/2	7/5	8/4	8/4	8/4	8/4	8/4
	(2)																		
	(3)	NL	NO	NL	NL	NO	L	NL	NO	NO	NO	L	L	NL	NL	NO	NO	NL	NO
	(4)	−10	−3	−11	+17	+1	+13	−5	+8	−1	+4	+13	−13	−10	+13	−2	+4	+9	−3
3 DAYS *** (ST03)	(1)	10/2	8/4	8/4	10/2	6/6	10/2	8/4	6/6	6/6	9/3	10/2	10/2	10/2	10/2	8/4	6/6	6/6	6/6
	(2)																		
	(3)	NL	L?	NL	L	NO	L	NL	NO	NO	L?	NL	NL	NL	L?	L?	NL	NL	NO
	(4)	−18	+9	−9	+13	−5	+17	−9	+3	−1	+8	+17	−19	−15	+11	−8	+7	+4	−3
7 DAYS *** (ST07)	(1)	10/2	10/2	12/0	10/2	9/3	8/4	6/6	8/4	8/4	10/2	10/2	12/0	12/0	12/0	8/4	7/5	8/4	6/6
	(2)																		
	(3)	NL	L?	NL	L	L?	L	NO	NO	NO	NL	NL	L	NL	L?	L?	NL	NL	NO
	(4)	−19	+18	−24	+15	−8	+12	−3	+1	−2	+19	+18	−24	−24	+24	−6	+10	+7	−4
28 DAYS *** (ST28)	(1)	8/4	6/6	6/6	12/0	8/4	6/6	8/4	10/2	10/2	7/5	10/2	10/2	6/6	6/6	8/4	8/4	10/2	8/4
	(2)																		
	(3)	L?	NO	NO	NL	NO	NO	NO	L?	L	NO	NL	NL	NO	NO	L?	NL	NL	NL
	(4)	−11	+5	−4	+17	−6	+2	−3	−6	−11	+2	+19	−16	−8	+8	−11	+9	+11	−12

FIGURE 7–2. *Results of plotting compressive strength values at 1, 3, 7 and 28 days of 1:2.75 (cement to graded Ottawa sand) mortars on the "Y" axis versus various independent variables on the "X" axis.*

*Note (1) Ratio of number of plotted points in pairs of diametrically opposite quadrants.
Note (2) General trend of lines drawn through plotted points.
Note (3) Apparent nature of relationship. L=linear; NL=nonlinear; NO=no apparent relationship; and L?=nature of relationship not determinable.
Note (4) Quadrant sum in corner test. (See reference [8].)
**Moist-air-stored.
***Stored in moist air 24 hours then in water.

values, and there was considerable overlapping of the values obtained with the different types.

The results of the preliminary plots of the 1-day compressive strength values versus various independent variables are presented in figure 7–2. The lines drawn through the 12 pairs of averages to indicate the trend, and the significance of the number of points in the opposite quadrants as well as the "quadrant-sum" have previously been discussed in section 1, subsections 4.1 and 5 [8]. It may be noted that at 1 day, Fe_2O_3, CaO, SO_3, C_3S, C_2S, and A/F all had quadrant-sum values greater than 11, a value which may be considered significant at the five percent confidence level.

Selected equations relating the 24-hr compressive strength values of the AE+NAE cements to various independent variables are presented in table 7–2. Equation 1 presents the relationships found for commonly determined independent variables. The use of C_2S in addition to the C_3S, or the use of the C_3S/C_2S ratio, did not result in a lower S.D. value.

Using the statistical techniques previously described it was determined that of the other variables, only SrO, Ni, and P had coef./s.d. ratios greater than one. The relationship is presented in eq 2. The S.D. value was lower than in eq 1 and by reference to table 7–75 [8] it may be noted that the reduction in variance was significant at the one percent probability level.

Equations 2A and 2B, calculated with the "odds" and "evens" in the array of cements, indicated uncertainties with respect to the coefficients for insoluble residue, SrO, and Ni. None of these three variables were highly significant in eq 2 where the larger group of cements were used in the calculations. The coefficients of other variables also differed but not so much that the coef./s.d. ratio was less than 1. Reasons for such variations have previously been discussed in earlier sections of this series of articles [9].[9]

When using the fineness values obtained by means of the Wagner turbidimeter method instead of those obtained by the air-permeability method, it was necessary to delete Loss (which then had a coef./s.d. ratio less than 1), and to include C_4AF as an independent variable in order to obtain S.D. values in eqs 3 and 4 comparable to those in eqs 1 and 2.

The series of eqs 5 through 8 were computed with the use of the major oxides instead of the potential C_3S and C_4AF compounds. All of the major oxides had significant coef./s.d. ratios. The

[8] A tabulation of the reduction in variance, "F" values, for all equations compared is presented in table 7-75. Presented also are the critical values for "F" which must be exceeded for significance at the one and five percent levels for the number of degrees of freedom (D.F.) involved in each comparison.

[9] If a number of cements having higher than normal values for an independent variable are included in one of the two groups (the "odds" or "evens") by the arbitrary division of the cements, spurious coefficients may be obtained for this variable. The estimated standard deviations of the coefficients of the smaller groups were usually larger than when a combination of the "odds" or "evens" in the array of cements were used in calculating the equations. If the coefficients of both the "odds" and "evens" of an independent variable are significant, a greater confidence can be placed in the equations and in the association of that independent variable with the dependent variable.

TABLE 7–3. *Equations relating the 1-day compressive strengths in psi of NAE cements to various independent variables*

Equation	Note		Const.	C_3S	C_4AF	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	Loss	Insol.	APF	WAGN	Air 1:4 mortar	K_2O	SrO	Ni	P	S.D.
1	[1]	STO1	=−2004	+18.29	------	------	------	------	------	+225.8	−166.2	−289.3	+0.5557	------	−23.94	+371.6	------	------	------	188.7
		s.d.	= (146)	(2.41)	------	------	------	------	------	(56.2)	(30.9)	(121.4)	(0.0384)	------	(8.76)	(76.4)	------	------	------	
2	[1]	STO1	=−2071	+19.17	------	------	------	------	------	+256.7	−188.4	−215.9	+0.5467	------	−18.75	+398.9	−394.3	+5957	−275.4	181.7
		s.d.	= (146)	(2.34)	------	------	------	------	------	(55.6)	(30.3)	(118.4)	(0.0376)	------	(8.60)	(74.1)	(172.0)	(4390)	(133.7)	
2A	[2]	STO1 (odd)	=−1951	+15.61	------	------	------	------	------	+329.8	−119.4	−120.8	+0.5329	------	−25.18	+276.3	−611.6	*+6275	−223.1	169.4
		s.d.	= (186)	(2.93)	------	------	------	------	------	(83.6)	(39.9)	(168.8)	(0.0507)	------	(12.10)	(96.0)	(227.2)	(6563)	(177.1)	
2B	[2]	STO1 (even)	=−2168	+24.88	------	------	------	------	------	+176.0	−270.1	−281.4	+0.5496	------	−21.99	+519.9	*−61.8	*+3768	−400.5	183.1
		s.d.	= (218)	(3.78)	------	------	------	------	------	(75.6)	(44.9)	(166.6)	(0.0556)	------	(12.67)	(115.6)	(257.0)	(5865)	(196.1)	
3	[1]	STO1	=−2222	+19.43	−20.63	------	------	------	------	+291.1	------	−203.0	------	+1.005	−15.52	+420.5	------	------	------	197.2
		s.d.	= (206)	(2.53)	(7.30)	------	------	------	------	(54.6)	------	(126.6)	------	(0.075)	(9.21)	(80.5)	------	------	------	
4	[1]	STO1	=−2216	+19.60	−24.29	------	------	------	------	+308.0	------	−165.2	------	+0.993	−11.68	+457.2	−385.0	+5602	−299.3	190.1
		s.d.	= (202)	(2.45)	(7.13)	------	------	------	------	(53.6)	------	(122.5)	------	(0.073)	(9.02)	(78.5)	(177.3)	(4672)	(139.6)	
5	[1]	STO1	=−4004	------	------	+91.37	−98.22	−128.9	−56.89	+239.6	−147.4	−249.4	+0.5475	------	−26.28	+484.2	------	------	------	181.2
		s.d.	= (1388)	------	------	(15.39)	(26.47)	(31.2)	(23.15)	(59.2)	(32.0)	(121.2)	(0.0379)	------	(8.60)	(82.7)	------	------	------	
6	[1]	STO1	=−3914	------	------	+89.96	−101.46	−109.4	−67.28	+237.6	−168.7	−227.2	+0.5529	------	−21.02	+480.0	−325.3	+7359	−283.3	175.4
		s.d.	= (1352)	------	------	(15.07)	(25.65)	(30.9)	(22.67)	(57.7)	(31.6)	(117.5)	(0.0370)	------	(8.51)	(80.8)	(179.6)	(4282)	(130.2)	
6A	[2]	STO1 (odd)	=−3040	------	------	+66.39	−78.07	−85.4	−81.78	+270.6	−107.2	−171.4	+0.5579	------	−28.88	+379.1	−545.6	+10576	−246.4	161.0
		s.d.	= (2188)	------	------	(23.90)	(34.23)	(41.4)	(31.75)	(81.1)	(40.6)	(167.3)	(0.0496)	------	(11.65)	(122.8)	(239.1)	(6423)	(172.0)	
6B	[2]	STO1 (even)	=−1638	------	------	+95.85	−183.80	−191.2	−83.93	+126.7	−273.3	−273.1	+0.5360	------	−26.23	+533.7	*−35.0	*+3596	−398.2	182.3
		s.d.	= (1985)	------	------	(21.65)	(43.17)	(48.8)	(33.89)	(91.0)	(51.2)	(170.7)	(0.0573)	------	(13.39)	(118.3)	(282.4)	(6027)	(198.5)	
7	[1]	STO1	=−4675	------	------	+103.3	−119.0	−115.2	−68.67	+290.7	------	−154.2	------	+0.9940	−13.97	+485.4	------	------	------	196.1
		s.d.	= (1393)	------	------	(16.3)	(25.6)	(31.7)	(24.88)	(63.3)	------	(129.3)	------	(0.0792)	(9.33)	(87.4)	------	------	------	
8	[1]	STO1	=−4998	------	------	+103.5	−114.2	−79.0	−75.86	+281.4	------	−145.3	------	+1.0242	*−7.31	+493.8*	−438.0	+5928	−336.8	188.3
		s.d.	= (1344)	------	------	(15.8)	(24.6)	(32.0)	(24.04)	(60.9)	------	(124.1)	------	(0.0767)	(9.18)	(84.3)	(189.3)	(4632)	(139.8)	

[1] 164 cements; Avg=980; S.D.=399.9. [2] 82 cements. *Coef./s.d. ratio less than 1.

use of the turbidimetric fineness values, as in eqs 7 and 8, resulted in the change in the significance (coef./s.d. ratio), of the Loss. (The interdependence of some of the so-called independent variables will be treated in the discussion.)

A comparable series of equations computed for the NAE cements are presented in table 7–3. The coefficients of the independent variables are in reasonable agreement with those presented in table 7–2, except that the "air, 1:4 mortars" had a somewhat lower coef./s.d. ratio. The increase in SrO and P appeared associated with lower 24-hr compressive strength, whereas an increase in Ni appeared associated with higher strength. In general the coefficients of the SrO and P were significant but those for Ni were questionable. Comparing the S.D. values of eqs 1 and 2, 3 and 4, 5 and 6, or 7 and 8 indicate that the use of the trace elements resulted in a significant reduction in the S.D. values.

Using the independent variables and their coefficients of eq 2, table 7–2, and the ranges of these variables, values were calculated for their contributions, and ranges of contribution to the 24-hr compressive strength. These calculated values, as presented in table 7–4, are approximations based on a single equation, and it may be noted that somewhat different values may be obtained by use of other equations.[10]

TABLE 7–4. *Calculated contribution of independent variables to 1-day compressive strength in psi of 1:2.75 (cement to graded Ottawa sand) mortar cubes, moist-air-stored, and the calculated ranges of such contributions*

Independent variable	Range of variable (percent)	Coefficients from eq 2 of table 7–2	Calculated contribution to STO1	Calculated range of contribution to STO1
			Const.=−2073	
C_3S	20 to 65	+19.0	+380 to +1235	855
SO_3	1.2 to 3.0	+259	+311 to +777	466
Loss	0.3 to 3.3	−186	−56 to −614	558
Insol	0 to 1.0	−163	0 to −163	163
APF	*2500 to 5500	+0.541	+1352 to +2976	1624
Air, 1:4 mortar	1 to 21	−15.5	−16 to −326	310
K_2O	0 to 1.1	+375	0 to +412	412
SrO	0 to 0.4	−359	0 to −144	144
Ni**	0 to 0.02	+5450	0 to +109	109
P	0 to 0.5	−282	0 to −141	141

*cm^2/g.
**Doubtful significance. Coef/s.d. less than 2.

Although the C_3S and the fineness were the principal contributors to the 24-hr compressive strength, the increase in SO_3 was associated with higher strength values as were K_2O and possibly Ni of the minor constituents. Increase in Loss, insoluble residue, and SrO were associated with lower strengths. In this and in corresponding tables throughout this paper, coefficients for which the coef./s.d. ratio is less than 2 (indicating

[10] Computations for contributions to compressive strengths at other ages will also be made from similar equations, i.e., one selected from the AE+NAE cements containing one or more of the potential major compounds, and using air-permeability fineness values in order that trends may be more easily followed.

only possible significance) are identified by a double asterisk.

5.3. Three-Day Compressive Strength

The frequency distributions of the 3-day compressive strength values for the different types of cement are presented in table 7–5. There was a considerable spread of values with each of the types, and an overlapping of values for the different types of cement.

The preliminary plots and trends of the relationships to various individual independent variables are presented in figure 7–2. SiO_2, CaO, SO_3, C_3S, C_2S, C_4AF, and A/F all had quadrant-sums with absolute values greater than 11.

TABLE 7–5. *Frequency distribution of cements with respect to 3-day compressive strength of 1:2.75 (cement to graded Ottawa sand) mortar cubes, water-stored*

Type cement	Compressive strength, psi×10^{-3}											Total
	0.5 to 1.0	1.0 to 1.5	1.5 to 2.0	2.0 to 2.5	2.5 to 3.0	3.0 to 3.5	3.5 to 4.0	4.0 to 4.5	4.5 to 5.0	5.0 to 5.5	5.5 to 6.0	
	Number of cements											
I	1	---	29	36	12	4	---	---	---	---	---	82
IA	---	4	4	---	---	---	---	---	---	---	---	8
II	---	9	36	21	2	---	---	---	---	---	---	68
IIA	---	1	---	2	---	---	---	---	---	---	---	3
III	---	---	---	1	1	5	3	6	3	---	1	20
IIIA	---	---	---	---	---	1	1	---	1	---	---	3
IV & V	---	4	9	2	---	---	---	---	---	---	---	15
Total	1	18	78	62	15	10	4	6	4	---	1	199

Equations selected from those computed to determine the relationships of various independent variables with the 3-day compressive strength values for AE+NAE cements are presented in table 7–6. Commonly determined variables which show relationships to the 3-day compressive strength are presented in eq 1. The use of the trace elements SrO, Mn, Cr, and V with the commonly determined independent variables, as in eq 2, resulted in a significant reduction in the S.D. value although the coef./s.d. ratio for Cr was of doubtful significance. In the calculated equations for the "odds" and "evens," eqs 2A and 2B, the coef./s.d. ratio was less than 1 in one or the other of the two equations for K_2O, SrO, Cr, and V. Reasons for such discrepencies have been discussed in previous sections. Equation 3 illustrates the effect of using the turbidimeter-fineness values instead of the air-permeability values. The loss on ignition, highly significant in eq 2, was not significant when turbidimeter results were used, and therefore was not included in eq 3. Use of the C_3A/SO_3 ratio in place of C_3A as an independent variable made no significant difference in the results (eq 3, 4, and 5). However, using the trace elements SrO, Mn, and V with C_3A/SO_3 as in eq 6 resulted in the lowest S.D. value obtained with this group of equations.

Equations 7 through 10 of table 7–6 were calculated using the major oxides, and resulted in S.D. values similar to those obtained with the major potential compounds in eqs 1 through 6. However, the use of the trace elements resulted in reduction of variance which was significant at the five percent level for eqs (7) and (8), and at the one percent level for eqs 9 and 10. (See table 7–75.)

A similar series of equations computed for the NAE cements are presented in table 7–7. Comparing eqs 1 and 2, 4 and 5, or 8 and 9 indicates that the use of the trace elements resulted in lower S.D. values significant at the one percent probability level, whereas in comparing eqs 6 and 7 the reduction of variance resulting from the use of the added independent variables was significant at the five percent level. (See table 7–75.) The K_2O and Cr had coef./s.d. ratios less than one as did Fe_2O_3 and SO_3 in one or the other of the equations for the "odds" and "evens" eqs 2A, 2B, 7A and 7B.

Contributions and the ranges of these contributions to the 3-day compressive strength, as calculated from one of the equations, eq 2, table 7–6, are presented in table 7–8. Increases in fineness, C_3S, C_3A, and SO_3 were associated with increasing or higher compressive strength values, whereas an increase in loss on ignition was associated with decreasing or lower strength values. Of the minor constituents, increased K_2O and V appeared associated with increased strength values, whereas, increased SrO and Mn appeared associated with decreased strength values. There is very little evidence that Cr had a significant effect.

5.4. Seven-Day Compressive Strength

The frequency distributions of the 7-day compressive strength values obtained with the different types of cement are presented in table 7–9. A wide distribution of values was obtained with each of the types of cement as well as some overlapping of the values of the cements as classified into the various types.

The results of the preliminary plots of the 7-day compressive strength values versus individual independent variables are given in figure 7–2. All of the major oxides, SO_3, and A/F, and the major potential compounds had absolute "quadrant-sum" values greater than 11.

The computed equations relating the 7-day compressive strength values to various independent variables are presented in table 7–10 for the AE+NAE cements, and in table 7–11 for the NAE cements. In eqs 1 and 2 are presented the relationship to some commonly determined variables, and in eq 3 the relationship to commonly determined variables plus SrO. Although the coef./s.d ratio of MgO and SrO were less than 1 in eq 3 where APF was used as a variable, both had ratios closer to 2 in eq 4 where WAGN was used as an independent variable. The S.D. value in eq 3 was significantly lower than in eq 1. Comparing eqs 2 and 4, or 5 and 6, indicated that the use of SrO in the equations did not result in a significant reduction in the S.D. values (see table 7–75). It may be noted in table 7–10,

Table 7–6. *Equations relating the 3-day compressive strengths*

Equation	Note	Const.		C₃S	C₃A	CaO	SiO₂	Al₂O₃	Fe₂O₃	SO₃
1	(1)	STO3	=−2950	+41.51	+22.05					+432.5
		s.d.	= (250)	(4.45)	(9.78)					(106.3)
2	(1)	STO3	=−3048	+38.50	+43.12					+447.6
		s.d.	= (261)	(4.38)	(10.98)					(105.2)
2A	(2)	STO3 (odd)	=−3110	+35.98	+48.80					+460.8
		s.d.	= (315)	(5.04)	(12.99)					(141.0)
2B	(2)	STO3(even)	=−2637	+40.25	+34.38					+367.9
		s.d.	= (421)	(7.82)	(18.01)					(153.2)
3	(1)	STO3	=−3940	+43.32	+41.83					+446.5
		s.d.	= (270)	(4.12)	(9.87)					(95.4)
4	(1)	STO3	=−4618	+40.15	*−53.27					+882.2
		s.d.	= (480)	(4.50)	(56.71)					(272.9)
5	(1)	STO3	=−4256	+41.71						+639.9
		s.d.	= (286)	(4.18)						(88.9)
6	(1)	STO3	=−4448	+39.04						+757.2
		s.d.	= (295)	(4.12)						(90.6)
7	(1)	STO3	=−8500			+215.3	−229.9	−153.7	−78.88	+396.6
		s.d.	= (2559)			(28.4)	(48.7)	(56.4)	(42.56)	(110.1)
8	(1)	STO3	=−5721			+180.8	−257.5	−113.8	−104.55	+368.5
		s.d.	= (2631)			(29.6)	(48.3)	(56.8)	(42.09)	(111.2)
8A	(2)	STO3 (odd)	=−5551			+167.7	−238.6	−85.1	−120.4	+378.3
		s.d.	= (3257)			(34.5)	(58.9)	(73.5)	(58.2)	(144.1)
8B	(2)	STO3(even)	=−4092			+178.8	−297.1	−154.9	−78.29	260.2
		s.d.	= (4255)			(51.4)	(81.3)	(92.5)	(64.47)	(174.7)
9	(1)	STO3	=−9248			+224.5	−258.7	−119.3	−101.4	+426.3
		s.d.	= (2249)			(26.5)	(42.0)	(51.4)	(40.1)	(104.3)
10	(1)	STO3	=−7981			+192.7	−264.0	−200.6	−122.7	+806.2
		s.d.	= (2356)			(27.7)	(43.2)	(130.4)	(39.4)	(364.6)

[1] 176 cements; Avg=2166; S.D.=702.5. [2] 88 cements. *Coef./s.d. ratio less than 1.

eqs 5 and 6, that the coefficients for Loss and MgO are positive, whereas they were negative in eqs 2, 3, and 4. Trace elements, other than those indicated in table 7–10, when tried, did not have coef./s.d. ratios greater than 1.

The comments and remarks relative to the results presented in table 7–10 are also applicable to the results presented in table 7–11 for the NAE cements. The "air, 1:4 mortar" was more highly significant in table 7–10 than in table 7–11. Equations for the "odds" and "evens" in both tables indicated that the coef./s.d. ratios of Loss, MgO, and SrO were less than 1 in a number of instances.

The contributions of the different independent variables to the 7-day compressive strength were computed from eq 3 of table 7–10 and are presented in table 7–12 together with the calculated ranges of the contributions. Differences in fineness and C_3S appear to have the dominant influence on the strength values, but differences in other variables can also result in rather large differences.

5.5. Twenty-Eight Day Compressive Strength

The frequency distributions of the 28-day compressive strength values of the different types of cement are presented in table 7–13. Each of the types of cement exhibit a range of values and there is considerable overlapping of the values of the different types.

The results of plotting the 28-day compressive strength values of the different cements versus various single independent variables are presented in figure 7–2. The independent variables having "quadrant-sum" absolute values of 11 or greater include SiO_2, CaO, total alkali, C_3S, C_2S, S/(A+F), and Wagner fineness and (Air, 1:4 mortar).

Selected equations indicating the relationships of various combinations of independent variables to the 28-day compressive strength values are presented in table 7–14 for the AE+NAE cements, and in table 7–15 for the NAE cements. In eq 1 of table 7–14 are presented the relations with commonly determined variables. C_4AF had a coef./s.d. ratio less than 1 in eq 1. This ratio was improved but still less than 2 in eq 4 where the trace elements and Loss were included. The S.D. value for eq 4, however, was significantly lower than that of eq 1. Equations 2 and 3 were computed using the turbidimeter fineness values with a substantial reduction in S.D. The use in eq 3 of the trace elements SrO, Cr, and Co resulted in a further significant reduction in the S.D. value (see table 7–75). The equations for the "odds" and "evens", eqs 3A and 3B, resulted in a positive coefficient for C_4AF in eq 3A and negative in 3B. The evidence suggests that C_4AF is not a very significant variable affecting 28 day strength.

Equations 5, 6, and 7 were calculated using the *in psi of AE+NAE cements to various independent variables*

Loss	APF	WAGN.	Air 1:4 mortar	K_2O	$\frac{C_3A}{SO_3}$	$\frac{Al_2O_3}{SO_3}$	SrO	Mn	Cr	V	S.D.
−249.4 (54.9)	+0.7573 (0.0706)		−49.55 (7.44)	+327.3 (138.9)							348.9
−246.9 (53.5)	+0.7890 (0.0695)		−47.48 (7.18)	+309.7 (136.1)			−855.1 (323.1)	−533.3 (224.1)	+6579 (6549)	+3138 (1661)	334.8
−150.3 (71.8)	+0.8235 (0.0866)		−60.49 (10.62)	*+114.3 (162.8)			*−127.6 (413.4)	−1148.6 (420.7)	+15987 (7054)	+3103 (1787)	286.6
−303.6 (79.1)	+0.7402 (0.1078)		−46.03 (10.20)	+430.2 (234.4)			−1192.0 (520.6)	−349.3 (297.2)	*−10638 (12616)	*+1784 (3432)	363.8
		+1.594 (0.130)	−47.06 (7.15)	+460.3 (134.8)							335.4
		+1.600 (0.129)	−46.07 (7.14)	+447.2 (134.3)	+178.2 (104.7)						333.5
		+1.604 (0.129)	−46.61 (7.11)	+449.8 (134.2)	+81.4 (18.1)						333.4
		+1.635 (0.125)	−44.47 (6.85)	+419.2 (130.9)	+119.5 (19.8)		−947.2 (29.9)	−440.4 (214.2)		+3271 (1428)	319.9
−197.2 (59.0)	+0.7654 (0.0700)		−48.06 (7.56)	+485.5 (151.3)							344.6
−223.0 (58.4)	−0.7916 (0.0699)		−46.40 (7.41)	+376.5 (153.4)			−810.7 (333.8)	−472.1 (235.0)	*+5848 (6611)	+2909 (1706)	335.6
−129.4 (77.0)	+0.8325 (0.0895)		−59.70 (10.99)	+195.4 (194.7)			*−84.1 (421.8)	−1063.2 (437.5)	+15160 (7240)	+2849 (1849)	289.0
−284.1 (90.2)	+0.7417 (0.1099)		−44.72 (10.57)	+461.5 (250.9)			−1251.7 (553.9)	−352.7 (321.8)	*−10822 (12792)	*+1862 (3470)	367.3
		+1.601 (0.129)	−45.04 (7.27)	+586.9 (142.9)							331.3
		+1.628 (0.127)	−42.41 (7.09)	+478.1 (143.9)		+269.7 (232.2)	−943.5 (318.3)	−351.9 (224.8)		+2874 (1496)	320.8

major oxides instead of the major potential compounds as independent variables. The use of four minor constituents in eq 6 resulted in a significantly lower S.D. value than was obtained in eq 5 although coef./s.d. ratios for two of the elements, Co and Ti, were not very significant. Comparing eqs 3 and 4, or 6 and 7, there is some evidence of a lower S.D. value where the turbidimeter fineness values were used, although an additional variable was used in the two equations with APF.

The use of trace elements in eq 4 of table 7–15 for the NAE cements resulted in a significantly lower S.D. value than in eq 1 where they were not used. Equation 3 also had a lower S.D. value than was obtained in eq 2, but the reduction caused by the additional variables was significant only at the five percent probability level. This reduction was also found in comparing the S.D. values of eqs 5 and 6. In comparing the equations for the "odds" and "evens," eqs 3A, 3B, 6A, 6B, there were instances where the SrO, Co, and Ti had coef./s.d. ratios less than 1.

Contributions of the independent variables to the 28-day compressive strength calculated from the coefficients of eq 4 table 7–14 are presented in table 7–16 together with the calculated ranges of such contributions. Increases in C_3S, C_3A, and fineness, and possibly C_4AF and Zr, were associated with higher 28-day compressive strengths, but increases in Loss, air content, and Cr, plus possibly SrO and Co appear associated with lower compressive strengths.

5.6. Compressive Strength of Water-Stored Specimens at 1 Year

The frequency distributions of the 1-year (water-stored) compressive strength values of the different types of cement are presented in table 7–17. There was a considerable range of values with each of the types as classified.

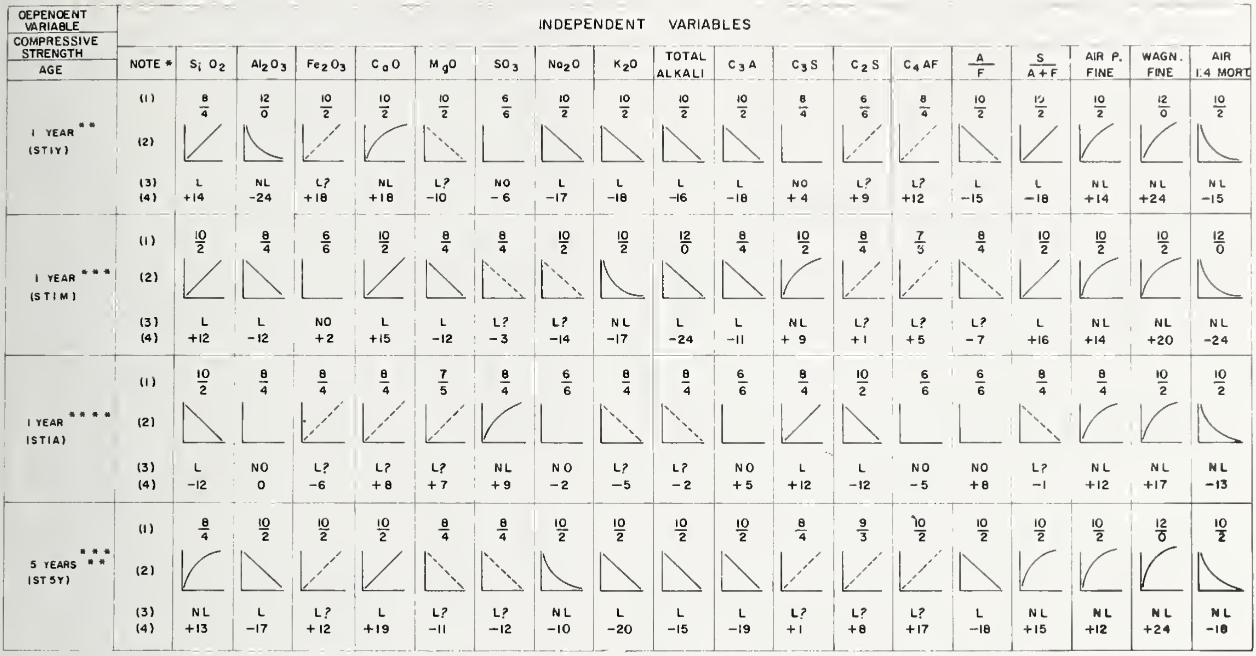
The results of plotting the compressive strength values versus some of the individual independent variables are presented in figure 7–3. This figure also presents the plots of the 1-year, moist-air-stored specimens (ST1M), the 1-year air-stored specimens (ST1A), and the 5-year water-stored specimens (ST5Y). The 1-year, water-stored specimens had "quadrant-sum" absolute values greater than 11 for the 4 major oxides, Na_2O, K_2O, C_3A, C_4AF, A/F, S/(A+F), fineness, and air content. It may be noted that the trends of the lines drawn through the plotted points were different in a number of instances than was observed at the earlier test ages and presented in figure 7–2.

Selected equations relating the 1-year (water-stored), compressive strength values of AE+NAE cements to various combinations of independent variables are presented in table 7–18. Equation 1 indicates the relationship between strength and

TABLE 7–7. *Equations relating the 3-day compressive strengths in psi of NAE cements to various independent variables*

Equation	Note	Const.	C_3S	C_3A	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	Loss	APF	WAGN.	Air 1:4 mortar	K_2O	$\frac{C_3A}{SO_3}$	SrO	Mn	Cr	V	S.D
1	(1)	STO3 = −2863 s.d. = (275)	+42.71 (4.67)	+18.90 (10.30)	------	------	------	------	+441.1 (111.2)	−249.8 (57.5)	+0.7477 (0.0738)	------	−67.42 (16.47)	+380.3 (147.3)	------	------	------	------	------	356.9
2	(1)	STO3 = −2935 s.d. = (284)	+39.53 (4.58)	+40.67 (11.41)	------	------	------	------	+445.7 (109.5)	−252.0 (56.1)	+0.7824 (0.0724)	------	−70.25 (15.86)	+376.5 (144.5)	------	−911.1 (340.6)	−536.8 (239.2)	+7477 (6859)	+3201 (1711)	341.2
2A	(2)	STO3 (odd) = −3077 s.d. = (321)	+37.95 (4.91)	+41.23 (13.20)	------	------	------	------	+695.4 (148.5)	−177.7 (69.5)	+0.7735 (0.0829)	------	−95.30 (20.07)	*+134.9 (165.7)	------	−795.4 (400.2)	−718.6 (438.1)	+14726 (7815)	+2433 (1873)	280.1
2B	(2)	STO3 (even) = −2684 s.d. = (477)	+42.12 (8.42)	+37.30 (18.96)	------	------	------	------	+245.7 (164.3)	−359.9 (89.0)	+0.8011 (0.1200)	------	−68.73 (25.67)	+630.6 (256.4)	------	−902.1 (568.9)	−393.5 (318.3)	*−5580 (12102)	+3456 (3293)	380.2
3	(1)	STO3 = −3928 s.d. = (305)	+44.36 (4.36)	+40.28 (10.51)	------	------	------	------	+445.4 (100.8)	------	------	+1.586 (0.139)	−55.54 (15.98)	+476.4 (143.1)	------	------	------	------	------	345.5
4	(1)	STO3 = −4243 s.d. = (323)	+42.82 (4.43)	------	------	------	------	------	+640.2 (94.2)	------	------	+1.598 (0.138)	−53.75 (15.93)	+465.4 (142.5)	+78.32 (19.24)	------	------	------	------	343.7
5	(1)	STO3 = −4400 s.d. = (327)	+40.07 (4.36)	------	------	------	------	------	+751.8 (95.0)	------	------	+1.631 (0.134)	−55.08 (15.37)	+443.7 (139.7)	+116.33 (20.83)	−969.2 (318.2)	−450.0 (231.3)	------	+3314 (1486)	329.7
-.-	(1)	STO3 = −8340 s.d. = (2695)	------	------	+218.7 (29.6)	−238.1 (51.4)	−170.8 (59.8)	−77.42 (44.73)	+402.0 (115.1)	−199.3 (61.6)	+0.7579 (0.0734)	------	−65.35 (16.61)	+538.5 (160.0)	------	------	------	------	------	352.7
7	(1)	STO3 = −5383 s.d. = (2762)	------	------	+182.6 (30.8)	−267.3 (50.8)	−130.7 (59.7)	−106.0 (44.2)	+372.9 (115.8)	−230.3 (61.1)	+0.7849 (0.0729)	------	−68.18 (16.27)	+439.1 (161.9)	------	−866.0 (350.5)	−478.6 (250.4)	*+6843 (6922)	+2958 (1757)	342.4
7A	(2)	STO3 (odd) = −437 s.d. = (3856)	------	------	+129.4 (41.1)	−313.3 (60.1)	−185.8 (71.9)	− 174.3 (55.7)	+573.3 (151.8)	−192.0 (73.0)	+0.7642 (0.0844)	------	−97.73 (20.38)	*+82.8 (207.6)	------	−848.5 (417.6)	−740.0 (452.1)	+14047 (7923)	+2553 (1965)	282.0
7B	(2)	STO3 (even) = −4714 s.d. = (4341)	------	------	+189.5 (49.6)	−304.3 (91.0)	−136.5 (103.8)	*−60.6 (72.0)	*+131.1 (190.7)	−338.2 (104.4)	+0.8112 (0.1221)	------	−60.08) (28.06)	+605.5 (264.6)	------	−1030.0 (594.7)	−429.4 (334.4)	*−8700 (12679)	+3924 (3352)	382.8
8	(1)	STO3 = −9216 s.d. = (2396)	------	------	+228.4 (28.0)	−267.1 (44.6)	−130.5 (55.0)	−97.7 (42.6)	+431.6 (110.2)	------	------	+1.594 (0.138)	−52.29 (16.16)	+601.9 (152.0)	------	------	------	------	------	341.8
9	(1)	STO3 = −7260 s.d. = (2456)	------	------	+202.5 +(28.7)	−284.2 (44.6)	− 73.9 (56.1)	−118.9 (41.9)	+399.1 (108.7)	------	------	+1.635 (0.135)	−52.67 (15.79)	+513.4 (153.3)	------ Al_2O_3/SO_3	−1025 (332)	−378.1 (242.4)	------	+2958 (1560)	331.2
10	(1)	STO3 = −7860 s.d. = (2525)	------	------	+196.6 (29.3)	−273.1 (45.9)	−201.4 (136.9)	−120.5 (42.0)	+776.1 (384.7)	------	------	+1.626 (0.135)	−51.60 (15.82)	+501.7 (153.7)	+248.9 (243.6)	−966 (337)	−363.9 (242.8)	------	+2931 (1560)	331.1

[1] 164 cements; Avg=2191; S.D.=695.3. [2] 82 cements. *Coef./s.d. ratio less than 1.



DEPENDENT VARIABLE COMPRESSIVE STRENGTH AGE	NOTE *	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TOTAL ALKALI	C_3A	C_3S	C_2S	C_4AF	A/F	S/(A+F)	AIR P. FINE	WAGN. FINE	AIR 1:4 MORT
1 YEAR ** (STIY)	(1)	8/4	12/0	10/2	10/2	10/2	6/6	10/2	10/2	10/2	10/2	8/4	6/6	8/4	10/2	10/2	10/2	12/0	10/2
	(3)	L	NL	L?	NL	L?	NO	L	L	L	L	NO	L?	L?	L	L	NL	NL	NL
	(4)	+14	−24	+18	+18	−10	−6	−17	−18	−16	−18	+4	+9	+12	−15	−18	+14	+24	−15
1 YEAR *** (STIM)	(1)	10/2	8/4	6/6	10/2	8/4	8/4	10/2	10/2	12/0	8/4	10/2	8/4	7/5	8/4	10/2	10/2	10/2	12/0
	(3)	L	L	NO	L	L	L?	L?	NL	L	L	NL	L?	L?	L?	L	NL	NL	NL
	(4)	+12	−12	+2	+15	−12	−3	−14	−17	−24	−11	+9	+1	+5	−7	+16	+14	+20	−24
1 YEAR **** (STIA)	(1)	10/2	8/4	8/4	8/4	7/5	8/4	6/6	8/4	8/4	6/6	8/4	10/2	6/6	6/6	8/4	8/4	10/2	10/2
	(3)	L	NO	L?	L?	L?	NL	NO	L?	L?	NO	L	L	NO	NO	L?	NL	NL	NL
	(4)	−12	0	−6	+8	+7	+9	−2	−5	−2	+5	+12	−12	−5	+8	−1	+12	+17	−13
5 YEARS ***** (ST5Y)	(1)	8/4	10/2	10/2	10/2	8/4	8/4	10/2	10/2	10/2	10/2	8/4	9/3	10/2	10/2	10/2	10/2	12/0	10/2
	(3)	NL	L	L?	L	L?	L?	NL	L	L	L	L?	L?	L?	L	NL	NL	NL	NL
	(4)	+13	−17	+12	+19	−11	−12	−10	−20	−15	−19	+1	+8	+17	−18	+15	+12	+24	−18

FIGURE 7–3. *Results of plotting compressive strength values at 1 year after water storage, moist air storage, air storage, and at 5 years after water storage of 1:2.75 (cement to graded Ottawa sand) mortars on the "Y" axis versus various independent variables on the "X" axis.*

*Note (1) Ratio of number of plotted points in pairs of diametrically opposite quadrants.
Note (2) General trend of lines drawn through plotted points.
Note (3) Apparent nature of relationship. L=linear; NL=nonlinear; NO=no apparent relationship; and L?=nature of relationship not determinable.
Note (4) Quadrant sum in corner test. (See reference [8].)
**Stored in moist air for 24 hr, then in water for 1 year.
***Stored in moist air (95–100% RH) for 1 year.
****Stored in moist air for 24 hr, then in water for 6 days, then in laboratory air 23 °C, 50 percent RH for 49 weeks, then in water for 2 weeks.
*****Stored in moist air for 24 hr, then in water for 5 years.

TABLE 7–8. *Calculated contribution of independent variables to 3-day compressive strength in psi of 1:2.75 (cement to graded Ottawa sand) mortar cubes, water-stored, and the calculated ranges of such contributions*

Independent variable	Range of variable (percent)	Coefficients from eq 2 of table 7–6	Calculated contribution to STO3	Calculated range of contribution to STO3
			Const. = −3048	
C_3S	20 to 65	+38.5	+770 to +2502	1732
C_3A	1 to 15	+43.1	+43 to +646	603
SO_3	1.2 to 3.0	+448	+538 to +1344	806
Loss	0.3 to 3.3	−247	−74 to −815	741
APF	*2500 to 5500	+0.789	+1972 to +4340	2368
Air, 1:4 mortar	1 to 21	−47.5	−48 to −998	950
K_2O	0 to 1.1	+310	0 to +341	341
SrO	0 to 0.4	−855	0 to −382	382
Mn	0 to 1.0	−533	0 to −533	533
Cr**	0 to 0.02	+6580	0 to +132	132
V**	0 to 0.1	+3140	0 to +314	314

*cm^2/g.
**Doubtful significance. Coef/s.d. ratio less than 2.

the normally determined variables which were found to be associated with the strength values. The use of Insol, Rb, Sr, Co, and Mn in eq 4 resulted in a significant reduction in the S.D. value (see table 7–75). Comparing eqs 2 and 3, where the turbidimeter fineness values were used, the use of the trace elements also resulted in a significant reduction in the S.D. value, but in comparing eqs 6 and 7, the reduction was significant only at the five percent probability level (see table 7–75). Equations computed for the "odds" and "evens" in the array of cements, eqs 3A, 3B, 7A, and 7B, indicated that there were instances where the Fe_2O_3, Insol, Co, and Mn had coef./s.d. ratios less than 1. The use of the turbidimeter fineness values resulted in lower S.D. values than when the air-permeability fineness values were used as may be noted in comparing eqs 3 and 4, or 7 and 8.

TABLE 7–9. *Frequency distribution of cements with respect to 7-day compressive strength of 1:2.75 (cement to graded Ottawa sand) mortar cubes, water-stored*

Type cement	Compressive strength, psi×10⁻³													Total
	1.5 to 2.0	2.0 to 2.5	2.5 to 3.0	3.0 to 3.5	3.5 to 4.0	4.0 to 4.5	4.5 to 5.0	5.0 to 5.5	5.5 to 6.0	6.0 to 6.5	6.5 to 7.0	7.0 to 7.5	7.5 to 8.0	
	Number of cements													
I	--	3	17	26	25	8	3	--	--	--	--	--	--	82
IA	1	4	3	--	--	--	--	--	--	--	--	--	--	8
II	3	6	34	22	2	1	--	--	--	--	--	--	--	68
IIA	--	1	--	2	--	--	--	--	--	--	--	--	--	3
III	--	--	--	--	1	4	3	4	4	3	--	--	1	20
IIIA	--	--	--	--	1	--	--	2	--	--	--	--	--	3
IV & V	2	5	7	1	--	--	--	--	--	--	--	--	--	15
Total	6	19	61	51	29	13	6	6	4	3	--	--	1	199

A similar series of equations are presented in table 7–19 for the NAE cements and the combinations of independent variables associated with the

TABLE 7–10. *Equations relating the 7-day compressive strengths in p.s.i. of AE+NAE cements to various independent variables*

Equation	Note	Const.	C_3S	C_3A	CaO	SiO_2	SO_3	Loss	APF	WAGN.	Air 1:4 mortar	K_2O	MgO	SrO	S.D.
1	(1)	ST07 = −2398	+51.26	+84.72					+0.8276		−57.91				459.4
		s.d. = (310)	(5.76)	(11.31)					(0.0727)		(9.45)				
2	(1)	ST07 = −4131	+56.16	+90.45			+378.1	−68.66		+1.911	−59.99	+592.8	−39.24		395.9
		s.d. = (336)	(5.06)	(11.57)			(110.7)	(60.01)		(0.158)	(8.57)	(166.8)	(27.97)		
3	(1)	ST07 = −2940	+54.95	+73.24			+312.2	−354.9	+0.9028		−63.85	+426.2	*−19.82	*−390.7	416.4
		s.d. = (307)	(5.39)	(12.85)			(122.6)	(66.6)	(0.0845)		(9.03)	(172.9)	(29.29)	(393.1)	
4	(1)	ST07 = −4109	+55.26	+100.0			+399.8	−85.3		+1.914	−58.65	+576.5	−38.76	−678.4	393.1
		s.d. = (331)	(5.04)	(12.6)			(110.6)	(60.3)		(0.157)	(8.54)	(165.9)	(27.78)	(370.6)	
4A	(2)	ST07 (odd) = −3660	+55.19	+107.1			+387.2	*−56.98		+1.640	−64.79	+348.2	*−9.31	*−336.6	371.8
		s.d. = (430)	(6.16)	(16.8)			(181.6)	(104.98)		(0.193)	(10.33)	(221.7)	(39.30)	(539.4)	
4B	(3)	ST07 (even) = −5057	+54.66	+102.5			+233.2	−96.21		+2.559	−42.25	+877.8	−72.68	−1054.1	402.4
		s.d. = (531)	(8.53)	(19.8)			(149.6)	(80.07)		(0.271)	(14.41)	(249.4)	(41.24)	(567.8)	
5	(1)	ST07 = −23551			+440.1	−266.1	+435.8	+110.7		+1.813	−56.85	+777.2	+142.4		396.4
		s.d. = (3009)			(41.0)	(32.7)	(118.6)	(63.6)		(0.150)	(8.62)	(174.1)	(40.1)		
6	(1)	ST07 = −23010			+435.7	−275.3	+439.8	+98.0		+1.807	−56.09	+765.0	+138.4	*−257.9	397.0
		s.d. = (3111)			(41.5)	(35.3)	(119.0)	(66.2)		(0.151)	(8.70)	(175.2)	(40.5)	(367.7)	

[1] 175 cements; Avg=3253; S.D.=862.9. [2] 88 cements. [3] 87 cements. *Coef./s.d. ratio less than 1.

TABLE 7–11. *Equations relating the 7-day compressive strengths in p.s.i. of NAE cements to various independent variables*

Equation	Note	Const.	C_3S	C_3A	CaO	SiO_2	SO_3	Loss	APF	WAGN.	Air 1:4 mortar	K_2O	MgO	SrO	S.D.
1	(1)	ST07 = −2317	+50.54	+83.87					+0.8179		−58.48				467.5
		s.d. = (344)	(5.99)	(11.80)					(0.0766)		(20.49)				
2	(1)	ST07 = −4133	+56.49	+87.94			+372.8	−69.0		+1.898	−54.87	+631.0	−44.71		406.1
		s.d. = (371)	(5.34)	(12.28)			(116.9)	(63.5)		(0.169)	(18.91)	(176.4)	(29.36)		
3	(1)	ST07 = −2813	+55.21	+70.23			+313.0	−361.6	+0.8927		−75.50	+524.3	*−26.08	−558.4	419.9
		s.d. = (331)	(5.58)	(13.18)			(126.3)	(68.9)	(0.0872)		(19.46)	(180.7)	(30.22)	(412.0)	
4	(1)	ST07 = −4098	+55.64	+98.05			+393.4	−91.1		+1.897	−52.67	+620.9	−43.22	−788.8	402.2
		s.d. = (368)	(5.31)	(13.17)			(116.2)	(63.8)		(0.168)	(18.76)	(174.8)	(29.08)	(394.1)	
4A	(2)	ST07 (odd) = −3334	+53.26	+105.80			+205.7	−142.5		+1.722	−56.44	+581.9	*−37.47	*−290.2	402.9
		s.d. = (503)	(6.84)	(19.21)			(193.5)	(100.4)		(0.226)	(27.15)	(244.5)	(41.66)	(574.9)	
4B	(3)	ST07 (even) = −4975	+58.82	+101.13			+460.9	*−37.9		+2.202	−52.62	+549.7	*−27.75	−1369.7	396.0
		s.d. = (569)	(8.81)	(19.30)			(151.4)	(87.5)		(0.259)	(25.98)	(265.2)	(43.51)	(581.1)	
5	(1)	ST07 = −23496			+438.3	−264.8	+419.4	+106.5		+1.820	−49.27	+810.9	+135.3		405.7
		s.d. = (3141)			(42.6)	(34.3)	(124.1)	(66.7)		(0.161)	(18.94)	(182.8)	(42.2)		
6	(1)	ST07 = −22724			+432.5	−278.7	+425.0	+85.3		+1.808	−47.92	+798.7	+130.0	−422.3	405.5
		s.d. = (3220)			(42.9)	(36.6)	(124.1)	(69.5)		(0.161)	(18.97)	(183.1)	(42.5)	(391.8)	

[1] 163 cements; Avg=3289; S.D.=844.8. [2] 82 cements. [3] 81 cements. *Coef./s.d. ratio less than 1.

Table 7–12. *Calculated contribution of independent variables to 7-day compressive strength in psi of 1:2.75 (cement to graded Ottawa sand) mortar cubes, water-stored, and the calculated ranges of such contributions*

Independent variable	Range of variable (percent)	Coefficients from eq 3 of table 7-10	Calculated contribution to STO7	Calculated range of contribution to STO7
			Const. = −2940	
C_3S	20 to 65	+55.0	+110 to +3575	3465
C_3A	1 to 15	+73.2	+73 to +1098	1025
SO_3	1.2 to 3.0	+312	+374 to +936	562
Loss	0.3 to 3.3	−355	−106 to −1172	1066
APF	*2500 to 5500	+0.903	+2258 to +4966	2708
Air, 1:4 mortar	1 to 21	−63.9	−64 to −1342	1278
K_2O	0 to 1.1	+426	0 to +469	469
MgO**	0 to 5	−19.8	0 to −99	99
SrO**	0 to 0.4	−391	0 to −156	156

*cm²/g.
**Coefficient less than s.d. for AE+NAE cements, but greater for NAE cements alone (see table 7-11).

Table 7–13. *Frequency distribution of cements with respect to 28-day compressive strength of 1:2.75 (cement to graded Ottawa sand) mortar cubes, water-stored*

Type cement	Compressive strength, p.s.i.×10⁻³: 2.0 to 2.5	2.5 to 3.0	3.0 to 3.5	3.5 to 4.0	4.0 to 4.5	4.5 to 5.0	5.0 to 5.5	5.5 to 6.0	6.0 to 6.5	6.5 to 7.0	7.0 to 7.5	7.5 to 8.0	Total
	Number of cements												
I	---	---	3	---	10	28	14	17	9	1	---	---	82
IA	1	---	3	1	2	1	---	---	---	---	---	---	8
II	---	---	---	3	14	22	18	10	1	---	---	---	68
IIA	---	---	---	1	1	---	1	---	---	---	---	---	3
III	---	---	---	---	---	1	1	4	3	5	2	4	20
IIIA	---	---	---	---	---	---	1	2	---	---	---	---	3
IV & V	---	---	1	2	6	5	---	---	1	---	---	---	15
Total	1	---	7	7	33	57	35	33	14	6	2	4	199

1 year compressive strengths of water-stored specimens. The results obtained with the NAE cements alone were similar to those presented in the previous table where computations for AE+NAE cements were reported.

The contributions of the variables to the 1-year compressive strength of water-stored specimens were calculated from the coefficients of eq 4, table 7–18, and are presented in table 7–20 together with the calculated ranges of such contributions. Increases in fineness, and Zr appeared associated with higher compressive strength values, and increases in C_3A, Na_2O, Insol, air content, Rb, Co, and Mn appeared associated with lower compressive strengths, though evidence for a significant relationship is doubtful with Insol, Co, and Mn.

5.7. Compressive Strength at 1 Year After Moist-Air Storage

The frequency distributions of the strength values after 1 year moist-air storage for the different types of cement are presented in table 7–21. A broad range of values was obtained and there was a great deal of overlapping of the values obtained with the different types of cement.

Table 7–14. *Equations relating the 28-day compressive strengths in psi of AE+NAE cements to various independent variables*

Equation	Note		Const.	C_3S	C_3A	C_4AF	CaO	SiO_2	Loss	APF	WAGN.	Air 1:4 mortar	SrO	Cr	Co	Zr	Ti	S.D.
1	(1)	ST28	=+1075	+42.08	+53.03	*+23.60				+0.5729		−95.61						631.8
		s.d.	= (613)	(8.14)	(18.33)	(26.42)				(0.1000)		(13.07)						
2	(1)	ST28	= −652	+43.07	+93.37	+39.43			−159.9		+1.785	−86.02						570.6
		s.d.	= (617)	(7.27)	(17.37)	(23.94)			(81.5)		(0.203)	(11.81)						
3	(1)	ST28	= −324	+44.98	+101.19	+46.49			−208.3		+1.702	−85.64	−1039	−26720	−45308			554.0
		s.d.	= (617)	(7.13)	(19.43)	(23.75)			(80.7)		(0.201)	(11.63)	(529)	(9810)	(31980)			
3A	(2)	ST28 (odd)	= −450	+45.72	+122.88	+79.63			−182.4		+1.445	−88.45	−1006	−22593	−48677			514.3
		s.d.	= (822)	(8.77)	(27.15)	(30.44)			(128.1)		(0.253)	(13.81)	(734)	(13480)	(35722)			
3B	(3)	ST28 (even)	= −650	+50.08	+79.17	−45.93			−298.0		+2.256	−81.58	−1266	−43292	−67765			586.3
		s.d.	= (946)	(11.87)	(28.34)	(38.80)			(115.5)		(0.331)	(20.14)	(816)	(15043)	(65805)			
4	(1)	ST28	= +923	+45.96	+70.50	+34.98			−456.2	+0.7257		−90.17	−952	−24438	−61820	+1720		586.4
		s.d.	= (596)	(7.64)	(20.07)	(25.15)			(95.1)	(0.1055)		(12.38)	(573)	(10450)	(33660)	(1138)		
5	(1)	ST28	=−3755				+200.9	−293.6	−144.1		+1.749	−83.72						570.3
		s.d.	= (2475)				(39.0)	(36.3)	(84.2)		(0.189)	(11.87)						
6	(1)	ST28	=−3727				+216.1	−307.1	−205.3		+1.641	−83.78	−1026	−25978	−50082		−425.8	551.9
		s.d.	= (2505)				(38.4)	(39.1)	(85.3)		(0.185)	(11.58)	(509)	(10065)	(31560)		(369.2)	
6A	(2)	ST28 (odd)	=+1053				+175.6	−383.5	−263.5		+1.405	−91.50	−1379	−18416	−55891		*−422.2	506.8
		s.d.	= (3342)				(50.1)	(57.8)	(136.9)		(0.237)	(13.60)	(740)	(13576)	(35060)		(516.5)	
6B	(3)	ST28 (even)	=−10312				+284.8	−248.3	−235.2		+2.258	−73.87	−943	−47455	−93304		−758.1	581.3
		s.d.	= (3902)				(60.2)	(55.7)	(119.1)		(0.308)	(19.94)	(754)	(15443)	(64657)		(549.3)	
7	(1)	ST28	=−2972				+202.8	−265.0	−448.8	+0.7304		−88.58	−1175	−22562	−63023	+2061	−511.6	585.9
		s.d.	= (2707)				(41.5)	(42.9)	(102.3)	(0.1015)		(12.33)	(558)	(10762)	(33432)	(1171)	(399.0)	

[1] 175 cements; Avg=5037; S.D.=868.2. [2] 88 cements. [3] 87 cements. *Coef./s.d. ratio less than 1.

Table 7–15. *Equations relating the 28-day compressive strengths in psi of NAE cements to various independent variables*

Equation	Note		Const.	C_3S	C_3A	C_4AF	CaO	SiO_2	Loss	APF	WAGN.	Air 1:4 mortar	SrO	Cr	Co	Zr	Ti	S.D.
1	(1)	ST28	=+1199	+41.47	+58.07	+30.33	---	---	---	+0.5645	---	−120.5	---	---	---	---	---	641.1
		s.d.	= (664)	(8.47)	(19.09)	(27.40)	---	---	---	(0.1050)	---	(28.2)	---	---	---	---	---	
2	(1)	ST28	= −711	+43.42	+97.21	+47.23	---	---	−159.0	---	+1.757	−88.42	---	---	---	---	---	583.9
		s.d.	= (685)	(7.65)	(18.23)	(25.04)	---	---	(86.1)	---	(0.217)	(25.76)	---	---	---	---	---	
3	(1)	ST28	= −344	+45.07	+103.47	+52.20	---	---	−208.6	---	+1.666	−84.84	−1111	−24739	−51345	---	---	568.9
		s.d.	= (686)	(7.51)	(20.19)	(24.88)	---	---	(85.9)	---	(0.215)	(25.29)	(568)	(10287)	(34192)	---	---	
3A	(2)	ST28 (odd)	= +688	+44.20	+90.74	+82.27	---	---	−245.1	---	+1.191	−105.4	*−225	−47357	−77021	---	---	512.2
		s.d.	= (919)	(8.74)	(27.63)	(33.32)	---	---	(121.1)	---	(0.268)	(33.8)	(733)	(14184)	(37697)	---	---	
3B	(3)	ST28 (even)	=−1528	+51.99	+105.26	+58.78	---	---	−198.9	---	+2.329	−77.9	−1901	−20849	*+43370	---	---	582.3
		s.d.	= (1017)	(12.82)	(28.14)	(36.79)	---	---	(122.0)	---	(0.342)	(36.3)	(843)	(14582)	(66298)	---	---	
4	(1)	ST28	=+1010	+45.51	+74.08	+41.95	---	---	−460.1	+0.7079	---	−101.5	−1131	−21990	−71667	+1717	---	596.2
		s.d.	= (649)	(7.95)	(20.68)	(26.10)	---	---	(99.7)	(0.1096)	---	(26.8)	(613)	(10850)	(35562)	(1174)	---	
5	(1)	ST28	=−3386	---	---	---	+199.5	−302.3	−149.8	---	+1.718	−87.32	---	---	---	---	---	581.6
		s.d.	= (2579)	---	---	---	(40.2)	(37.9)	(88.1)	---	(0.201)	(25.86)	---	---	---	---	---	
6	(1)	ST28	=−3328	---	---	---	+213.1	−312.5	−211.1	---	+1.609	−87.83	−1074	−23192	−53824	---	−475	564.8
		s.d.	= (2631)	---	---	---	(39.8)	(40.9)	(90.1)	---	(0.198)	(25.43)	(552)	(10576)	(33680)	---	(393)	
6A	(2)	ST28 (odd)	= +99	---	---	---	+167.4	−292.5	−261.8	---	+1.219	−108.3	*−482	−45121	−76593	---	*+134	513.9
		s.d.	= (3190)	---	---	---	(49.0)	(53.1)	(129.6)	---	(0.246)	(33.7)	(722)	(14421)	(37513)	---	(546)	
6B	(3)	ST28 (even)	=−9203	---	---	---	+290.5	−320.9	−147.5	---	+2.203	−82.1	−1726	−17835	*+9936	---	−1147	575.9
		s.d.	= (4317)	---	---	---	(64.6)	(59.2)	(121.5)	---	(0.320)	(36.3)	(806)	(15181)	(63385)	---	(554)	
7	(1)	ST28	=−2092	---	---	---	+194.7	−272.2	−462.9	+0.7109	---	−104.1	−1322	−19046	−71211	+2107	−574	593.7
		s.d.	= (2811)	---	---	---	(42.5)	(44.4)	(106.7)	(0.1058)	---	(26.9)	(600)	(11197)	(35262)	(1200)	(419)	

[1] 163 cements; Avg=5160; S.D.=823.9. [2] 82 cements. [3] 81 cements. *Coef./s.d. ratio less than 1.

Table 7–16. *Calculated contribution of independent variables to 28-day compressive strength in psi of 1:2.75 (cement to graded Ottawa sand) mortar cubes, water-stored, and the calculated ranges of such contributions*

Independent variable	Range of variable (percent)	Coefficients from eq 4 of table 7–14	Calculated contribution to ST28	Calculated range of contribution to ST28
			Const. =+923	
C_3S	20 to 65	+46.0	+920 to +2990	2070
C_3A	1 to 15	+70.5	+70 to +1058	988
C_4AF**	1 to 16	+35.0	+35 to +560	525
Loss	0.3 to 3.3	−456	−137 to −1505	1368
APF	*2500 to 5500	+0.726	+1815 to +3993	2178
Air, 1:4 mortar	1 to 21	−90.2	−90 to −1894	1804
SrO**	0 to 0.4	−952	0 to −381	381
Cr	0 to 0.02	−24400	0 to −488	488
Co**	0 to 0.01	−61800	0 to −618	618
Zr**	0 to 0.5	+1720	0 to +860	860

*cm^2/g.
**Doubtful significance. Coef/s.d. ratio less than 2.

Table 7–17. *Frequency distribution of cements with respect to 1-year, water-stored, compressive strength of 1:2.75 (cement to graded Ottawa sand) mortar cubes*

Type Cement	Compressive strength, psi×10^{-3}: 3.0 to 3.5	3.5 to 4.0	4.0 to 4.5	4.5 to 5.0	5.0 to 5.5	5.5 to 6.0	6.0 to 6.5	6.5 to 7.0	7.0 to 7.5	7.5 to 8.0	8.0 to 8.5	Total
	Number of cements											
I	---	---	1	9	12	20	22	12	4	1	---	81
IA	1	2	2	---	2	1	---	---	---	---	---	8
II	---	---	---	1	---	11	26	14	8	7	1	68
IIA	---	---	---	1	---	2	---	---	---	---	---	3
III	---	---	---	---	1	---	3	6	7	1	2	20
IIIA	---	---	---	---	1	---	---	2	---	---	---	3
IV & V	---	---	---	---	1	1	4	3	6	---	---	15
Total	1	2	3	11	17	35	55	37	25	9	3	198

The results of plotting the 1-year compressive strength values versus the different individual independent variables are presented in figure 7–3. The variables having quadrant-sum absolute values greater than 11 were, except for the Fe_2O_3, C_4AF, and the A/F ratio, the same as was obtained when plotting the results of the 1-year water-stored specimens.

Equations relating the 1-year compressive-strength values of the moist-air stored specimens to combinations of the various independent variables are presented in table 7–22 for the AE+NAE cements, and in table 7–23 for the NAE cements. Equation 1 of table 7–22 indicates the relationship to commonly determined variables all of which were found to be significant except SO_3, and eq 2 indicates the relationship with the addition of the trace elements which were found to be promising. The S.D. value obtained in eq 2 was significantly lower than in eq 1. This decrease was also found in comparing eqs 4 and 5 where the major oxides were used as independent variables in the computations. It may be noted in eq 1 that C_3A was the only one of the 4 major potential compounds which met the requirement that the coef./s.d. ratio be greater than 1 when associated with the other independent variables used in this equation. The SO_3 did not meet this

Table 7–18. *Equations relating the 1-year (water-stored) compressive strengths in psi of AE+NAE cements to various independent variables*

Equation	Note		Const.	C_3A	Al_2O_3	Fe_2O_3	Na_2O	Insol.	APF	WAGN.	Air 1:4 mortar	Rb	Zr	Co	Mn	S.D.
1	(1)	ST1Y	=+6518	−103.4			−687.7		+0.4345		−100.2					575.0
		s.d.	= (324)	(13.9)			(270.2)		(0.0829)		(12.0)					
2	(1)	ST1Y	=+5603	−81.4			−735.8			+1.193	−94.6					551.5
		s.d.	= (389)	(13.7)			(257.6)			(0.178)	(11.5)					
3	(1)	ST1Y	=+5937	−66.9			−939.3	−569.3		+1.073	−92.2	−51046	+2002	−45465	−547	535.0
		s.d.	= (399)	(14.6)			(259.3)	(317.4)		(0.179)	(11.3)	(22253)	(1010)	(30116)	(340)	
3A	(2)	ST1Y(odd)	=+5607	−44.4			−1070.6	−715.3		+1.279	−97.2	−44837	+1564	−61432	−1674	514.5
		s.d.	= (577)	(19.7)			(329.2)	(417.1)		(0.259)	(17.7)	(28535)	(1058)	(49152)	(732)	
3B	(3)	ST1Y (even)	=+6171	−87.8			−827.1	*−293.4		+0.940	−93.1	−73682	+5176	*−25983	*−163	555.5
		s.d.	= (560)	(22.4)			(417.7)	(520.3)		(0.251)	(15.7)	(36160)	(2770)	(39456)	(405)	
4	(1)	ST1Y	=+6714	−83.8			−917.9	−647.3	+0.4091		−97.3	−61703	+2303	−53332	−671	549.5
		s.d.	= (324)	(14.7)			(267.0)	(326.6)	(0.0812)		(11.7)	(22621)	(1040)	(30816)	(348)	
5	(1)	ST1Y	=+6950		−286.5	+91.8	−731.1	−480.1	+0.4329		−99.6					572.4
		s.d.	= (470)		(46.3)	(60.5)	(272.7)	(337.6)	(0.0833)		(12.1)					
6	(1)	ST1Y	=+5908		−219.1	+81.8	−782.2	−436.9		+1.181	−93.6					550.8
		s.d.	= (530)		(46.4)	(58.0)	(261.3)	(324.0)		(0.181)	(11.7)					
7	(1)	ST1Y	=+5953		−178.2	+109.9	−938.9	−571.3		+1.073	−92.3	−50885	+2003	−45336	−545	536.8
		s.d.	= (523)		(47.5)	(57.5)	(261.3)	(319.4)		(0.181)	(11.4)	(22575)	(1015)	(30373)	(346)	
7A	(2)	ST1Y (odd)	=+5809		−135.7	* +39.4	−1048.2	−709.3		+1.279	−98.1	−41301	+1535	−53418	−1660	517.2
		s.d.	= (717)		(65.3)	(79.6)	(334.6)	(419.6)		(0.261)	(17.9)	(29635)	(1066)	(52116)	(737)	
7B	(3)	ST1Y (even)	=+5979		−218.1	+175.3	−834.1	*−313.6		+0.958	−92.3	−74271	+5266	*−25433	*−197	558.8
		s.d.	= (792)		(72.7)	(88.5)	(420.7)	(525.5)		(0.257)	(16.0)	(36409)	(2794)	(39734)	(419)	
8	(1)	ST1Y	=+6811		−229.7	+125.2	−911.7	−642.6	+0.4071		−97.6	−60646	+2290	−52418	−654	551.3
		s.d.	= (460)		(47.6)	(59.3)	(269.0)	(328.7)	(0.0818)		(11.8)	(22991)	(1045)	(31099)	(356)	

[1] 177 cements; Avg=6202; S.D.=844.0. [2] 89 cements. [3] 88 cements. *Coef./s.d. ratio less than 1.

TABLE 7–19. *Equations relating the 1-year (water-stored) compressive strengths in psi of NAE cements to various independent variables*

Equation	Note		Const.	C_3A	Al_2O_3	Fe_2O_3	Na_2O	Insol.	APF	WAGN.	Air 1:4 mortar	Rb	Zr	Co	Mn	S.D.
1	(1)	ST1Y	=+6660	−102.5			−568.5		+0.4089		−112.7					577.6
		s.d.	= (359)	(14.2)			(283.8)		(0.0872)		(26.5)					
2	(1)	ST1Y	=+5668	−81.5			−662.6			+1.137	−91.4					556.3
		s.d.	= (441)	(14.2)			(270.7)			(0.189)	(25.4)					
3	(1)	ST1Y	=+5981	−67.3			−912.8	−579.7		+0.989	−77.4	−55188	+2059	−47925	−461	539.6
		s.d.	= (451)	(15.1)			(275.0)	(350.9)		(0.190)	(25.3)	(22886)	(1037)	(31591)	(358)	
3A	(2)	ST1Y (odd)	=+6014	−41.2			−1030.6	−1013.7		+1.110	−108.1	−37290	+2106	−124006	−1706	521.1
		s.d.	= (657)	(21.5)			(362.6)	(481.2)		(0.283)	(38.9)	(32605)	(1041)	(50939)	(642)	
3B	(3)	ST1Y (even)	=+6105	−100.6			−1064.7	*−63.2		+0.941	−53.8	−83089	*−7107	*+10048	*−58	527.0
		s.d.	= (626)	(20.7)			(420.7)	(507.7)		(0.247)	(33.7)	(33241)	(8546)	(39945)	(419)	
4	(1)	ST1Y	=+6820	−82.7			−858.2	−713.0	+0.3694		−95.0	−62975	+2216	−58458	−576	552.
		s.d.	= (359)	(15.2)			(283.2)	(358.9)	(0.0857)		(26.1)	(23255)	(1063)	(32120)	(366)	
5	(1)	ST1Y	=+7038		−274.4	+106.1	−623.6	−559.0	+0.4062		−115.8					575.7
		s.d.	= (505)		(47.7)	(61.9)	(286.5)	(369.9)	(0.0875)		(26.5)					
6	(1)	ST1Y	=+5919		−212.7	+99.5	−711.2	−444.7		+1.118	−93.5					556.9
		s.d.	= (586)		(47.9)	(59.7)	(274.9)	(357.4)		(0.192)	(25.6)					
7	(1)	ST1Y	=+5880		−170.1	+127.9	−919.9	−587.7		+0.997	−76.6	−56195	+2081	−48592	−480	541.4
		s.d.	= (580)		(49.3)	(58.9)	(277.0)	(352.6)		(0.193)	(25.6)	(23267)	(1043)	(31794)	(364)	
7A	(1)	ST1Y (odd)	=+6233		−125.9	*+32.6	−1029.6	−999.4		+1.105	−110.3	−35108	+2080	−118155	−1669	524.2
		s.d.	= (835)		(69.8)	(92.6)	(364.8)	(485.5)		(0.285)	(39.5)	(33225)	(1049)	(53007)	(652)	
7B	(3)	ST1Y (even)	=+5499		−220.6	+248.8	−1179.8	*−53.7		+9.998	−48.3	−90932	*−6367	*+14319	*−45	526.4
		s.d.	= (810)		(67.2)	(76.6)	(431.7)	(507.1)		(0.251)	(33.7)	(33910)	(8554)	(40069)	(428)	
8	(1)	ST1Y	=+6818		−218.5	+139.4	−858.7	−716.0	+0.3697		−95.1	−62994	+2221	−58516	−578	554.6
		s.d.	= (497)		(49.3)	(60.5)	(285.4)	(361.0)	(0.0863)		(26.4)	(23698)	(1069)	(32367)	(374)	

[1] 165 cements; Avg=6295; S.D.=752.7. [2] 83 cements. [3] 82 cements. *Coef/s.d. ratio less than 1.

TABLE 7–20. *Calculated contribution of independent variables to 1-year compressive strength in psi of 1:2.75 (cement to graded Ottawa sand) mortar cubes, water-stored, and the calculated ranges of such contributions*

Independent variable	Range of variable (percent)	Coefficients from eq 4 of table 7–18	Calculated contribution to ST1Y	Calculated range of contribution to ST1Y
			Const. = +6714	
C_3A	1 to 15	−83.8	−84 to −1257	1173
Na_2O	0 to 0.7	−918	0 to −643	643
Insol**	0 to 1.0	−647	0 to −647	647
APF	*2500 to 5500	+0.409	+1022 to +2250	1228
Air, 1:4 mortar	1 to 21	−97.3	−97 to −2043	1946
Rb	0 to 0.01	−61700	0 to −617	617
Zr	0 to 0.5	+2300	0 to +1150	1150
Co**	0 to 0.01	−53300	0 to −533	533
Mn**	0 to 1.0	−671	0 to −671	671

*Cm^2/g.
**Doubtful significance. Coef/s.d. ratio less than 2.

TABLE 7–21. *Frequency distribution of cements with respect to 1-year, moist-air-stored, compressive strength of 1:2.75 (cement to graded Ottawa sand) mortar cubes*

Type Cement	Compressive strength, psi×10⁻³												Total
	3.0 to 3.5	3.5 to 4.0	4.0 to 4.5	4.5 to 5.0	5.0 to 5.5	5.5 to 6.0	6.0 to 6.5	6.5 to 7.0	7.0 to 7.5	7.5 to 8.0	8.0 to 8.5	8.5 to 9.0	
	Number of cements												
I	---	---	1	1	8	18	19	18	12	4	1	---	82
IA	1	---	1	2	2	2	---	---	---	---	---	---	8
II	---	---	---	---	---	8	16	20	10	9	4	1	68
IIA	---	---	---	---	1	1	---	1	---	---	---	---	3
III	---	---	---	---	---	1	---	1	5	7	3	3	20
IIIA	---	---	---	---	---	---	1	2	---	---	---	---	3
IV & V	---	---	---	---	---	2	3	3	6	1	---	---	15
Total	1	---	2	3	11	32	39	45	33	21	8	4	199

requirement with the variables in eq 1 but did with those in eqs 2, 3, 4, 5, and 6. The coef./s.d. ratio for Na_2O was greater than 1 in eqs 1 and 2, (but not in eq 2B) and was less than 1 when Na_2O was used with the variables in eqs 3 through 6. Equations for the "odds" and "evens," 2A, 2B, 5A, and 5B, indicated other instances where the coef./s.d. ratios were less than 1. These variables were C_3A, Al_2O_3, SO_3, V, Co, and Cu. Comparing eqs 2 and 3, or 5 and 6, it may be noted that the S.D. values in equations calculated using the Wagner fineness values were lower than when the air-permeability fineness values were used, although differences in other variables used in the two pairs of equations make the evidence for the difference doubtful. Considering the group of equations as a whole, the evidence for a significant effect due to SO_3, V, Co, or Cu is rather small.

The coefficients of the different variables associated with the 1-year strengths of the NAE cements alone, (table 7–23), were generally consistent with those presented in table 7–22 for the AE+NAE cements.

The contributions of the various independent variables to the 1-year compressive strength of the moist-air-stored specimens were calculated from eq 3 of table 7–22 and are presented in table 7–24 together with the ranges of these con-

TABLE 7–22. *Equations relating the 1-year (moist-air-stored) compressive strengths in psi of AE+NAE cements to various independent variables*

Equation	Note		Const	C_3A	CaO	Al_2O_3	Fe_2O_3	Na_2O	SO_3	MgO	APF	WAGN.	Air 1:4 mortar	Rb	Mn	P	V	Co	Cu	SrO	S.D.
1	(1)	ST1M	=+4937	−37.15	-------	-------	-------	−691.3	*+141.8	−108.9	-------	+1.558	−93.14	-------	------	------	------	-------	-------	------	603.8
		s.d.	= (441)	(17.09)	-------	-------	-------	(283.3)	(156.7)	(39.9)	-------	(0.214)	(14.17)	-------	------	------	------	-------	-------	------	------
2	(1)	ST1M	=+5575	−42.69	-------	-------	-------	−456.2	+260.7	−116.5	-------	+1.297	−98.60	−91617	------	+939	−3999	-------	−8988	−1171	572.0
		s.d.	= (464)	(19.57)	-------	-------	-------	(285.1)	(151.2)	(39.2)	-------	(0.211)	(13.55)	(24477)	------	(425)	(2639)	-------	(5328)	(572)	------
2A	(2)	ST1M (odd)	=+6055	*−20.30	-------	-------	-------	−710.4	*+106.4	−117.3	-------	+1.024	−80.87	−64108	------	+772	*−2427	-------	−7972	−986	509.7
		s.d.	= (557)	(26.24)	-------	-------	-------	(425.2)	(214.5)	(52.5)	-------	(0.251)	(16.83)	(30646)	------	(616)	(3764)	-------	(7553)	(674)	------
2B	(2)	ST1M (even)	=+5180	−66.43	-------	-------	-------	*−397.4	+379.2	−108.9	-------	+1.586	−118.45	−129880	------	+1326	−6333	-------	−7824	−1477	623.2
		s.d.	= (797)	(31.10)	-------	-------	-------	(427.8)	(220.4)	(60.8)	-------	(0.365)	(21.92)	(40369)	------	(644)	(3972)	-------	(7615)	(971)	------
3	(1)	ST1M	=+6306	−56.36	-------	-------	-------	-------	+187.5	−79.3	+0.5455	-------	−109.4	−105598	−607	+904	------	−36031	−9605	−1323	591.7
		s.d.	= (364)	(18.01)	-------	-------	-------	-------	(169.3)	(40.9)	(0.1046)	-------	(13.8)	(25136)	(385)	(433)	------	(35372)	(5764)	(569)	------
4	(1)	ST1M	=−5599	-------	+157.0	−123.2	+147.1	-------	+321.7	-------	-------	+1.392	−98.26	-------	------	------	------	-------	-------	------	605.1
		s.d.	= (3090)	-------	(45.7)	(55.1)	(70.8)	-------	(163.4)	-------	-------	(0.225)	(14.09)	-------	------	------	------	-------	-------	------	------
5	(1)	ST1M	=−4558	-------	+146.3	−94.5	+194.4	-------	+392.0	-------	-------	+1.162	−99.15	−85843	------	+827	−3289	−42331	−7538	−1448	572.0
		s.d.	= (2985)	-------	(44.5)	(63.0)	(71.0)	-------	(156.7)	-------	-------	(0.223)	(13.58)	(24802)	------	(427)	(2653)	(34061)	(5591)	(555)	------
5A	(2)	ST1M (odd)	=−2884	-------	+134.8	−100.7	+106.1	-------	+345.9	-------	-------	+0.786	−83.86	−71028	------	+816	*−2047	*−37054	*−5641	−1209	521.7
		s.d.	= (3626)	-------	(54.2)	(85.2)	(91.1)	-------	(227.7)	-------	-------	(0.279)	(17.81)	(31065)	------	(631)	(3778)	(44526)	(8130)	(688)	------
5B	(2)	ST1M (even)	=−7209	-------	+169.9	*−84.4	+344.1	-------	+451.1	-------	-------	+1.544	−117.03	−119198	------	+1075	−4347	*−44698	−11138	−1801	611.4
		s.d.	= (4966)	-------	(73.8)	(95.6)	(115.7)	-------	(222.4)	-------	-------	(0.364)	(21.18)	(40205)	------	(636)	(3921)	(53328)	(8147)	(903)	------
6	(1)	ST1M	=−4469	-------	+155.5	−129.9	+219.9	-------	+283.1	-------	+0.5062	-------	−102.9	−94195	------	+810	------	−43431	−8838	−1173	584.5
		s.d.	= (3045)	-------	(44.7)	(56.5)	(71.9)	-------	(173.0)	-------	(0.1055)	-------	(13.8)	(25166)	------	(429)	------	(34884)	(5722)	(565)	------

[1] 174 cements; Avg=6629; S.D.=864. [2] 87 cements. *Coef./s.d. ratio less than 1.

TABLE 7–23. *Equations relating the 1-year (moist-air-stored) compressive strengths in psi of NAE cements to various independent variables*

Equation	Note		Const	C_3A	CaO	Al_2O_3	Fe_2O_3	Na_2O	SO_3	MgO	APF	WAGN.	Air 1:4 mortar	Rb	Mn	P	V	Co	Cu	SrO	S.D.
1	(1)	ST1M	=+5093	−40.77	-------	-------	-------	−607.6	+208.6	−115.4	-------	+1.468	−105.6	-------	-------	-------	-------	-------	-------	-------	616.8
		s.d.	= (497)	(17.84)	-------	-------	-------	(305.0)	(168.0)	(41.5)	-------	(0.230)	(30.1)	-------	-------	-------	-------	-------	-------	-------	-------
2	(1)	ST1M	=+5788	−47.52	-------	-------	-------	−381.7	+325.7	−118.9	-------	+1.162	−101.3	−91848	-------	+941	−4236	−38400	−7244	−1343	581.4
		s.d.	= (506)	(20.12)	-------	-------	-------	(307.1)	(162.3)	(41.0)	-------	(0.228)	(30.1)	(25287)	-------	(444)	(2708)	(36324)	(5899)	(613)	-------
2A	(2)	ST1M (odd)	=+5932	−32.76	-------	-------	-------	*−232.9	+260.4	−156.1	-------	+1.382	−165.1	−83749	-------	+1086	−3513	−137262	*−1770	−1252	537.8
		s.d.	= (710)	(26.28)	-------	-------	-------	(430.9)	(248.0)	(52.7)	-------	(0.360)	(48.7)	(34963)	-------	(592)	(3237)	(65486)	(9392)	(731)	-------
2B	(3)	ST1M (even)	=+5615	−60.98	-------	-------	-------	−649.3	+366.2	−69.7	-------	+1.005	−49.8	−107537	-------	+824	*−4655	*−13520	*−5803	−1461	622.9
		s.d.	= (766)	(31.95)	-------	-------	-------	(483.2)	(254.1)	(66.9)	-------	(0.320)	(41.8)	(38622)	-------	(722)	(4776)	(49347)	(8329)	(1091)	-------
3	(1)	ST1M	=+6502	−57.88	-------	-------	-------	-------	+270.5	−82.9	+0.5064	-------	−138.7	−99836	−500	+993	-------	−49673	−7188	−1462	594.6
		s.d.	= (392)	(18.28)	-------	-------	-------	-------	(175.6)	(42.0)	(0.1087)	-------	(28.7)	(25671)	(401)	(444)	-------	(37084)	(6012)	(595)	-------
4	(1)	ST1M	=−5833	-------	+163.5	−130.5	+168.3	-------	+409.4	-------	-------	+1.283	−122.9	-------	-------	-------	-------	-------	-------	-------	615.3
		s.d.	= (3232)	-------	(47.4)	(57.2)	(73.8)	-------	(172.3)	-------	-------	(0.240)	(28.6)	-------	-------	-------	-------	-------	-------	-------	-------
5	(1)	ST1M	=−4750	-------	+151.9	−104.0	+215.9	-------	+465.9	-------	-------	+1.040	−109.3	−85951	-------	+893	−3539	−52514	−6785	−1599	578.7
		s.d.	= (3124)	-------	(46.0)	(64.7)	(74.1)	-------	(165.3)	-------	-------	(0.236)	(28.7)	(25520)	-------	(441)	(2699)	(35989)	(5908)	(583)	-------
5A	(2)	ST1M (odd)	=−4563	-------	+158.2	−107.7	+113.6	-------	+471.5	-------	-------	+1.197	−185.4	−77705	-------	+1065	*−3194	−153106	*+1585	−1330	540.4
		s.d.	= (3896)	-------	(56.5)	(88.3)	(103.3)	-------	(234.4)	-------	-------	(0.357)	(46.0)	(35347)	-------	(592)	(3252)	(67315)	(9289)	(703)	-------
5B	(3)	ST1M (even)	=−4658	-------	+139.1	*−79.7	+313.2	-------	+433.6	-------	-------	+1.027	−56.5	−104195	-------	*+708	*−3161	*−14407	−13273	−1968	613.0
		s.d.	= (5285)	-------	(78.2)	(105.2)	(115.7)	-------	(266.6)	-------	-------	(0.338)	(38.9)	(38288)	-------	(713)	(4680)	(48405)	(9118)	(1051)	-------
6	(1)	ST1M	=−4209	-------	+153.5	−131.5	+230.4	-------	+363.6	-------	+0.4672	-------	−126.0	−90710	-------	+894	-------	−56108	−7013	−1376	586.4
		s.d.	= (3160)	-------	(46.0)	(57.4)	(74.4)	-------	(179.1)	-------	(0.1091)	-------	(28.8)	(25748)	-------	(440)	-------	(36429)	(5992)	(591)	-------

[1] 163 cements, Avg=6705; S.D.=811.6. [2] 82 cements. [3] 81 cements. *Coef./s.d. ratio less than 1.

tributions. Increases in fineness and P appear to be associated with higher compressive strength, and increases in C_3A, air content, Rb, and SrO associated with lower compressive strength of the moist-air-cured specimens. There is also a possibility that SO_3 and MgO are associated with higher compressive strength and Mn, Co, and Cu are associated with lower compressive strength.

5.8. Compressive Strength at 1 Year of Laboratory-Air-Stored Specimens

As mentioned in a previous subsection, these specimens were stored in water for 6 days after the first 24 hr in the damp-closet. They were then stored in laboratory air for 49 weeks, then in water for 2 weeks, and tested in compression in what was believed to be a saturated condition.

The frequency distributions of the compressive strength values obtained with the different types of cement are presented in table 7–25. The average compressive strength values were close to those obtained for the specimens stored in water for 28 days before testing. The relationship will be dealt with in subsection 5.20.

TABLE 7–24. *Calculated contribution of independent variables to 1-year compressive strength in psi of 1:2.75 (cement to graded Ottawa sand) mortar cubes, moist-air-stored and the calculated ranges of such contributions*

Independent variable	Range of variable (percent)	Coefficients from eq 3 of table 7–22	Calculated contribution to ST1M	Calculated range of contribution to ST1M
			Const. = +6306	
C_3A	1 to 15	−56.4	−56 to −846	790
SO_3**	1.2 to 3.0	+188	+226 to +564	338
MgO**	0 to 5.0	−79.3	0 to −396	396
APF	*2500 to 5500	+0.546	+1365 to +3003	1638
Air, 1:4 mortar	1 to 21	−109	−109 to −2289	2180
Rb	0 to 0.01	−106000	0 to −1060	1060
Mn**	0 to 1.0	−607	0 to −607	607
P	0 to 0.5	+904	0 to +452	452
Co**	0 to 0.01	−36000	0 to −360	360
Cu**	0 to 0.05	−9600	0 to −480	480
SrO	0 to 0.4	−1320	0 to −528	528

*cm^2/g.
**Doubtful significance. Coef./s.d. ratio less than 2.

TABLE 7–25. *Frequency distribution of cements with respect to 1-year, laboratory-air-stored, compressive strength of 1:2.75 (cement to graded Ottawa sand) mortar cubes*

Type cement	Compressive strength, psi×10^{-3}									Total
	3.0 to 3.5	3.5 to 4.0	4.0 to 4.5	4.5 to 5.0	5.0 to 5.5	5.5 to 6.0	6.0 to 6.5	6.5 to 7.0	7.0 to 7.5	
	Number of cements									
I	----	4	3	20	29	21	4	1	----	82
IA	1	1	1	4	1	----	----	----	----	8
II	----	----	6	20	25	11	5	----	1	68
IIA	----	----	1	----	----	2	----	----	----	3
III	----	----	----	1	----	1	8	8	2	20
IIIA	----	----	----	----	----	2	----	----	----	2
IV & V	----	3	1	3	7	----	1	----	----	15
Total	1	8	12	48	62	37	18	9	3	198

The results of plotting the 1-year compressive strength values of the air-stored specimens versus various individual independent variables are presented in figure 7–3. Only the SiO_2, C_3S, C_2S, fineness, and air content had "quadrant-sum" absolute values greater than 11. A number of differences from those obtained with the water or moist-air-stored specimens may be noted in the slopes or trends of some of the variables.

The relationship of the 1-year strength values of air-stored specimens made of AE+NAE cements to combinations of independent variables are presented in equations in table 7–26. Equations 1, 2 and 5 indicate the relationships obtained with commonly determined variables, all of which were significant except Insol. The other equations include trace elements which may have an effect. However, Ba was the only one which showed strong evidence of a significant effect. The reduction in variance resulting from the use of the added variables was, in every instance, highly significant (see table 7–75).

In equations calculated for the "odds" and "evens", 3A, 3B, 6A, and 6B, there were instances where the SiO_2, MgO, Insol, Cu, and Pb had coef./s.d. ratios less than one. Equations 4 and 7 calculated using the air-permeability fineness values had higher S.D. values than were obtained in comparable eqs 3 and 6 where the turbidimeter fineness values were used.

A comparable series of equations are presented in table 7–27 to indicate the relationships calculated for the NAE cements alone. The coefficients of the independent variables and the significance of these coefficients are fairly similar to those presented in the previous table for the AE+NAE cements.

The contributions of the independent variables to the compressive-strength values of the 1-year air-stored specimens were calculated from the coefficients of eq 4, table 7–26 and are presented in table 7–28 together with the calculated ranges of these contributions. Increases in C_3S, fineness, MgO, SO_3 and possibly Pb appear associated with higher compressive strength, and increases in air content and Ba with possibly Insol and Cu appear associated with lower compressive strength.

5.9. Compressive Strength at 5 Years of Water-Stored Specimens

The frequency distributions of the 5-year compressive-strength values of the cements of the different types are presented in table 7–29. It was previously noted in figure 7–1 that the average compressive strength at 1, 5, and 10 years of the type I cements was lower than the averages obtained with the other types. It is apparent, however, from table 7–29 that there was considerable overlapping of the values in the different types.

The results of plotting the 5-year compressive-strength values versus individual independent variables are presented in figure 7–3. Of the various independent variables for which plots

Table 7–26. *Equations relating the 1-year (lab.-air-stored) compressive strengths in p.s.i. of AE+NAE cements to various independent variables*

Equation	Note		Const.	C_3S	CaO	SiO_2	K_2O	SO_3	MgO	WAGN.	APF	Air 1:4 Mortar	Insol.	Cu	Ba	Pb	S.D.
1	(1)	ST1A	=+1104	+28.80				+577.4		+1.144		−56.18	*−174.9				481.5
		s.d.	= (361)	(5.65)				(112.8)		(0.164)		(10.21)	(268.3)				
2	(1)	ST1A	=+1589	+32.03				+433.9	+116.7		+0.4639	−67.68	−452.0				494.9
		s.d.	= (346)	(6.08)				(126.9)	(33.6)		(0.0877)	(10.61)	(277.4)				
3	(1)	ST1A	=+1142	+30.26				+530.7	+78.5	+1.153		−61.88	−362.5	−7573	−3791	+7821	447.2
		s.d.	= (365)	(5.42)				(106.2)	(31.5)	(0.153)		(9.65)	(256.9)	(4070)	(1037)	(5679)	
3A	(2)	ST1A (odd)	=+679	+31.20				+454.4	+181.9	+1.376		−72.43	*−156.9	*−3084	−4085	+6841	382.6
		s.d.	= (448)	(6.10)				(122.0)	(38.3)	(0.193)		(11.56)	(293.9)	(4726)	(1442)	(5237)	
3B	(3)	ST1A (even)	=+1661	+26.89				+567.0	*−21.4	+1.033		−51.61	−588.2	−15503	−4345	*+14494	486.5
		s.d.	= (577)	(9.86)				(178.6)	(51.4)	(0.233)		(15.17)	(440.8)	(7094)	(1540)	(21395)	
4	(1)	ST1A	=+1923	+30.44				+427.0	+86.7		+0.4537	−67.19	−521.2	−7322	−3485	+9388	479.2
		s.d.	= (359)	(5.98)				(124.7)	(33.8)		(0.0860)	(10.28)	(275.6)	(4369)	(1117)	(6088)	
5	(1)	ST1A	=−9077		+210.2	−108.9		+522.0	+192.3	+1.307		−61.01	−377.2				462.3
		s.d.	= (3165)		(44.3)	(36.0)		(135.7)	(44.7)	(0.163)		(9.99)	(264.4)				
6	(1)	ST1A	=−11041		+226.7	−73.2	+349.4	+542.9	+176.9	+1.350		−63.83	−402.5		−3421	+7116	446.7
		s.d.	= (3155)		(43.3)	(36.9)	(190.5)	(134.0)	(43.4)	(0.166)		(9.74)	(258.9)		(1062)	(5683)	
6A	(2)	ST1A (odd)	=−10623		+230.5	−115.2	+252.6	+403.2	+256.9	+1.590		−69.95	*−230.4		−3558	+7913	377.2
		s.d.	= (3906)		(53.6)	(42.7)	(224.2)	(150.5)	(49.2)	(0.200)		(11.55)	(289.2)		(1414)	(5215)	
6B	(3)	ST1A (even	=−10178		+194.9	*−7.86	+385.6	+716.5	+82.6	+1.127		−57.22	−493.8		−5029	*−3181	499.8
		s.d.	= (5077)		(71.7)	(63.55)	(328.5)	(234.9)	(76.0)	(0.277)		(15.67)	(462.1)		(1697)	(21020)	
7	(1)	ST1A	=−13867		+259.7	*−10.41	+254.9	+529.5	+221.9		+0.5491	−69.05	−522.5	−4842	−3414	+8422	472.7
		s.d.	= (3373)		(46.2)	(38.34)	(206.2)	(148.5)	(46.3)		(0.0855)	(10.28)	(276.4)	(4426)	(1126)	(6040)	

[1] 177 cements; Avg.=5237; S.D.=702.4 [2] 89 cements. [3] 88 cements. *Coef./s.d. ratio less than 1.

Table 7–27. *Equations relating the 1-year (lab-air-stored) compressive strengths in psi of NAE cements to various independent variables*

Equation	Note		Const.	C_3S	CaO	SiO_2	K_2O	SO_3	MgO	WAGN.	APF	Air 1:4 Mortar	Insol.	Cu	Ba	Pb	S.D.
1	(1)	ST1A	=+1208	+28.63				+628.7		+1.096		−69.94	*−219.7				488.1
		s.d.	= (412)	(5.82)				(118.9)		(0.175)		(22.35)	(296.9)				
2	(1)	ST1A	=+1855	+31.11				+503.6	+111.1		+0.4363	−98.52	−601.2				499.0
		s.d.	= (378)	(6.24)				(132.6)	(34.7)		(0.0911)	(22.68)	(304.2)				
3	(1)	ST1A	=+1250	+29.70				+572.1	+68.3	+1.106		−67.62	−414.5	−7159	−3888	+7802	455.3
		s.d.	= (403)	(5.64)				(113.7)	(33.0)	(0.164)		(21.70)	(285.7)	(4288)	(1065)	(5801)	
3A	(2)	ST1A (odd)	=+819	+35.63				+673.6	+125.1	+1.167		−115.64	*+33.5	−12082	−4022	+11034	426.8
		s.d.	= (562)	(6.95)				(144.8)	(41.6)	(0.246)		(31.92)	(373.1)	(5988)	(1637)	(6160)	
3B	(3)	ST1A (even)	=+1751	+25.12				+529.1	*+5.7	+0.972		−31.87	−79.19	*−5773	−4737	*+15844	472.0
		s.d.	= (599)	(9.72)				(185.5)	(53.3)	(0.230)		(31.43)	(441.3)	(6106)	(1489)	(17134)	
4	(1)	ST1A	=+2130	+29.54				+494.4	+80.3		+0.4251	−89.63	−654.6	−6226	−3538	+9263	483.6
		s.d.	= (385)	(6.16)				(131.6)	(35.1)		(0.0896)	(22.62)	(302.1)	(4554)	(1137)	(6166)	
5	(1)	ST1A	=−8394		+202.2	−109.9		+555.6	+179.4	+1.254		−71.74	−442.9				471.8
		s.d.	= (3311)		(46.0)	(37.6)		(141.9)	(47.0)	(0.175)		(21.79)	(294.7)				
6	(1)	ST1A	=−10642		+221.1	−69.3	+430.4	+575.4	+161.0	+1.311		−77.83	−495.3		−3510	+7317	452.6
		s.d.	= (3273)		(44.7)	(38.2)	(198.5)	(138.6)	(45.3)	(0.176)		(21.26)	(287.4)		(1085)	(5786)	
6A	(2)	ST1A (odd)	=−12429		+261.0	−116.5	+362.6	+624.9	+228.4	+1.439		−112.2	*−173.9		−3369	+9896	427.4
		s.d.	= (4543)		(60.3)	(52.9)	(276.5)	(187.7)	(61.7)	(0.254)		(31.8)	(371.4)		(1636)	(6190)	
6B	(3)	ST1A (even)	=−9925		+189.6	*+2.22	+387.1	670.4	+91.2	+1.084		−47.7	*−70.8		−5112	*+12067	473.8
		s.d.	= (4767)		(67.4)	(59.03)	(293.3)	(221.5)	(69.0)	(0.258)		(30.8)	(450.5)		(1649)	(17153)	
7	(1)	ST.1A	=−13401		+253.4	*−6.14	+393.7	+563.1	+208.7		+0.5370	−96.11	−698.2	*−3189	−3442	+8415	476.0
		s.d.	= (3484)		(47.6)	(39.46)	(217.4)	(152.6)	(48.1)		(0.0891)	(23.02)	(303.5)	(4638)	(1146)	(6104)	

[1] 165 cements; Avg=5274; S.D.=684.2. [2] 83 cements. [3] 82 cements. *Coef./s.d. ratio less than 1.

TABLE 7–28. *Calculated contribution of independent variables to 1-year compressive strength in psi of 1:2.75 (cement to graded Ottawa sand) mortar cubes, air-stored, and the calculated ranges of such contributions*

Independent variable	Range of variable (percent)	Coefficients from eq 4 of table 7–26	Calculated contribution to ST1A	Calculated range of contribution to ST1A
			Const.=+1923	
C_3S	20 to 65	+30.4	+608 to +1976	1368
SO_3	1.2 to 3.0	+427	+512 to +1281	769
MgO	0 to 5.0	+86.7	0 to +434	434
APF	*2500 to 5500	+0.454	+1135 to +2497	1362
Air, 1:4 mortar.	11 to 21	−67.2	−67 to −1411	1344
Insol.**	0 to 1.0	−521	0 to −521	521
Cu**	0 to 0.05	−7322	0 to −366	366
Ba	0 to 0.2	−3485	0 to −697	697
Pb**	0 to 0.05	+9390	0 to +470	470

*cm^2/g.
**Doubtful significance. Coef./s.d. ratio less than 2.

TABLE 7–29. *Frequency distribution of cements with respect to 5-year, water-stored, compressive strength of 1:2.75 (cement to graded Ottawa sand) mortar cubes*

Type cement	Compressive strength, psi × 10^{-3}: 2.5 to 3.0	3.0 to 3.5	3.5 to 4.0	4.0 to 4.5	4.5 to 5.0	5.0 to 5.5	5.5 to 6.0	6.0 to 6.5	6.5 to 7.0	7.0 to 7.5	7.5 to 8.0	8.0 to 8.5	Total
	Number of cements												
1	---	---	1	5	14	12	18	20	7	3	---	---	80
1A	---	2	2	1	2	---	1	---	---	---	---	---	8
II	---	---	---	1	1	4	6	17	22	12	1	1	65
IIA	---	---	---	---	---	---	1	---	---	---	---	---	1
III	---	---	---	---	---	---	1	3	8	5	1	1	19
IIIA	---	---	---	---	---	1	---	---	1	---	---	---	2
IV & V	---	---	---	---	---	---	1	1	4	6	3	---	15
Total	---	2	3	7	17	17	28	41	42	26	5	2	190

were made, only Na_2O, C_3S, and C_2S had quadrant sum absolute values less than 11.

Equations relating the 5-year compressive-strength values of the AE+NAE cements to combinations of independent variables are presented in table 7–30. In eqs 1 and 4 are presented the relationships with commonly determined variables, and in eqs 2 and 5 the trace elements having coef./s.d. ratios greater than 1 were included. Of all the trace elements included here, only Rb showed strong consistent evidence of having a significant effect. The S.D. value of eq 2 with the added variables was significantly lower than the S.D. value of eq 1. (Equations 4 and 5 are strictly not comparable but there was approximately the same reduction in the S.D. value as in eqs 1 and 2.) In the equations calculated for the "odds" and "evens," 2A, 2B, 5A, and 5B, there were instances where MgO, Insol, Zn, Zr, Ni, and SrO had coef./s.d. ratios less than 1. Although the quadrant sum of SO_3 was greater than 11 in figure 7–3 it was not significant in the multiple regression equations. C_2S, on the other hand, had a quadrant sum less than 11 in figure 7–3 but was significant in the equations in table 7–30. Equations 2 and 5 calculated using the turbidimeter fineness values had slightly lower

TABLE 7–30. *Equations relating the 5-year compressive strengths in psi of water-stored AE+NAE cements to various independent variables*

Equation	Note		Const.	C_2S	C_3A	SiO_2	Fe_2O_3	Na_2O	APF	WAGN.	Air 1:4 mortar	MgO	Insol.	Rb	Zn	Zr	Ni	SrO	S.D.
1	(1)	ST5Y	=+5331	+16.25	−85.22	-------	-------	−1091	-------	+1.341	−106.5	−107.9	−507.8	-------	-------	-------	-------	-------	527.4
		s.d.	= (521)	(6.75)	(16.72)	-------	-------	(255)	-------	(0.184)	(11.9)	(35.1)	(319.6)	-------	-------	-------	-------	-------	
2	(1)	ST5Y	=+5069	+17.42	−60.21	-------	-------	−1188	-------	+1.318	−103.6	−73.0	−563.9	−52949	+2330	+1936	+20890	−616.7	508.4
		s.d.	= (523)	(6.55)	(17.95)	-------	-------	(262)	-------	(0.181)	(11.7)	(35.1)	(312.5)	(21756)	(1293)	(1021)	(12468)	(509.4)	
2A	(2)	ST5Y (odd)	=+4747	+20.87	−55.32	-------	-------	−1036	-------	+1.533	−113.7	−162.6	*+85.4	−36386	*+306	+1705	*+2882	*−501.2	561.9
		s.d.	= (796)	(9.86)	(25.57)	-------	-------	(357)	-------	(0.308)	(19.2)	(60.2)	(685.1)	(33548)	(2560)	(1288)	(20973)	(852.2)	
2B	(3)	ST5Y (even)	=+5337	+15.79	−68.26	-------	-------	−1476	-------	+1.151	−89.0	*−23.7	−836.0	−76020	+2865	*+2326	+37997	−728.6	456.9
		s.d.	= (765)	(9.80)	(27.74)	-------	-------	(441)	-------	(0.231)	(15.1)	(45.4)	(363.9)	(29160)	(1455)	(4408)	(15533)	(630.6)	
3	(1)	ST5Y	=+5978	+19.08	−87.49	-------	-------	−1227	+0.5039	-------	−112.9	−64.5	−701.8	−68940	+1896	+2190	+17729	-------	533.3
		s.d.	= (499)	(7.16)	(16.96)	-------	-------	(265)	(0.0875)	-------	(12.2)	(36.9)	(327.6)	(22520)	(1351)	(1058)	(13057)	-------	
4	(1)	ST5Y	=−1260	-------	-------	+247.2	+163.8	−1130	-------	+1.470	−102.9	−51.3	−529.9	-------	-------	-------	-------	-------	532.0
		s.d.	= (892)	-------	-------	(34.7)	(55.9)	(252)	-------	(0.168)	(12.2)	(36.4)	(317.9)	-------	-------	-------	-------	-------	
5	(1)	ST5Y	= −646	-------	-------	+220.6	+142.1	−1296	-------	+1.394	−101.7	-------	+595.8	−53707	+2734	+1868	+25685	-------	510.4
		s.d.	= (859)	-------	-------	(33.6)	(54.5)	(248)	-------	(0.166)	(11.7)	-------	(306.6)	(21642)	(1283)	(1001)	(12337)	-------	
5A	(2)	ST5Y (odd)	=−1620	-------	-------	+254.2	+94.6	−1046	-------	+1.654	−116.7	-------	*−317.7	−35260	*+1677	+1641	*+6843	-------	559.5
		s.d.	= (1401)	-------	-------	(54.1)	(84.9)	(338)	-------	(0.287)	(19.0)	-------	(626.9)	(32014)	(2431)	(1231)	(20819)	-------	
5B	(3)	ST5Y (even)	= −88	-------	-------	+202.4	+184.0	−1662	-------	+1.216	−83.3	-------	−950.0	−77671	+2995	*+1760	+41383	-------	465.6
		s.d.	= (1099)	-------	-------	(43.7)	(74.3)	(395)	-------	(0.203)	(15.0)	-------	(353.6)	(29847)	(1470)	(4462)	(15470)	-------	
6	(1)	ST5Y	=−1546	-------	-------	+283.8	+178.3	−1244	+0.5967	-------	−108.7	-------	−682.1	−64952	+1985	+2325	+22364	-------	527.2
		s.d.	= (954)	-------	-------	(35.7)	(56.4)	(257)	(0.0800)	-------	(12.0)	-------	(316.6)	(22127)	(1327)	(1035)	(12740)	-------	

[1] 173 cements; Avg.=6068; S.D.=967.2. [2] 87 cements. [3] 86 cements. *Coef./s.d. ratio less than 1.

TABLE 7–31. *Equations relating the 5-year compressive strengths in psi of water-stored NAE cements to various independent variables*

Equation	Note		Const.	C_3S	C_3A	SiO_2	Fe_2O_3	Na_2O	APF	WAGN.	Air 1:4 mortar	MgO	Insol.	Rb	Zn	Zr	Ni	SrO	S.D.
1	[1]	ST5Y	=+6078	+13.28	−87.68	...	...	−885	...	+1.194	−163.6	−107.2	−651.9	...	...	...	...	...	514.6
		s.d.	= (552)	(6.82)	(16.83)			(285)		(0.187)	(24.0)	(34.9)	(341.9)						
2	[1]	ST5Y	=+5728	+15.11	−62.21	...	...	−1006	...	+1.172	−149.0	−72.9	−725.3	−47542	+2347	+1622	+21399	−667	497.7
		s.d.	= (551)	(6.66)	(18.02)			(270)		(0.184)	(23.7)	(35.1)	(335.1)	(21896)	(1267)	(1010)	(12303)	(518)	
2A	[2]	ST5Y (odd)	=+5688	+19.45	−48.47	...	...	−1099	...	+0.961	−124.0	−73.7	*−340.6	−41667	+2226	+1872	+30990	−1246	561.0
		s.d.	= (804)	(9.92)	(28.62)			(412)		(0.274)	(43.3)	(54.1)	(535.3)	(35881)	(1769)	(1252)	(20261)	(819)	
2B	[2]	ST5Y (even)	=+5807	*+6.62	−69.31	...	...	−1061	...	+1.385	−155.4	−77.4	−1320.3	−53541	+2684	*+1878	*+5044	−1722	443.1
		s.d.	= (795)	(9.52)	(24.87)			(389)		(0.264)	(28.9)	(49.4)	(485.0)	(28076)	(2041)	(2586)	(16613)	(707)	
3	[1]	ST5Y	=+6505	+17.75	−85.40	...	...	−1028	+0.4695	...	−170.2	−64.7	−927.5	−60014	+1993	+1745	+19274	...	513.3
		s.d.	= (507)	(7.14)	(17.00)			(268)	(0.0867)		(24.5)	(36.2)	(345.5)	(22272)	(1302)	(1028)	(12670)		
	[1]	ST5Y	= −334	...	...	+230.0	+174.6	−969	...	+1.344	−152.4	−54.9	−716.7	...	...	...	...	...	524.3
		s.d.	= (927)			(35.1)	(55.9)	(257)		(0.175)	(24.6)	(36.7)	(342.5)						
	[1]	ST5Y	= +134	...	...	+207.5	+151.4	−1167	...	+1.259	−139.9	...	−796.6	−52242	+2776	+1628	+26632	...	503.5
		s.d.	= (888)			(33.8)	(54.7)	(254)		(0.174)	(24.0)		(329.9)	(21770)	(1267)	(997)	(12252)		
A	[2]	ST5Y (odd)	= −802	...	...	+236.3	*+80.9	−1306	...	+0.978	−119.4	...	*−397.4	−44542	+2536	+1761	+38461	...	563.1
		s.d.	= (1358)			(50.9)	(89.5)	(385)		(0.261)	(43.7)		(508.0)	(34030)	(1771)	(1215)	(19730)		
B	[2]	ST5Y (even)	= +758	...	...	+163.3	+168.2	−1162	...	+1.545	−147.2	...	−1381.3	−56301	+3103	*+2129	*+10288	...	444.6
		s.d.	= (1192)			(45.3)	(70.1)	(359)		(0.239)	(27.9)		(469.3)	(28340)	(1953)	(2487)	(16435)		
6	[1]	ST5Y	= −656	...	...	+266.0	+181.8	−1079	+0.5546	...	−160.7	...	−937.2	−58897	+2104	+1949	+24042	...	511.4
		s.d.	= (961)			(35.4)	(55.7)	(260)	(0.0815)		(24.5)		(333.9)	(21951)	(1288)	(1013)	(12447)		

[1] 162 cements; Avg=6166; S.D.=879.7. [2] 81 cements. *Coef./s.d. ratio less than 1.

S.D. values than corresponding eqs 3 and 6 using the air-permeability fineness values.

Equations calculated for the relationships of various independent variables to the 5-year compressive-strength values of the NAE cements are presented in table 7–31. The coefficients differ to a limited extent from those presented in the previous table for the AE+NAE cements. In table 7–31, the addition of the trace elements in eq 2 resulted in an S.D. value lower only at the five percent probability level than the S.D. value in eq 1. Equations for the "odds" and "evens" indicated instances where C_2S, Fe_2O_3, Zr and Ni had coef./s.d. ratios less than 1. As in the previous equation, MgO and SrO were not included in eqs 4 through 6 because the coef./s.d. ratio was less than 1 for these variables.

The contributions and ranges of contributions of the independent variables to the 5-year compressive strength were calculated from eq 3 of table 7–30 and are presented in table 7–32 together with the ranges of these contributions. Increases in C_2S, fineness, and Zr with possibly Zn and Ni appeared associated with higher strengths, and increases in C_3A, Na_2O, air content, Insol, and Rb with possibly MgO appeared associated with lower strengths at 5 years.

5.10. Compressive Strength at 10 Years of Water-Stored Specimens

The frequency distributions of the 10-year compressive-strength values obtained with cements of the different types are presented in table 7–33. There was a broad distribution as well as a great deal of overlapping of the compressive-strength values of the different types of cement.

TABLE 7–32. *Calculated contribution of independent variables to 5-year compressive strength in psi of 1:2.75 (cement to graded Ottawa sand) mortar cubes, water-stored, and calculated ranges of such contributions.*

Independent variable	Range of variable (percent)	Coefficients from eq 3 of table 7–30	Calculated contribution to ST5W	Calculated range of contribution to ST5W
			Const.=+5978	
C_2S	5 to 50	+19.1	+96 to +955	859
C_3A	1 to 15	−87.5	−88 to −1302	1214
Na_2O	0 to 0.7	−1230	0 to −861	861
APF	*2500 to 5500	+0.504	+1260 to +2772	1512
Air, 1:4 mortar	1 to 21	−113	−113 to −2373	2260
MgO**	0 to 5.0	−64.5	0 to −322	322
Insol	0 to 1.0	−702	0 to −702	702
Rb	0 to 0.01	−68900	0 to −689	689
Zn**	0 to 0.2	+1900	0 to +380	380
Zr	0 to 0.5	+2190	0 to +1080	1080
Ni**	0 to 0.02	+17700	0 to +354	354

*cm²/g.
**Doubtful significance. Coef./s.d. ratio less than 2.

Equations indicating the relationship of different combinations of independent variables to the 10-year compressive strength values of AE+NAE cements are presented in table 7–34. Equations 1, 2, 3, 6, and 7 were computed with

TABLE 7–33. *Frequency distribution of cements with respect to 10-year compressive strength of 1:2.75 (cement to graded Ottawa sand) mortar cubes, water-stored.*

Type Cement	Compressive strength changes, psi×10⁻³												Total
	2.5 to 3.0	3.0 to 3.5	3.5 to 4.0	4.0 to 4.5	4.5 to 5.0	5.0 to 5.5	5.5 to 6.0	6.0 to 6.5	6.5 to 7.0	7.0 to 7.5	7.5 to 8.0	8.0 to 8.5	
	Number of cements												
I	---	2	8	9	9	17	21	9	3	---	---	---	78
IA	1	3	2	1	---	---	1	---	---	---	---	---	8
II	---	---	1	2	2	5	18	7	14	4	3	---	56
IIA	---	---	---	1	---	---	---	1	---	---	---	---	2
III	---	---	---	---	---	3	5	4	3	1	---	---	16
IIIA	---	---	---	1	---	---	1	---	---	---	---	---	2
IV & V	---	---	---	---	---	1	1	2	---	1	1	1	7
Total	1	5	11	14	11	26	47	23	20	6	4	1	169

commonly determined variables, and eqs 4, 5, 8, and 9 with the addition of the trace elements found to have coef./s.d. ratios greater than 1. Equation 1 had a significantly lower S.D. value than was obtained for the 155 strength values of the cements themselves. Comparisons of eqs 1 and 3, 3 and 4, 2 and 5, 6 and 7, or 7 and 8 indicate that a highly significant reduction in the S.D. value was obtained in every instance as a result of the added independent variables. However, of the trace elements added, only Zr consistently showed a strong significant relationship.

Equations calculated for the "odds" and "evens" in the array of cements indicated that C_4AF, Insol, SrO, Zr, Co, and Cr had coef./s.d. ratios less than 1 in one or the other of the groups. The coef./s.d. ratio for Cr was less than 1 when the oxide values were used in the computations as in eqs 8 and 9, and was not significant in eqs 3 and 5 where the compounds were used.

A similar series of equations are presented in table 7–35 for the NAE cements alone. The same variables were significant but there were slight differences in the coefficients for these variables than when the AE cements were included as in table 7–34. It may be noted that the "air, 1:4 mortar" was highly significant in both tables 7–34 and 7–35. Also, in both of these tables the S.D. values of equations calculated using the Wagner finenesses were lower than when the APF values were used.

The contributions of the various independent variables to the 10-year compressive-strength values were calculated from eq 5 of table 7–34 and are presented in table 7–36 together with the ranges of these contributions. Increases in C_2S, fineness, and Zr, with possibly Zn and Cr, appear associated with higher compressive strength values at 10 years, and increases in C_3A, C_4AF, Na_2O, and air content, plus possibly Insol and SrO, appear associated with lower strength values.

5.11. Gain in Compressive Strength Between 7 and 28 Days

The frequency distributions of the 7- to 28-day compressive-strength gain of the different types of cement are presented in table 7–37. There was a range of values within each of the types and a considerable overlapping of the values found for the different types of cement.

The results of plotting the 28-day minus 7-day compressive-strength difference versus individual variables are presented in figure 7–4. Of the

DEPENDENT VARIABLE COMPRESSIVE STRENGTH DIFFERENCE	NOTE *	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TOTAL ALKALI	C_3A	C_3S	C_2S	C_4AF	A/F	S/(A+F)	AIR P. FINE	WAGN. FINE	AIR 1:4 MORT
28 DAY MINUS 7 DAY (ST28–ST07)	(1)	10/2	8/4	10/2	6/6	6/6	10/2	10/2	10/2	10/2	10/2	8/4	10/2	10/2	8/4	10/2	10/2	6/6	10/2
	(2)																		
	(3)	L	NL	L	NO	NO	L	L?	L?	NL	NO	L	L	L	L	L?	NL	NO	NL
	(4)	+15	−11	+15	−2	0	−20	−8	−17	−20	−14	−10	+16	+16	−12	+13	−13	−3	−17
1 YEAR WATER-STORED MINUS 7 DAY (ST1Y–ST07)	(1)	12/0	12/0	12/0	6/6	8/4	12/0	10/2	12/0	12/0	10/2	10/2	12/0	10/2	12/0	10/2	8/4	8/4	10/2
	(2)																		
	(3)	L	L	NL	L?	L?	L	L?	L	L?	L	L	L	NL	L	L	NL	NO	L?
	(4)	+24	−24	+24	−7	−7	−24	−14	−24	−24	−20	−16	+24	+16	−24	+20	−7	+2	−13
1 YEAR AIR STORED** MINUS 7 DAY (ST1A–ST07)	(1)	12/0	10/2	8/4	10/2	10/2	10/2	7/5	6/6	8/4	10/2	12/0	12/0	8/4	10/2	10/2	8/4	6/6	6/6
	(2)																		
	(3)	L	L	L	L	NL	NL	L?	L?	L?	L	NL	L	L	L	L?	NL	NO	NO
	(4)	+24	−18	+15	−17	+15	−15	+3	−7	−4	−19	−24	+24	+12	−19	+14	−10	−1	−5

FIGURE 7–4. *Result of plotting difference of compressive strength at different ages of 1:2.75 (cement to graded Ottawa sand) mortars on the "Y" axis versus various independent variables on the "X" axis.*

*Note (1) Ratio of number of plotted points in pairs of diametrically opposite quadrants.
Note (2) General trend of lines drawn through plotted points.
Note (3) Apparent nature of relationship. L=linear: NL-nonlinear; NO-no apparent relationship; and L?-nature of relationship not determinable.
Note (4) Quadrant sum in corner test. (See reference [8].)

**Stored in moist air for 24 hrs., then water for 6 days, then in laboratory air at 23° C, 50 percent RH for 49 weeks, then water for 2 weeks.

Table 7–34. *Equations relating the 10-year compressive strengths in psi of AE+NAE cements water-stored to various independent variables*

Equation	Note		Const.	C_3A	C_2S	C_4AF	SiO_2	Fe_2O_3	Insol.	Na_2O	APF	WAGN.	Air 1:4 mortar	SrO	Zr	Zn	Co	Cr	S.D.
1	(1)	STXY	=+9288	−204.4		−83.29							−135.4						668.5
		s.d.	= (463)	(21.8)		(30.38)							(14.0)						
2	(1)	STXY	=+7833	−161.5	+18.77	−71.00			−723.5	−1578	+0.2496		−122.2						611.3
		s.d.	= (726)	(23.1)	(8.59)	(27.90)			(387.1)	(308)	(0.1124)		(13.2)						
3	(1)	STXY	=+6754	−138.2	+20.78	−60.13			−766.9	−1613		+0.8495	−117.6						594.4
		s.d.	= (777)	(23.8)	(8.00)	(27.36)			(374.8)	(299)		(0.2292)	(12.9)						
4	(1)	STXY	=+5804	−102.9	+22.47	−41.63			−729.1	−1660		+1.0161	−107.9	−1022	+3070	+4539	+41512	+13507	561.9
		s.d.	= (777)	(24.9)	(7.63)	(26.58)			(360.4)	(299)		(0.2244)	(12.5)	(598)	(1206)	(2393)	(38209)	(10803)	
4A	(2)	STXY (odd)	=+5750	−114.8	+18.94	−62.41			−1038.3	−1393		+1.3334	−111.1	*−811	+2143	+5565	*−45276	*+10667	549.5
		s.d.	= (1084)	(33.1)	(9.57)	(39.62)			(559.4)	(360)		(0.3237)	(18.1)	(823)	(1372)	(3648)	(72544)	(14928)	
4B	(3)	STXY (even)	=+4894	−67.8	+32.74	*−2.71			*−331.6	−2495		+0.9475	−94.6	−1407	*+6115	+4592	+86242	*+13153	568.2
		s.d.	= (1211)	(39.2)	(13.18)	(37.60)			(499.0)	(560)		(0.3276)	(18.8)	(883)	(9454)	(3212)	(47058)	(17491)	
5	(1)	STXY	=+7043	−131.7	+19.97	−52.42			−719.2	−1654	+0.3090		−112.8	−847	+3377	+3654		+15114	583.1
		s.d.	= (733)	(24.3)	(8.21)	(27.17)			(375.2)	(311)	(0.1094)		(12.9)	(620)	(1249)	(2469)		(11195)	
6	(1)	STXY	=−5672				+455.2	+211.3			+0.5241		−127.7						654.0
		s.d.	= (1191)				(46.9)	(72.7)			(0.1091)		(13.8)						
7	(1)	STXY	=−4331				+427.7	+183.2	−709.2	−1686	+0.4362		−110.5						592.1
		s.d.	= (1129)				(43.8)	(66.3)	(367.5)	(293)	(0.1003)		(12.8)						
8	(1)	STXY	=−3383				+382.7	+164.3	−611.8	−1678	+0.4567		−106.3	−945	+3285	+2959	+57095		565.2
		s.d.	= (1215)				(46.4)	(64.0)	(359.2)	(298)	(0.0990)		(12.4)	(584)	(1208)	(2372)	(38251)		
9	(1)	STXY	=−2479				+321.1	+142.4	−596.3	−1673		+1.1140	−100.7	−1113	+2919	+3796	+56206		545.7
		s.d.	= (1058)				(42.9)	(61.9)	(346.6)	(287)		(0.1931)	(11.9)	(559)	(1170)	(2302)	(36645)		
9A	(2)	STXY (odd)	=−3083				+324.4	+110.0	−861.6	−1389		+1.5230	−106.8	−839	+2049	+4427	*−36570		517.6
		s.d.	= (1360)				(54.4)	(89.5)	(513.2)	(337)		(0.2734)	(16.1)	(755)	(1292)	(3420)	(67588)		
9B	(3)	STXY (even)	=−2038				+307.3	+205.8	*−233.3	−2442		+0.8495	−86.7	−1331	*+6332	+3949	+91050		556.9
		s.d.	= (1625)				(67.5)	(86.0)	(486.0)	(523)		(0.2757)	(17.9)	(827)	(8728)	(3120)	(44933)		

[1] 155 cements; Avg=5557; S.D.=1038.6. [2] 78 cements. [3] 77 cements. *Coef./s.d. ratio less than 1.

TABLE 7–35. *Equations relating the 10-year compressive strengths in psi of NAE cements water-stored to various independent variables*

Equation	Note		Const.	C_3A	C_2S	C_4AF	SiO_2	Fe_2O_3	Insol.	Na_2O	APF	WAGN.	Air 1:4 mortar	SrO	Zr	Zn	Co	Cr	S.D.
1	[1]	STXY	=+10166	−198.4		+83.67							−267.3						618.9
		s.d.	= (492)	(20.9)		(29.01)							(28.7)						
2	[1]	STXY	= +8638	−156.6	+18.51	−74.70			−1031	−1205	+0.2613		−245.0						574.4
		s.d.	= (716)	(22.5)	(8.35)	(26.99)			(403)	(305)	(0.1100)		(28.2)						
3	[1]	STXY	= +7987	−141.4	+17.83	−65.50			−979	−1277		+0.6702	−228.3						568.7
		s.d.	= (808)	(23.6)	(7.96)	(26.96)			(397)	(301)		(0.2294)	(27.8)						
4	[1]	STXY	= +6854	−105.3	+19.98	−44.46			−902	−1314		+0.8558	−205.6	−1077	+2429	+4394	+49933	+16134	537.8
		s.d.	= (812)	(24.4)	(7.59)	(26.24)			(381)	(303)		(0.2252)	(27.1)	(597)	(1179)	(2303)	(38531)	(10611)	
4A	[2]	STXY (odd)	= +5853	−76.3	+14.50	*−5.87			−1057	−893		+1.2529	−237.8	−1253	+2760	*−1888	*−31641	+21896	449.1
		s.d.	= (879)	(26.9)	(8.08)	(32.33)			(427)	(325)		(0.2738)	(33.3)	(705)	(1191)	(3980)	(57462)	(12149)	
4B	[3]	STXY (even)	= +6670	−91.9	+35.39	*−44.20			−767	−2572		+0.5036	−135.7	−1111	+9307	+3919	+90613	*+4466	582.1
		s. d.	= (1634)	(46.1)	(14.94)	(46.61)			(737)	(613)		(0.3811)	(45.7)	(1002)	(3794)	(3175)	(55912)	(18897)	
5	[1]	STXY	= 7774	−126.2	+19.62	−53.66			−985	−1256	+0.3081		−223.5	−993	+2586	+3729		+18313	548.2
		s.d.	= (725)	(23.4)	(7.99)	(26.34)			(391)	(310)	(0.1067)		(27.6)	(607)	(1200)	(2331)		(10801)	
6	[1]	STXY	= −4250				+433.4	+196.0			+0.5092		−249.2						612.6
		s.d.	= (1172)				(45.5)	(69.6)			(0.1082)		(28.5)						
7	[1]	STXY	= −3083				+408.5	+164.8	−999	−1372	+0.4242		−216.2						564.0
		s.d.	= (1135)				(43.2)	(64.9)	(387)	(294)	(0.1015)		(27.8)						
8	[1]	STXY	= −2223				+365.8	+148.9	−863	−1336	+0.4422		−206.0	−1060	+2664	+2977	+66849		537.6
		s.d.	= (1208)				(45.4)	(62.4)	(377)	(301)	(0.1001)		(27.1)	(586)	(1172)	(2265)	(38351)		
9	[1]	STXY	= −1353				+307.8	+136.3	−771	−1394		+0.9849	−184.6	−1217	+2490	+3626	+66244		529.6
		s.d.	= (1090)				(42.8)	(61.6)	(372)	(295)		(0.2003)	(26.5)	(572)	(1156)	(2243)	(37603)		
9A	[2]	STXY (odd)	= +445				+207.5	+149.1	−907	−921		+1.3466	−227.2	−1582	+2624	*−1225	*−2987		457.0
		s.d.	= (1301)				(51.4)	(77.4)	(420)	(329)		(0.2562)	(34.0)	(690)	(1219)	(4007)	(55894)		
9B	[3]	STXY(even)	= −2373				+370.2	+168.5	*−536	−2347		+0.5343	−128.3	−992	+8617	*+2882	+98525		559.9
		s.d.	= (1846)				(70.7)	(105.1)	(698)	(529)		(0.3131)	(40.1)	(926)	(3554)	(2976)	(52163)		

[1] 143 cements; Avg=5667; S.D.=963.3. [2] 72 cements. [3] 71 cements. *Coef./s.d. ratio less than 1.

Table 7–36. *Calculated contribution of independent variables to 10-year compressive strength in psi of 1:2.75 (cement to graded Ottawa sand) mortar cubes, water-stored, and the calculated ranges of such contributions*

Independent variable	Range of variable (percent)	Coefficients from eq (5) of table 7–34	Calculated contribution to STXY	Calculated range of contribution to STXY
			Const. = +7043	
C_3A	1 to 15	−132	−132 to −1980	1848
C_2S	5 to 50	+20.0	+100 to +1000	900
C_4AF	1 to 16	−52.4	−52 to −838	786
Insol.**	0 to 1.0	−719	0 to −719	719
Na_2O	0 to 0.7	−1650	0 to −1155	1155
APF	*2500 to 5500	+0.309	+773 to +1700	927
Air, 1:4 mortar	1 to 21	−113	−113 to −2373	2260
SrO**	0 to 0.4	−847	0 to −339	339
Zr	0 to 0.5	+3380	0 to −1690	1690
Zn**	0 to 0.2	+3650	0 to +730	730
Cr**	0 to 0.02	+15100	0 to +302	302

*cm^2/g.
**Doubtful significance. Coef./s.d. ratio less than 2.

Table 7–37. *Frequency distribution of cements with respect to compressive strength gain from 7 to 28 days of 1:2.75 (cement to graded Ottawa sand) mortar cubes, water-stored*

Type cement	Compressive strength gain, psi×10^{-3}								Total
	0 to 0.5	0.5 to 1.0	1.0 to 1.5	1.5 to 2.0	2.0 to 2.5	2.5 to 3.0	3.0 to 3.5	3.5 to 4.0	
	Number of cements								
I	----	4	24	36	14	4	----	----	82
IA	----	1	5	1	1	----	----	----	8
II	----	1	6	25	22	13	----	1	68
IIA	----	1	----	2	----	----	----	----	3
III	2	3	7	7	1	----	----	----	20
IIIA	1	1	1	----	----	----	----	----	3
IV & V	----	----	1	9	3	1	----	1	15
Total	3	11	44	80	41	18	----	2	199

variables for which plots were made, all but CaO, MgO, Na_2O, C_3S, and WAGN had quadrant-sum absolute values greater than 11.

Equations relating the 7- to 28-day compressive-strength gain to combinations of independent variables are presented in table 7–38 for the AE+NAE cements, and in table 7–39 for the NAE cements. The use of the variables in eq 1 or the use of additional variables as in eqs 2 and 3 each resulted in a significantly lower S.D. value. Similar reductions may also be noted in comparing eqs 5 and 6, or 6 and 7 (see table 7–75). Comparisons may be made of the variables in table 7–39 with the variables associated with the compressive strength values at 7 and 28 days in tables 7–10 and 7–14 respectively. Some of the independent variables which were significant at 7 and/or 28 days (tables 7–10 and 7–14) were not significant in table 7–38 where the difference in strength was the dependent variable. Also, some variables which were significant in table 7–38 were not significant in tables 7–10 or 7–14.

Equations calculated for the "odds" and "evens" in the array of cements indicated, that for the smaller groups, there were instances where C_4AF, Fe_2O_3, K_2O, APF, Zr, Cr, Co, V, and Ni had coef./s.d. ratios less than one.

The coefficients for the independent variables in equations calculated for the NAE cements alone and presented in table 7–39 were, in general, concordant with those of the previous table, 7–38, where the AE cements were included.

The contributions of the variables to the strength-gain values between 7 and 28 days were calculated from the coefficients of eq 4, table 7–38, and are presented in table 7–40 together with the calculated ranges of these contributions. Of the different variables, increases in C_4AF and Zr were the only ones associated with a greater compressive-strength gain. The values in the last column appear to indicate that no one variable is highly dominant in its effect. Cr was associated with lower strength gain and Rb, Co, V, and Ni were of doubtful significance.

5.12. Compressive Strength-Gain Ratio, (28 day—7 day)/7 day, or SGR(1)

Frequency distributions of the compressive-strength-gain ratios, (SGR(1)), are presented in table 7–41 for the different types of cement. Although there was considerable overlapping of the values obtained with the cements in the different types, most of the Type III cements had low ratios as may be expected with the higher early-strength cements.

Equations relating SGR(1) for AE+NAE cements to combinations of independent variables are presented in table 7–42, and for the NAE cements alone, in table 7–43. Equations 1, 2, 5, and 6 were calculated using commonly determined independent variables, and the other equations with additional variables, the trace elements found to have a coef./s.d. ratio greater than one. The addition of these elements resulted, in every instance, in a highly significant reduction of the S.D. values. (See table 7–75.) Of the trace elements used, however, only Zr and Cr showed strong evidence of a significant effect, and Ti was borderline.

Equations calculated for the "odds" and "evens" indicated that Na_2O, Zr, Ti, Pb, and V had coef./s.d. ratios less than one in one or the other of the smaller groups of cement.

The equations for the NAE cements in table 7–43 are fairly concordant with those in the previous table where the AE cements were included. In the equation for the "odds" and "evens," Na_2O and Zr had coef./s.d. ratios greater than 1, and that for Cr was less than 1.

A comparison of tables 7–42, 7–38, 7–10, and 7–14 shows that, of all the trace elements investigated, Cr was the only one which showed strong consistent evidence of a significant relationship to the strength alone, and then only at 28 days. However, with both the strength gain and strength-gain ratio, both Cr and Zr showed good evidence of a significant effect. None of the other trace elements showed strong evidence of in-

TABLE 7–38. *Equations relating the compressive strength gain in psi from 7 to 28 days of AE+NAE cements water-stored to various independent variables*

Equation	Note		Const.	C_3S	C_3S/C_2S	C_4AF	Fe_2O_3	CaO	Na_2O	K_2O	APF	SO_3	Air 1:4 mortar	Zr	Cr	Rb	Co	V	Ni	S.D.
1	[1]	SG(1)	=+2093		−81.59	+61.18					−0.2028									416.4
		s.d.	= (264)		(30.73)	(14.18)					(0.0699)									
2	[1]	SG(1)	=+2994		−80.62	+46.67			−402.0	−289.2	−0.1264	−352.2	−23.94							365.5
		s.d.	= (266)		(27.34)	(12.62)			(173.1)	(142.1)	(0.0730)	(102.1)	(8.16)							
3	[1]	SG(1)	=+3363		−73.92	+52.92			−457.2	−256.9	−0.1895	−324.3	−27.28	+1371	−22483	−27059	−23308	−2161		336.1
		s.d.	= (267)		(25.70)	(11.81)			(161.9)	(154.2)	(0.0697)	(94.5)	(7.70)	(650)	(6688)	(15637)	(19191)	(1578)		
3A	[2]	SG(1) (odd)	=+3189		−69.39	+74.50			−408.7	*−188.0	−0.2200	−283.7	−34.66	*+50	*−5042	−38052	−69190	−4710		303.8
		s.d.	= (369)		(32.67)	(14.44)			(196.3)	(207.6)	(0.0859)	(142.4)	(9.74)	(3565)	(9691)	(20117)	(28126)	(2614)		
3B	[2]	SG(1) (even)	=+3543		−90.77	*+14.97			−822.2	*−164.0	*−0.0590	−454.4	−20.19	+1805	−36578	−40567	*+8461	*+107		355.4
		s.d.	= (398)		(41.84)	(19.68)			(304.5)	(253.6)	(0.1199)	(141.5)	(12.43)	(766)	(10052)	(24753)	(27703)	(2063)		
4	[1]	SG(1)	=+3994	−12.03		+48.58			−470.5	−332.2	−0.2164	−340.3	−27.10	+1338	−23043	−25000	−23764	−2352		337.3
		s.d.	= (327)	(4.52)		(12.26)			(163.2)	(152.7)	(0.0670)	(94.8)	(7.73)	(652)	(6694)	(15627)	(19256)	(1591)		
5	[1]	SG(1)	= +120				+220.5	+31.65			−0.2996									423.5
		s.d.	= (1890)				(46.0)	(28.82)			(0.0618)									
6	[1]	SG(1)	=+9505				+99.0	−94.89	−445.6	−506.7	−0.1967	−400.4	−25.65							363.9
		s.d.	= (2035)				(42.4)	(29.81)	(173.9)	(151.2)	(0.0662)	(104.0)	(8.17)							
7	[1]	SG(1)	=+8447				+133.2	−74.93	−455.0	−451.7	−0.2410	−380.3	−28.53	+1276	−21765	−19111	−23852		−11507	337.3
		s.d.	= (1903)				(40.3)	(28.11)	(163.8)	(159.7)	(0.0625)	(97.1)	(7.76)	(655)	(6964)	(15639)	(19179)		(9303)	
7A	[2]	SG(1) (odd)	=+8087				+212.1	−74.11	−341.7	−452.3	−0.2464	−323.9	−33.93	*+45	*−236	−24997	−71046		−35558	302.0
		s.d.	= (2551)				(49.0)	(38.00)	(192.9)	(223.4)	(0.0789)	(149.6)	(9.62)	(3540)	(10562)	(20507)	(27588)		(15332)	
7B	[2]	SG(1) (even)	=+9339				*+9.4	−82.84	−916.0	−398.8	−0.1739	−500.4	−23.06	+1839	−35141	−32580	*+5508		*+4040	357.7
		s.d.	= (2980)				(66.8)	(43.74)	(321.3)	(243.9)	(0.1069)	(143.5)	(12.64)	(777)	(10382)	(24594)	(27860)		(12314)	

[1] 172 cements; Avg=1788; S.D.=479.7. [2] 86 cements. *Coef./s.d. ratio less than 1.

Table 7–39. *Equations relating the compressive strength gain in psi from 7 to 28 days of NAE cements water-stored to various independent variables*

Equation	Note		Const.	C_3S	C_3S/C_2S	C_4AF	Fe_2O_3	CaO	Na_2O	K_2O	APF	SO_3	Air 1:4 mortar	Zr	Cr	Rb	Co	V	Ni	S.D.
1	(1)	SG(1)	=+2157	-------	−76.86	+59.10	-------	-------	-------	-------	−0.2109	-------	-------	-------	-------	-------	-------	-------	-------	400.7
		s.d.	= (264)	-------	(30.09)	(13.98)	-------	-------	-------	-------	(0.0696)	-------	-------	-------	-------	-------	-------	-------	-------	-------
2	(1)	SG(1)	=+2946	-------	−74.22	+50.44	-------	-------	−299.4	−253.0	−0.1447	−278.3	−33.11	-------	-------	-------	-------	-------	-------	370.4
		s.d.	= (285)	-------	(28.20)	(13.02)	-------	-------	(186.6)	(149.3)	(0.0766)	(106.4)	(18.80)	-------	-------	-------	-------	-------	-------	-------
3	(1)	SG(1)	=+3246	-------	−72.46	+55.63	-------	-------	−423.2	−224.7	−0.2040	−289.8	−21.39	+1414	−20021	−31405	−26066	−2386	-------	34 .0
		s.d.	= (287)	-------	(26.51)	(12.22)	-------	-------	(177.0)	(163.1)	(0.0733)	(98.8)	(17.72)	(669)	(7012)	(16188)	(20158)	(1636)	-------	-------
3A	(2)	SG(1) (odd)	=+3167	-------	−75.41	+52.46	-------	-------	−534.1	*−98.2	−0.2470	−183.7	*−24.02	+4827	*−6558	−38196	−59060	−4694	-------	233.4
		s.d.	= (408)	-------	(34.38)	(18.09)	-------	-------	(217.5)	(234.0)	(0.0942)	(157.2)	(25.43)	(1699)	(11461)	(23386)	(31080)	(2658)	-------	-------
3B	(2)	SG(1) (even)	=+3294	-------	−89.58	+55.84	-------	-------	−574.7	−354.0	*−0.0751	−440.0	*−23.22	+865	−33979	−39578	*+16740	*−1049	-------	358.1
		s.d.	= (425)	-------	(42.62)	(18.13)	-------	-------	(330.0)	(257.3)	(0.1241)	(146.5)	(26.79)	(786)	(10227)	(24867)	(29315)	(2269)	-------	-------
4	(1)	SG(1)	=+3907	−12.55	-------	+50.36	-------	-------	−440.7	−304.6	−0.2300	−302.9	−21.01	+1385	−20554	−29440	−26332	−2596	-------	342.4
		s.d.	= (353)	(4.71)	-------	(12.72)	-------	-------	(178.2)	(161.5)	(0.0701)	(99.0)	(17.74)	(669)	(7001)	(16137)	(20178)	(1645)	-------	-------
5	(1)	SG(1)	=+1535	-------	-------	-------	+205.1	*+10.48	-------	-------	−0.2974	-------	-------	-------	-------	-------	-------	-------	-------	408.8
		s.d.	= (1914)	-------	-------	-------	(46.2)	(29.02)	-------	-------	(0.0623)	-------	-------	-------	-------	-------	-------	-------	-------	-------
6	(1)	SG(1)	=+9168	-------	-------	-------	+109.6	−90.58	−346.9	−467.3	−0.2123	−347.5	−33.42	-------	-------	-------	-------	-------	-------	368.5
		s.d.	= (2138)	-------	-------	-------	(44.4)	(31.17)	(187.8)	(159.9)	(0.0696)	(108.6)	(18.71)	-------	-------	-------	-------	-------	-------	-------
7	(1)	SG(1)	=+8734	-------	-------	-------	+141.0	−75.61	−396.8	−420.7	−0.2526	−336.8	−26.40	+1266	−18383	−22690	−25013	-------	−14856	342.3
		s.d.	= (1995)	-------	-------	-------	(42.3)	(29.29)	(178.5)	(168.8)	(0.0656)	(101.8)	(17.53)	(672)	(7357)	(16101)	(20119)	-------	(9646)	-------
7A	(2)	SG(1) (odd)	=+9661	-------	-------	-------	+120.3	−96.20	−490.5	−325.8	−0.2642	−293.3	−28.88	+4075	*+1773	−31885	−70585	-------	−35558	312.2
		s.d.	= (2457)	-------	-------	-------	(59.3)	(35.82)	(209.4)	(231.8)	(0.0840)	(155.9)	(24.70)	(1647)	(11827)	(22030)	(30185)	-------	(13188)	-------
7B	(2)	SG(1) (even)	=+7932	-------	-------	-------	+151.5	−67.38	−576.2	−513.7	−0.1683	−493.8	*−24.20	+857	−34169	−35016	*+12788	-------	*+3031	364.7
		s.d.	= (3396)	-------	-------	-------	(63.8)	(49.85)	(345.4)	(268.8)	(0.1120)	(156.4)	(26.45)	(812)	(10717)	(25848)	(29787)	-------	(15577)	-------

[1] 160 cements; Avg=1822; S.D.=464.7. [2] 80 cements. *Coef./s.d. ratio less than 1.

Table 7–40. *Calculated contribution of independent variables to compressive strength gain in psi from 7 to 28 days, SG(1), of 1:2.75 (cement to graded Ottawa sand) mortar cubes, water-stored, and the calculated ranges of such contributions*

Independent variable	Range of variable (percent)	Coefficients from eq (4) of table 7–38	Calculated contribution to SG(1)	Calculated range of contribution to SG(1)
			Const.=+3994	
C_3S	20 to 65	−12.03	−24 to −782	758
C_4AF	1 to 16	+48.58	+49 to +777	728
Na_2O	0 to 0.7	−470.5	0 to −329	329
K_2O	0 to 1.1	−332.2	0 to −365	365
APF	*2500 to 5500	−0.2164	−541 to −1190	649
SO_3	1.2 to 3.0	−340.3	−408 to −1021	613
Air, 1:4 mortar	1 to 21	−27.10	−27 to −569	542
Zr	0 to 0.5	+1338	0 to +669	669
Cr	0 to 0.02	−23043	0 to −461	461
Rb**	0 to 0.01	−25000	0 to −250	250
Co**	0 to 0.01	−23764	0 to −238	238
V**	0 to 0.1	−2352	0 to −235	235

*cm^2/g.
**Doubtful significance. Coef./s.d. ratio less than 2.

fluencing strength. Fe_2O_3 and Na_2O also appeared to have an effect on the strength gain and the ratio, but not on the 7- and 28-day strengths per se.

The contributions of various independent variables to the compressive-strength-gain ratios were calculated from eq 3, table 7–42, and are presented in table 7–44 together with the calculated ranges of these contributions. Zr appeared to be associated with higher strength gain ratio, and Ti, Pb, and V were not highly significant. Increases in all other independent variables appeared to be associated with lower strength-gain ratios.

Table 7–41. *Frequency distribution of cements with respect to strength-gain ratio from 7 to 28 days of 1:2.75 (cement to graded Ottawa sand) mortar cubes stored in water. Strength-gain ratio, SGR(1)=(28-day—7-day)/7-day*

Tyyc Cement	Strength-gain ratio													Total
	0 to 0.15	0.15 to 0.30	0.30 to 0.45	0.45 to 0.60	0.60 to 0.75	0.75 to 0.90	0.90 to 1.05	10.5 to 1.20	1.20 to 1.35	1.35 to 1.50	1.50 to 1.65	1.65 to 1.80	1.80 to 1.95	
	Number of cements													
I		3	27	34	15	2		1						82
IA			1	4	2	1								8
II		1	2	15	18	20	7	2	1	1			1	68
IIA		1		1		1								3
III	4	10	4	2										20
IIIA	2		1											3
IV & V				2	5	3	1	2		1		1		15
Total	6	15	35	58	40	27	8	5	1	2		1	1	199

5.13. Compressive Strength Gain from 7 Days to 1 Year

The frequency distributions of the compressive-strength gain values from 7 days to 1 year for water-stored specimens made of the cements of the different types are presented in table 7–45. In one instance the compressive strength at 1 year was less than at 7 days. Although there was considerable overlapping obtained with the different types, the cements classified as types IV and V had a higher mean value than was obtained with the other types. The average gain of each of the types of cements was previously presented graphically in figure 7–1 but does not indicate the spread of the individual values.

The results of plotting the compressive strength gain from 7 days to 1 year for both water-stored

Table 7–42. *Equations relating the compressive-strength-gain ratio, (28-day*

Equation	Note	Const.		C_3A	C_3S	CaO	SiO_2	Fe_2O_3	SO_3	Na_2O
1	[1]	SGR(1)	=+1.825	−0.0297	−0.0104					
		s.d.	= (0.099)	(0.0036)	(0.0019)					
2	[1]	SGR(1)	=+2.055	−0.0179	−0.0128				−0.1309	−0.1353
		s.d.	= (0.103)	(0.0039)	(0.0018)				(0.0399)	(0.0645)
3	[1]	SGR(1)	=+2.238	−0.0218	−0.0124				−0.1226	−0.1724
		s.d.	= (0.102)	(0.0038)	(0.0017)				(0.0369)	(0.0594)
3A	[2]	SGR(1) (odd)	=+2.165	−0.0237	−0.0108				−0.1009	*−0.0651
		s.d.	= (0.143)	(0.0052)	(0.0021)				(0.0595)	(0.0776)
3B	[3]	SGR(1) (even)	=+2.372	−0.0206	−0.0158				−0.1498	−0.4021
		s.d.	= (0.161)	(0.0057)	(0.0028)				(0.0509)	(0.1037)
4	[1]	SGR(1)	=+2.304	−0.0221	−0.0128				−0.1569	−0.1725
		s.d.	= (0.116)	(0.0039)	(0.0017)				(0.0360)	(0.0607)
5	[1]	SGR(1)	=+1.870			−0.0458	+0.0853	+0.0640		
		s.d.	= (0.650)			(0.0104)	(0.0092)	(0.0164)		
6	[1]	SGR(1)	=+5.100			−0.0772	+0.0510	+0.0354	−0.1442	−0.1606
		s.d.	= (0.792)			(0.0108)	(0.0102)	(0.0156)	(0.0409)	(0.0625)
7	[1]	SGR(1)	=+4.537			−0.0692	+0.0567	+0.0448	−0.1362	−0.1884
		s.d.	= (0.739)			(0.0101)	(0.0095)	(0.0145)	(0.0377)	(0.0582)
7A	[2]	SGR(1) (odd)	=+3.952			−0.0607	+0.0536	+0.0699	−0.1354	*−0.0616
		s.d.	= (1.089)			(0.0150)	(0.0121)	(0.0196)	(0.0596)	(0.0723)
7B	[3]	SGR(1) (even)	=+5.695			−0.0903	+0.0702	*+0.0137	−0.1495	−0.4619
		s.d.	= (1.073)			(0.0151)	(0.0148)	(0.0219)	(0.0509)	(0.1026)
8	[1]	SGR(1)	=+4.872			−0.0750	+0.0607	+0.0444	−0.1557	−0.2017
		s.d.	= (0.784)			(0.0106)	(0.0098)	(0.0149)	(0.0370)	(0.0597)

[1] 169 cements; Avg=0.5811; S.D.=0.2146. [2] 85 cements. [3] 84 cements. *Coef./s.d. ratio less than 1.

and air-stored specimens versus various independent variables are presented in figure 7–4. Of the various independent variables, for which relationships were plotted for the water-stored specimens, only CaO, MgO and fineness had quadrant sum absolute values less than 11.

Equations relating the 7-day to 1-year compressive-strength gain of AE+NAE cements to various independent variables are presented in table 7–46. The use of only 3 independent variables and the constant as in eq 1 resulted in a highly significant decrease in the S.D. value. The addition of 3 more commonly determined variables as in eq 2 resulted in a further significant decrease in the S.D. values. The further inclusion of 4 trace elements as in eq 4 also resulted in a significant decrease in the S.D. value although two of the latter, P and Rb, did not appear to be highly significant. Similar compaiisons may be made for eqs 6 and 7 or 7 and 8 (see table 7–75). C_2S was used in eq 3 and resulted in a slightly higher S.D. value than when C_3S was used as in eq 2. In eqs 5 and 6, the use of Fe_2O_3 instead of Al_2O_3 also resulted in a lower S.D. value. In eqs 4A, 4B, 8A, and 8B for the "odds" and "evens" in the array of cements P and Rb had coef./s.d. ratios less than one in eqs 4B and 8B.

The equations for the NAE cements presented in table 7–47 were consistent with those of table 7–46 where the AE cements were included except that in the "odds" and "evens" there were instances in eqs 4B and 8B where the coef./s.d. ratios of Loss, Zr, P, and Ti were less than one.

The contributions and ranges of contributions of the independent variables of the 7-day to 1-year compressive-strength gain as calculated from eq 4 of table 7–46 are presented in table 7–48. Of the variables, increases in Loss and Zr and possibly P appear associated with greater strength gain, and increases in the others with lower strength-gain values.

5.14. Compressive-Strength-Gain Ratio, (1 year −7 day)/7 day, (SGR(2)), for Water-Stored Specimens

The frequency distributions of the 7 days to 1 year compressive-strength-gain-ratio values obtained with the different types of cement are presented in table 7–49. The cements classified as types II, IV, and V had the higher values although there was considerable overlapping of the values obtained with the different types.

Equations relating the compressive-strength-gain ratios obtained with the AE+NAE cements, and with the NAE cements alone, are presented in tables 7–50 and 7–51 respectively. The use of the independent variables in eq 1, table 7–50 resulted in a highly significant reduction in the S.D. value. The use of additional commonly determined variables, as in eq 2 resulted in a further significant reduction in the S.D. value, and use of the trace elements and Loss, as in eq 3, resulted in a further significant reduction in the S.D. value. Similar comparisons may be made with eqs 5 and 6, or with eqs 6 and 7, where the major oxides were included as independent variables, and the reduction of the S.D. values were in both instances highly significant (see table 7–75). In eqs 3 and 7, however, air in 1:4 mortar, Rb, and P did not show evidence of being highly

−7 day)/7-day, water-stored, for AE+NAE cements to various independent variables

K_2O	APF	WAGN.	Zr	Cr	Ti	Pb	V	Loss	S.D.
---------	−0.000137 (0.000023)	---------	---------	---------	---------	---------	---------	---------	0.1475
−0.1634 (0.0544)	−0.000097 (0.000027)	---------	---------	---------	---------	---------	---------	---------	0.1365
−0.1707 (0.0506)	−0.000122 (0.000025)	---------	+0.761 (0.242)	−7.213 (2.431)	−0.1694 (0.0901)	−2.276 (1.608)	−0.959 (0.620)	---------	0.1238
−0.1926 (0.0689)	−0.000137 (0.000034)	---------	*−0.097 (1.286)	−5.616 (3.422)	*−0.0947 (0.1409)	−2.258 (1.745)	−1.246 (1.133)	---------	0.1185
−0.1108 (0.0809)	−0.000092 (0.000041)	---------	+1.026 (0.280)	−10.232 (3.843)	*−0.1762 (0.2130)	*−0.861 (5.431)	*−0.675 (0.821)	---------	0.1299
−0.1638 (0.0520)	---------	−0.000203 (0.000052)	+0.917 (0.251)	−7.873 (2.335)	−0.1910 (0.0917)	−2.394 (1.642)	---------	−0.0264 (0.0203)	0.1264
---------	−0.000122 (0.000022)	---------	---------	---------	---------	---------	---------	---------	0.1455
−0.2496 (0.0583)	−0.000114 (0.000024)	---------	---------	---------	---------	---------	---------	---------	0.1322
−0.2290 (0.0543)	−0.000125 (0.000023)	---------	+0.795 (0.237)	−7.659 (2.275)	−0.1673 (0.0876)	−2.386 (1.574)	---------	---------	0.1215
−0.2425 (0.0728)	−0.000121 (0.000029)	---------	*+0.098 (1.243)	−6.610 (3.061)	−0.1312 (0.1266)	−2.520 (1.620)	---------	---------	0.1137
−0.1707 (0.0822)	−0.000114 (0.000036)	---------	+1.070 (0.268)	−10.613 (3.531)	*−0.0870 (0.2077)	*+0.359 (5.204)	---------	---------	0.1249
−0.2374 (0.0561)	---------	−0.000209 (0.000047)	+0.988 (0.245)	−6.780 (2.308)	−0.1787 (0.0896)	−2.450 (1.599)	---------	−0.0509 (0.0204)	0.1232

TABLE 7–43. *Equations relating the compressive-strength-gain ratio, (28-day*

Equation	Note	Const.		C_3A	C_3S	CaO	SiO_2	Fe_2O_3	SO_3	Na_2O
1	[1]	SGR(1)	=+1.809	−0.0292	−0.0103					
		s.d.	= (0.104)	(0.0037)	(0.0020)					
2	[1]	SGR(1)	=+2.035	−0.0180	−0.0126				−0.1258	−0.1166
		s.d.	= (0.110)	(0.0041)	(0.0019)				(0.0416)	(0.0673)
3	[1]	SGR(1)	=+2.220	−0.0213	−0.0124				−0.1209	−0.1605
		s.d.	= (0.109)	(0.0040)	(0.0018)				(0.0388)	(0.0623)
3A	[2]	SGR(1) (odd)	=+2.122	−0.0212	−0.0119				−0.1243	−0.1386
		s.d.	= (0.145)	(0.0059)	(0.0022)				(0.0629)	(0.0840)
3B	[3]	SGR(1) (even)	=+2.398	−0.0190	−0.0146				−0.1500	−0.2746
		s.d.	= (0.183)	(0.0058)	(0.0032)				(0.0556)	(0.1075)
4	[1]	SGR(1)	=+2.291	−0.0218	−0.0129				−0.1557	−0.1624
		s.d.	= (0.126)	(0.0041)	(0.0018)				(0.0379)	(0.0637)
5	[1]	SGR(1)	=+1.819			−0.0440	+0.0817	+0.0695		
		s.d.	= (0.690)			(0.0109)	(0.0096)	(0.0173)		
6	[1]	SGR(1)	=+4.990			−0.0751	+0.0488	+0.0394	−0.1396	−0.1405
		s.d.	= (0.848)			(0.0115)	(0.0106)	(0.0167)	(0.0427)	(0.0651)
7	[1]	SGR(1)	=+4.461			−0.0676	+0.0549	+0.0475	−0.1331	−0.1736
		s.d.	= (0.793)			(0.0108)	(0.0099)	(0.0155)	(0.0395)	(0.0609)
7A	[2]	SGR(1) (odd)	=+5.076			−0.0753	+0.0496	+0.0319	−0.1545	−0.1663
		s.d.	= (1.099)			(0.0146)	(0.0137)	(0.0235)	(0.0630)	(0.0826)
7B	[3]	SGR(1) (even)	=+4.086			−0.0624	+0.0587	+0.0567	−0.1401	−0.2616
		s.d.	= (1.298)			(0.0183)	(0.0151)	(0.0234)	(0.0573)	(0.1055)
8	[1]	SGR(1)	=+4.752			−0.0731	+0.0597	+0.0477	−0.1535	−0.1874
		s.d.	= (0.839)			(0.0113)	(0.0103)	(0.0160)	(0.0390)	(0.0627)

[1] 157 cements; Avg=0.5847; S.D.=0.2150. [2] 79 cements. [3] 78 cements. *Coef./s.d. ratio less than 1.

significant. In the equations for the "odds" and "evens" in the array of cements, eqs 3A, 3B, 7A and 7B it may be noted that the air content and the trace elements had coef./s.d. ratios less than one in one or both of the equations.

The equations presented in table 7–51 for the NAE cements alone are consistent with those presented in the previous table where the AE cements were included.

The contributions and ranges of contributions of the various independent variables to the strength-gain ratio as calculated from eq 3 of table 7–50 are presented in table 7–52. Increases in Zr, and Loss with possibly air content were associated with higher compressive-strength-gain ratios, and increases in the other variables associated with lower strength-gain ratios. Rb and P were not highly significant.

5.15. Compressive Strength Gain From 28 Days to 1 Year (SG(3))

The frequency distributions of the compressive-strength-gain values from 28 days to 1 year for the different types of cement are presented in table 7–53. Eight of the cements had lower compressive strength values at 1 year than at 28 days. Other cements had a large strength gain during this period.

TABLE 7–44. *Calculated contribution of independent variables to compressive strength gain ratio, (28-day —7-day)/7-day, (SGR(1)), of 1:2.75 (cement to graded Ottawa sand) mortar cubes, water-stored, and the calculated ranges of such contributions*

Independent variable	Range of variable (percent)	Coefficients from eq (3) of table 7–42	Calculated contribution to SGR(1)	Calculated range of contribution to SGR(1)
			Const.=+2.238	
C_3A	1 to 15	−0.0218	−0.022 to −0.327	0.305
C_3S	20 to 65	−0.0124	−0.248 to −0.806	0.558
SO_3	1.2 to 3.0	−0.1226	−0.147 to −0.368	0.221
Na_2O	0 to 0.7	−0.1724	0 to −0.121	0.121
K_2O	0 to 1.1	−0.1707	0 to −0.188	0.188
APF	*2500 to 5500	−0.000122	−0.305 to −0.671	0.366
Zr	0 to 0.5	+0.761	0 to +0.381	0.381
Cr	0 to 0.02	−7.213	0 to −0.144	0.144
Ti**	0 to 1.0	−0.1694	0 to −0.169	0.169
Pb**	0 to 0.05	−2.276	0 to −0.119	0.119
V**	0 to 0.1	−0.959	0 to −0.096	0.096

*cm^2/g.
**Doubtful significance. Coef./s.d. ratio less than 2.

Equations relating the compressive-strength gain of the AE+NAE cements to various independent variables are presented in table 7–54. The use of the independent variables in eq 1 resulted in a significant reduction in the S.D. value. The use of the additional commonly determined variables in eq 2 resulted in a further

−7-day)/7-day, water-stored, for NAE cements to various independent variables

K_2O	APF	WAGN.	Zr	Cr	Ti	Pb	V	Loss	S.D.
----	−0.000136 (0.000025)	----	----	----	----	----	----	----	0.1490
−0.1643 (0.0572)	−0.000098 (0.000028)	----	----	----	----	----	----	----	0.1392
−0.1733 (0.0536)	−0.000119 (0.000027)	----	+0.763 (0.250)	−6.650 (2.564)	−0.2042 (0.0957)	−2.246 (1.652)	−0.857 (0.643)	----	0.1270
−0.1094 (0.0792)	−0.000112 (0.000037)	----	+1.319 (0.656)	*−1.593 (4.212)	−0.2454 (0.1260)	−2.093 (1.908)	−1.743 (1.084)	----	0.1280
−0.2575 (0.0799)	−0.000105 (0.000043)	----	+0.681 (0.286)	−11.996 (3.685)	*−0.0993 (0.2137)	*−3.528 (4.614)	*−0.408 (0.855)	----	0.1302
−0.1649 (0.0549)	----	−0.000198 (0.000055)	+0.917 (0.259)	−7.180 (2.474)	−0.2248 (0.0974)	−2.344 (1.688)	----	−0.0268 (0.0216)	0.1296
----	−0.000122 (0.000023)	----	----	----	----	----	----	----	0.1471
−0.2503 (0.0615)	−0.000115 (0.000026)	----	----	----	----	----	----	----	0.1349
−0.2318 (0.0577)	−0.000125 (0.000024)	----	+0.785 (0.244)	−7.079 (2.395)	−0.1947 (0.0931)	−2.331 (1.616)	----	----	0.1245
−0.2077 (0.0854)	−0.000112 (0.000033)	----	+1.398 (0.634)	*−2.395 (3.819)	−0.2817 (0.1162)	−2.856 (1.832)	----	----	0.1240
−0.2730 (0.0868)	−0.000127 (0.000039)	----	+0.685 (0.285)	−11.411 (3.561)	*−0.0779 (0.2198)	*−3.142 (4.649)	----	----	0.1304
−0.2347 (0.0594)	----	−0.000207 (0.000050)	+0.980 (0.254)	−6.173 (2.445)	−0.2055 (0.0956)	−2.410 (1.648)	----	−0.0505 (0.0217)	0.1266

Table 7–45. Frequency distribution of cements with respect to compressive strength change from 7 days to 1 year of 1:2.75 (cement to graded Ottawa sand) mortar cubes, water-stored

Type Cement	Compressive strength changes, psi×10⁻³													Total
	−0.5 to 0	0 to +0.5	+0.5 to +1.0	+1.0 to +1.5	+1.5 to +2.0	+2.0 to +2.5	+2.5 to +3.0	+3.0 to +3.5	+3.5 to +4.0	+4.0 to +4.5	+4.5 to +5.0	+5.0 to +5.5	+5.5 to +6.0	
	Number of cements													
I	-----	-----	-----	3	16	23	21	14	3	1	-----	-----	-----	81
IA	-----	-----	-----	1	3	1	2	-----	1	-----	-----	-----	-----	8
II	-----	-----	-----	-----	1	1	13	12	19	11	10	1	-----	68
IIA	-----	-----	-----	-----	-----	-----	3	-----	-----	-----	-----	-----	-----	3
III	1	-----	4	3	6	2	1	1	2	-----	-----	-----	-----	20
IIIA	-----	1	-----	-----	1	-----	1	-----	-----	-----	-----	-----	-----	3
IV & V	-----	-----	-----	-----	-----	-----	-----	2	3	3	6	-----	1	15
Total	1	1	4	7	27	27	41	29	28	15	16	1	1	198

significant decrease in the S.D. value, and by use of three trace elements as in eq 3 a further significant decrease in the S.D. value was attained although two of the three, P and Ti, did not appear highly significant. Similar reductions were obtained in eqs 5, 6, and 7 where the major oxides were used in the equations (see also table 7–75). In the equations for the "odds" and "evens" in the array of cements, C_4AF, P, and Ti had coef./s.d. ratios less than 1 in one or both of the groups. The differences of the coefficient and the coef./s.d. ratio of APF in eqs 1, 2, and 3, or in eqs 4, 5, and 6 indicate, to some extent, as in previous tables the interrelation of this variable with other variables. This will be dealt with more fully in the discussion (subsection 6).

The equations for the NAE cements alone (table 7–55) are consistent with those in table 7–54 where the AE cements were included except that the use of the additional variables in eq 3, table 7–55 resulted in a reduction of the S.D. value which was significant only at the five percent probability level.

TABLE 7–46. *Equations relating the compressive strength gain in psi from 7 days to 1 year water-stored of AE+NAE cements to various independent variables*

Equation	Note		Const.	C_3A	C_3S	C_2S	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	APF	Loss	Zr	P	Rb	Ti	S.D.
1	(1)	SG(2) =	+8553	−206.1	−49.52								−0.4046						615.4
		s.d. =	(399)	(14.7)	(7.65)								(0.0975)						
2	(1)	SG(2) =	+9869	−164.2	−60.26						−1012	−1246	−0.5918	+238.2					536.6
		s.d. =	(389)	(14.5)	(6.83)						(250)	(200)	(0.0943)	(84.0)					
3	(1)	SG(2) =	+4760	−127.1		+60.67					−937	−948	−0.5708	+295.2					543.5
		s.d. =	(492)	(16.2)		(7.17)					(253)	(200)	(0.0967)	(85.7)					
4	(1)	SG(2) =	+10168	−167.0	−63.70						−1187	−1079	−0.5626	+169.1	+2860	+671.9	−31963	−976	515.4
		s.d. =	(396)	(14.2)	(6.62)						(245)	(212)	(0.0920)	(83.9)	(1022)	(369.6)	(23242)	(341)	
4A	(2)	SG(2) (odd) =	+10774	−158.5	−60.27						−1093	−1031	−0.8361	+236.9	+2065	+1092.2	−47647	−1062	497.8
		s.d. =	(599)	(18.6)	(9.16)						(299)	(298)	(0.1478)	(126.0)	(1098)	(526.1)	(31751)	(538)	
4B	(3)	SG(2) (even) =	+9946	−168.5	−70.37						−1417	−1034	−0.3922	+173.3	+5584	*+334.4	*−9169	−1220	537.7
		s.d. =	(563)	(23.8)	(10.51)						(436)	(325)	(0.1269)	(119.9)	(2801)	(543.5)	(36835)	(511)	
5	(1)	SG(2) =	+12114				+426.9	−234.6		−249.1			−0.3842						658.1
		s.d. =	(3281)				(79.3)	(96.5)		(44.6)			(0.1107)						
6	(1)	SG(2) =	+1317				+552.8		+406.9	−169.6			−0.2455						603.4
		s.d. =	(2674)				(38.0)		(64.5)	(43.2)			(0.0913)						
7	(1)	SG(2) =	+9295				+486.7		+340.1	−247.3	−1014	−1134	−0.5209	+259.0					532.8
		s.d. =	(3091)				(38.2)		(59.9)	(43.7)	(249)	(232)	(0.0921)	(88.9)					
8	(1)	SG(2) =	+9438				+499.2		+364.4	−253.1	−1170	−950	−0.4982	+191.3	+2784	+681.0	−32134	−1026	510.3
		s.d. =	(2978)				(37.4)		(58.0)	(42.2)	(243)	(239)	(0.0894)	(88.4)	(1016)	(365.6)	(22950)	(339)	
8A	(2)	SG(2) (odd) =	+10004				+458.4		+368.7	−234.9	−1071	−933	−0.7604	+250.1	+2034	+1096.7	−49130	+1186	497.5
		s.d. =	(4172)				(51.7)		(80.0)	(58.5)	(303)	(348)	(0.1494)	(130.5)	(1099)	(529.0)	(30596)	(537)	
8B	(3)	SG(2) (even) =	+11024				+517.4		+361.3	−290.6	−1387	−974	−0.3562	+170.3	+5282	*+341.2	*−8674	−1199	533.5
		s.d. =	(4640)				(58.6)		(91.2)	(65.6)	(424)	(364)	(0.1191)	(131.1)	(2831)	(536.2)	(36448)	(510)	

[1] 178 cements; Avg=2984; S.D.=1040.7. [2] 89 cements. [3] 88 cements. *Coef./s.d. ratio less than 1.

TABLE 7–47. *Equations relating the compressive strength gain in psi from 7 days to 1 year water-stored of NAE cements to various independent variables*

Equation	Note		Const.	C_3A	C_3S	C_2S	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	APF	Loss	Zr	P	Rb	Ti	S.D
1	(1)	SG(2)	= +8600	−197.0	−50.88								−0.4116						597.7
		s.d.	= (402)	(14.8)	(7.61)								(0.0979)						
2	(1)	SG(2)	= +9842	−158.0	−61.56						−908	−1153	−0.5936	+243.0					529.1
		s.d.	= (400)	(14.7)	(6.92)						(252)	(205)	(0.0954)	(84.8)					
3	(1)	SG(2)	= +4642	−121.2		+61.64					−837	−848	−0.5712	+297.8					539.2
		s.d.	= (501)	(16.7)		(7.35)					(255)	(205)	(0.0984)	(87.1)					
4	(1)	SG(2)	=+10138	−158.7	−65.65						−1086	−906	−0.5598	+161.6	+2959	+632.4	−52281	−958	502.8
		s.d.	= (403)	(14.4)	(6.65)						(244)	(218)	(0.0920)	(83.9)	(1005)	(361.8)	(23417)	(342)	
4A	(2)	SG(2) (odd)	=+10535	−154.3	−61.49						−992	−830	−0.7408	+206.8	+2889	+1166.0	−54929	−1538	477.7
		s.d	= (579)	(19.4)	(8.61)						(292)	(296)	(0.1416)	(117.4)	(1017)	+498.0	(31143)	(527)	
4B	(2)	SG(2) (even)	= +9979	−154.5	−73.06						−1405	−914	−0.4226	+139.4	*−5376	*+193.1	−42423	*−120	530.5
		s.d.	= (587)	(23.3)	(11.30)						(480)	(346)	(0.1333)	(127.9)	(6733)	(546.0)	(37014)	(622)	
5	(1)	SG(2)	=+13995				+412.6	−225.0		−272.8			−0.4028						641.4
		s.d.	= (3267)				(79.6)	(96.8)		(44.4)			(0.1114)						
6	(1)	SG(2)	= +3129				+534.7		+387.8	−189.0			−0.2711						591.1
		s.d.	= (2745)				(38.2)		(65.6)	(43.7)			(0.0930)						
7	(1)	SG(2)	=+10767				+473.9		+317.6	−264.3	−925	−1086	−0.5333	+249.1					527.1
		s.d.	= (3181)				(38.6)		(61.8)	(44.6)	(251)	(236)	(0.0941)	(89.3)					
8	(1)	SG(2)	=+10830				+484.0		+343.4	−268.5	−1076	−818	−0.5074	+169.3	+2900	+644.5	−50646	−982	500.4
		s.d.	= (3041)				(37.5)		(59.4)	(42.8)	(243)	(244)	(0.0905)	(88.3)	(1003)	(359.6)	(23206)	(343)	
8A	(2)	SG(2) (odd)	=+10773				+440.7		+386.3	−244.4	−982	−777	−0.6907	+221.8	+2850	+1165.8	−51034	−1648	471.8
		s.d.	= (4564)				(50.8)		(79.2)	(62.9)	(292)	(354)	(0.1423)	(119.3)	(1006)	(496.2)	(30151)	(520)	
8B	(2)	SG(2) (even)	=+13035				+508.6		+274.3	−312.6	−1457	−861	−0.4111	*+111.5	*−5266	*207.2	−39507	*−71	530.7
		s.d.	= (4501)				(58.4)		(96.7)	(64.6)	(480)	(370)	(0.1266)	(140.9)	(6721)	(547.5)	(37408)	(624)	

[1] 166 cements; Avg=3043; S.D.=1024.8. [2] 83 cements. *Coef./s.d. ratio less than 1.

Table 7–48. *Calculated contribution of independent variables to compressive strength in psi gain from 7 days to 1 year, SG(2), of 1:2.75 (cement to graded Ottawa sand) mortar cubes, water-stored, and calculated ranges of such contributions*

Independent variable	Range of variable (percent)	Coefficients from eq (4) of table 7–46	Calculated contribution to SG(2)	Calculated range of contribution to SG(2)
			Const. = +10168	
C_3A	1 to 15	−167.0	−167 to −2505	2338
C_3S	20 to 65	−63.7	−1274 to −4141	2867
Na_2O	0 to 0.7	−1187	0 to −831	831
K_2O	0 to 1.1	−1079	0 to −1187	1187
APF	*2500 to 5500	−0.5626	−1407 to −3094	1687
Loss	0.3 to 3.3	+169.1	+51 to +558	507
Zr	0 to 0.5	+2860	0 to +1430	1430
P**	0 to 0.5	+671.9	0 to +336	336
Rb**	0 to 0.01	−31953	0 to −320	320
Ti	0 to 1.0	−976	0 to −976	976

*cm^2/g.
**Doubtful significance. Coef./s.d. ratio less than 2.

Table 7–49. *Frequency distribution of cements with respect to strength-gain ratio from 7 days to 1 year of 1:2.75 (cement to graded Ottawa sand) mortar cubes stored in water*

Strength-gain ratio SGR(2) = (1-year—7-day)/7-day

Type Cement	Strength-gain ratio													Total
	−0.3 to 0	0 to 0.3	0.3 to 0.6	0.6 to 0.9	0.9 to 1.2	1.2 to 1.5	1.5 to 1.8	1.8 to 2.1	2.1 to 2.4	2.4 to 2.7	2.7 to 3.0	3.0 to 3.3	3.3 to 3.6	
	Nymber of Cements													
I	----	--	22	36	20	3	---	---	---	---	---	---	---	81
IA	----	--	1	3	3	---	1	---	---	---	---	---	---	8
II	----	--	1	7	21	21	12	4	---	1	---	1	---	68
IIA	----	--	--	3	---	---	---	---	---	---	---	---	---	3
III	1	8	7	2	2	---	---	---	---	---	---	---	---	20
IIIA	----	1	1	1	---	---	---	---	---	---	---	---	---	3
IV & V	----	--	--	---	---	5	2	5	1	---	1	---	1	15
Total	1	9	32	52	46	29	15	9	1	1	1	1	1	198

Table 7–50. *Equations relating the compressive-strength-gain ratio (1-year — 7-day)/*

Equation	Note	Const.	C_3A	C_3S	CaO	SiO_2	Fe_2O_3	Na_2O	K_2O
1	(1)	SGR(2) = +3.925	−0.0874	−0.0297	----	----	----	----	----
		s.d. = (0.170)	(0.0063)	(0.0033)	----	----	----	----	----
2	(1)	SGR(2) = +4.378	−0.0665	−0.0337	----	----	----	−0.3848	−0.5075
		s.d. = (0.168)	(0.0065)	(0.0030)	----	----	----	(0.1099)	(0.0923)
3	(1)	SGR(2) = +4.561	−0.0682	−0.0353	----	----	----	−0.4361	−0.4223
		s.d. = (0.169)	(0.0062)	(0.0028)	----	----	----	(0.1049)	(0.0955)
3A	(2)	SGR(2) (odd) = +4.456	−0.0733	−0.0353	----	----	----	−0.3235	−0.2791
		s.d. = (0.245)	(0.0088)	(0.0038)	----	----	----	(0.1291)	(0.1409)
3B	(2)	SGR(2) (even) = +4.717	−0.0595	−0.0354	----	----	----	−0.6152	−0.5328
		s.d. = (0.261)	(0.0097)	(0.0045)	----	----	----	(0.1948)	(0.1441)
4	(1)	SGR(2) = +4.818	−0.0735	−0.0358	----	----	----	−0.4471	−0.4139
		s.d. = (0.190)	(0.0065)	(0.0027)	----	----	----	(0.1045)	(0.0949)
5	(1)	SGR(2) = +3.863	----	----	−0.1341	+0.2682	+0.1269	----	----
		s.d. = (1.102)	----	----	(0.0179)	(0.0162)	(0.0276)	----	----
6	(1)	SGR(2) = +8.720	----	----	−0.1814	+0.2182	+0.0889	−0.4038	−0.5967
		s.d. = (1.290)	----	----	(0.0179)	(0.0171)	(0.0261)	(0.1057)	(0.0975)
7	(1)	SGR(2) = +7.765	----	----	−0.1716	+0.2310	+0.1062	−0.4399	−0.4805
		s.d. = (1.299)	----	----	(0.0179)	(0.0170)	(0.0254)	(0.1032)	(0.1025)
7A	(2)	SGR(2) (odd) = +6.650	----	----	−0.1628	+0.2448	+0.1252	−0.3332	−0.3191
		s.d. = (1.824)	----	----	(0.0242)	(0.0242)	(0.0334)	(0.1288)	(0.1590)
7B	(2)	SGR(2) (even) = +8.921	----	----	−0.1779	+0.2118	+0.0807	−0.5806	−0.6097
		s.d. = (2.010)	----	----	(0.0287)	(0.0260)	(0.0424)	(0.1916)	(0.1499)
8	(1)	SGR(2) = +8.008	----	----	−0.1778	+0.2450	+0.1124	−0.4499	−0.4738
		s.d. = (1.225)	----	----	(0.0171)	(0.0165)	(0.0250)	(0.1011)	(0.0996)

[1] 174 cements; Avg=0.9842; S.D.=0.4698. [2] 87 cements. *Coef./s.d. ratio less than 1.

The contributions of the various independent variables to the compressive-strength gain between 28 days and 1 year for the water-stored specimens were calculated from eq 3 of table 7–54 and are presented in table 7–56 together with the calculated ranges of these contributions. Increases in Loss, V, and possibly P, appear to be associated with higher compressive-strength-gain values, and increases in the other variables appear associated with a decrease in the strength-gain values. Ti was not highly significant. C_3A, C_3S, and Loss appear to have the dominant role with respect to this property.

5.16. Compressive-Strength-Gain Ratio (1 Year −28 Day)/28 Day, SGR(3), for Specimens Stored in Water

The frequency distributions of the 28-day to 1-year compressive-strength-gain-ratio values for the different types of cement are presented in table 7–57. Although there is considerable overlapping, the median values for the different types of cement increase from type III, to type I, to type II, to types IV and V.

Equations relating the compressive-strength-ratio values to combinations of independent variables are presented in table 7–58 for the AE+NAE cements, and in table 7–59 for the NAE cements alone. The use of some commonly determined variables, as in eqs 1 and 5, resulted in highly significant reductions in the S.D. values. Additional commonly determined independent variables added in eqs 2 and 6, resulted in a further significant reduction in the S.D. values, but the addition of two trace elements in eqs 3 and 7 did not result in a reduction of the S.D. value significant at the five percent probability level. Similar results were obtained for the NAE

7-day, water-stored, for AE+NAE cements to various independent variables

SO_3	WAGN.	APF	Air 1:4 mortar	Zr	Rb	Ti	P	Loss	S.D.
		−0.000210 (0.000041)							0.2576
−0.1298 (0.0664)		−0.000199 (0.000044)	+0.0110 (0.0050)						0.2288
−0.1626 (0.0628)		−0.000231 (0.000044)	+0.0095 (0.0048)	+1.232 (0.425)	−12.79 (9.89)	−0.3333 (0.1443)	+0.2015 (0.1536)	+0.1010 (0.0350)	0.2138
−0.2127 (0.0988)		−0.000177 (0.000056)	+0.0106 (0.0067)	+1.269 (0.452)	−30.25 (13.96)	−0.4559 (0.2335)	+0.4628 (0.2568)	+0.0967 (0.0489)	0.2071
−0.1671 (0.0915)		−0.000287 (0.000073)	+0.0106 (0.0073)	*+1.234 (1.248)	*+6.38 (14.81)	−0.2520 (0.2210)	*+0.0267 (0.2017)	+0.1152 (0.0532)	0.2238
−0.1730 (0.0576)	−0.000452 (0.000084)		+0.0082 (0.0048)	+1.599 (0.415)	−19.39 (9.89)	−0.3554 (0.1431)	+0.2266 (0.1533)		0.2139
		−0.000160 (0.000037)							0.2492
−0.0752 (0.0676)		−0.000215 (0.000040)	+0.0077 (0.0050)						0.2216
−0.0756 (0.0645)		−0.000241 (0.000041)	+0.0071 (0.0048)	+1.270 (0.421)	−10.61 (9.71)	−0.2873 (0.1425)	+0.2137 (0.1513)	+0.0736 (0.0367)	0.2108
−0.1065 (0.1011)		−0.000193 (0.000053)	+0.0092 (0.0067)	+1.301 (0.448)	−27.37 (13.49)	−0.4115 (0.2289)	+0.4951 (0.2548)	+0.0817 (0.0521)	0.2052
−0.1019 (0.0950)		−0.000284 (0.000071)	*+0.0066 (0.0073)	*+1.191 (1.258)	*+8.31 (14.75)	*−0.1858 (0.2220)	*+0.0237 (0.2002)	+0.0710 (0.0564)	0.2221
−0.0977 (0.0614	−0.000467 (0.000077)		+0.0055 (0.0048)	+1.581 (0.406)	−17.00 (9.66)	−0.2951 (0.1404)	+0.2488 (0.1495)		0.2092

Table 7–51. *Equations relating the compressive-strength-gain ratio (1-year*

Equation	Note	Const.		C_3A	C_3S	CaO	SiO_2	Fe_2O_3	Na_2O	K_2O
1	(1)	SGR(2)	=+3.912	−0.0874	−0.0291					
		s.d.	= (0.179)	(0.0066)	(0.0034)					
2	(1)	SGR(2)	=+4.333	−0.0656	−0.0337				−0.3934	−0.5190
		s.d.	= (0.182)	(0.0069)	(0.0031)				(0.1203)	(0.0988)
3	(1)	SGR(2)	=+4.519	−0.0663	−0.0356				−0.4475	−0.4274
		s.d.	= (0.185)	(0.0066)	(0.0030)				(0.1157)	(0.1011)
3A	(2)	SGR(2) (odd)	=+4.350	−0.0697	−0.0334				−0.3260	−0.4711
		s.d.	= (0.262)	(0.0096)	(0.0040)				(0.1444)	(0.1484)
3B	(2)	SGR(2) (even)	=+4.825	−0.0640	−0.0387				−0.7022	−0.3284
		s.d.	= (0.287)	(0.0097)	(0.0047)				(0.2038)	(0.1530)
4	(1)	SGR(2)	=+4.797	−0.0725	−0.0361				−0.4450	−0.4031
		s.d.	= (0.211)	(0.0070)	(0.0029)				(0.1153)	(0.1004)
5	(1)	SGR(2)	=+3.760			−0.1313	+0.2644	+0.1342		
		s.d.	= (1.177)			(0.0188)	(0.0169)	(0.0292)		
6	(1)	SGR(2)	=+8.846			−0.1821	+0.2139	+0.0889	−0.4121	−0.6154
		s.d.	= (1.372)			(0.0189)	(0.0180)	(0.0276)	(0.1152)	(0.1045)
7	(1)	SGR(2)	=+7.900			−0.1723	+0.2260	+0.1064	−0.4445	−0.4901
		s.d.	= (1.379)			(0.0188)	(0.0180)	(0.0269)	(0.1137)	(0.1093)
7A	(2)	SGR(2) (odd)	=+7.926			−0.1720	+0.2203	+0.1147	−0.3447	−0.5787
		s.d.	= (2.023)			(0.0270)	(0.0246)	(0.0359)	(0.1435)	(0.1684)
7B	(2)	SGR(2) (even)	=+9.117			−0.1889	+0.2311	+0.0799	−0.6962	−0.3921
		s.d.	= (1.975)			(0.0277)	(0.0275)	(0.0435)	(0.1981)	(0.1577)
8	(1)	SGR(2)	=+8.022			−0.1777	+0.2454	+0.1124	−0.4111	−0.4518
		s.d.	= (1.308)			(0.0181)	(0.0173)	(0.0264)	(0.1040)	(0.1046)

[1] 162 cements; Avg=0.9923; S.D.=0.4746. [2] 81 cements. *Coef./s.d. ratio less than 1.

Table 7–52. *Calculated contribution of independent variables to compressive-strength-gain ratio, (1-year—7-day)/7-day, (SGR(2)), of 1:2.75 (cement to graded Ottawa sand) mortar cubes, water-stored, and the calculated ranges of such contributions*

Independent variable	Range of variable (percent)	Coefficients from eq (3) of table 7-50	Calculated contribution to SGR(2)	Calculated range of contribution to SGR(2)
			Const.=+4.561	
C_3A	1 to 15	−0.0682	−0.068 to −1.023	0.955
C_3S	20 to 65	−0.0353	−0.706 to −2.295	1.589
Na_2O	0 to 0.7	−0.4361	0 to −0.305	0.305
K_2O	0 to 1.1	−0.4223	0 to −0.465	0.465
SO_3	1.2 to 3.0	−0.1626	−0.195 to −0.488	0.293
APF	*2500 to 5500	−0.000231	−0.578 to −1.271	0.693
Air, 1:4 mortar**	1 to 21	+0.0095	+0.010 to +0.200	0.190
Zr	0 to 0.5	+1.232	0 to +0.666	0.666
Rb**	0 to 0.01	−12.79	0 to −0.128	0.128
Ti	0 to 1.0	−0.3333	0 to −0.333	0.333
P**	0 to 0.5	+0.2015	0 to +0.101	0.101
Loss	0.3 to 3.3	+0.1010	+0.030 to +0.333	0.303

*cm²/g.
**Doubtful significance. Coef./s.d. ratio less than 2.

Table 7–53. *Frequency distribution of cements with respect to compressive strength change from 28 days to 1 year of 1:2.75 (cement to graded Ottawa sand) mortar cubes, water-stored*

Type Cement	Compressive strength change, psi×10⁻³: −1.0 to −0.5	−0.5 to 0	0 to +0.5	+0.5 to +1.0	+1.0 to +1.5	+1.5 to +2.0	+2.0 to +2.5	+2.5 to +3.0	+3.0 to +3.5	+3.5 to +4.0	+4.0 to +4.5	Total
	Number of cements											
I		1	21	33	18	7	1					81
IA			1	5	1	1						8
II			2	7	18	25	11	5				68
IIA				1	1	1						3
III	2	4	5	5	2		2					20
IIA		1		1	1							3
IV & V					3	3	4	2	1	1	1	15
Total	2	6	29	52	44	37	18	7	1	1	1	198

—7-day)/7-day, water-stored, for NAE cements to various independent variables

SO_3	WAGN.	APF	Air 1:4 mortar	Zr	Rb	Ti	P	Loss	S.D.
		−0.000216 (0.000043)							0.2607
−0.1258 (0.0700)		−0.000206 (0.000047)	+0.0204 (0.0117)						0.2341
−0.1623 (0.0661)		−0.000234 (0.000045)	+0.0186 (0.0113)	+1.281 (0.442)	−14.87 (10.26)	−0.3473 (0.1525)	+0.1693 (0.1605)	+0.0956 (0.0369)	0.2187
−0.1605 (0.1159)		−0.000217 (0.000059)	+0.0252 (0.0162)	+1.247 (0.456)	*−9.12 (14.03)	−0.6125 (0.2416)	+0.4818 (0.2569)	+0.1042 (0.0495)	0.2106
−0.1671 (0.0888)		−0.000261 (0.000076)	*+0.0064 (0.0176)	−3.629 (3.101)	−17.37 (15.75)	*+0.1419 (0.2887)	*+0.1016 (0.2152)	+0.0796 (0.0582)	0.2248
−0.1769) (0.0615)	−0.000453 (0.000090)		+0.0136 (0.0114)	+1.625 (0.431)	−21.16 (10.29)	−0.3665 (0.1517)	+0.2066 (0.1606)		0.2195
		−0.000165 (0.00040)							0.2583
−0.0788 (0.0712)		−0.000223 (0.000043)	+0.0156 (0.0114)						0.2271
−0.0775 (0.0680)		−0.000246 (0.000043)	+0.0140 (0.0112)	+1.294 (0.439)	−12.11 (10.11)	−0.2891 (0.1512)	+0.1902 (0.1586)	+0.0681 (0.0386)	0.2164
*−0.0957 (0.1158)		−0.000224 (0.000055)	+0.0218 (0.0161)	+1.243 (0.451)	*−8.62 (13.56)	−0.5891 (0.2347)	+0.5313 (0.2537)	+0.0830 (0.0507)	0.2073
*−0.0741 (0.0934)		−0.000268 (0.000073)	*−0.0019 (0.0172)	−4.191 (3.043)	*−10.75 (15.90)	*+0.2686 (0.2838)	*+0.0952 (0.2126)	*+0.0271 (0.0629)	0.2220
−0.0880 (0.0635)	−0.000480 (0.000083)			+1.544 (0.419)	−18.23 (10.07)	−0.3059 (0.1990)	+0.2595 (0.1541)		0.2152

cements in table 7–59 (see also table 7–75). Equation 5 in table 7–58 and also in table 7–59 indicates APF had a coef./s.d. ratio less than 1, but the variable was highly significant in eqs 6 and 7. In both of these tables, in the equations for the "odds" and "evens" in the array of cements, eqs 3A, 3B, 7A, and 7B, both P and Co had coef./s.d. ratios less than 1 in one or the other of the smaller groups. Also, in table 7–58, the C_4AF had a coef./s.d. ratio less than 1 in eq 3B.

The contributions of the different variables to the strength-gain-ratio values were calculated from eq 3 of table 7–58 and are presented in table 7–60 together with the calculated ranges of these contributions. The C_3A and C_3S were the dominant variables with respect to the calculated range of possible contribution to the compressive-strength-gain-ratio values.

5.17. Compressive Strength Gain From 28 Days to 10 Years

The frequency distributions of the compressive-strength-gain values from 28 days to 10 years of water-stored specimens of the different types of cement are presented in table 7–61. Fifty-five of the 169 cements had lower compressive strength values at 10 years than they had at 28 days. Only 5 of these were classified as type II, the others being of types I or III. There was a broad distribution of strength-gain values within each of the type classifications.

Equations relating the compressive-strength gain from 28 days to 10 years to various combinations of independent variables are presented in table 7–62 for the AE+NAE cements, and in table 7–63 for the NAE cements. Using 3 commonly determined variables and a constant as in eq 1 of table 7–62, resulted in a highly significant

TABLE 7–54. *Equations relating the compressive strength gain in psi from 28 days to 1 year of water-stored AE+NAE cements to various independent variables*

Equation	Note		Const.	C_3A	C_3S	C_4AF	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	APF	Loss	P	Ti	V	S.D.
1	[1]	SG(3)	=+5887	−180.5	−42.81	−62.74	------	------	------	------	------	------	−0.1358	------	------	------	------	496.0
		s.d.	= (465)	(14.2)	(6.32)	(20.35)	------	------	------	------	------	------	(0.0786)	------	------	------	------	------
2	[1]	SG(3)	=+6605	−158.0	−48.93	−53.40	------	------	------	------	−611.4	−650.5	−0.3331	+335.2	------	------	------	445.9
		s.d.	= (435)	(14.3)	(5.79)	(18.47)	------	------	------	------	(208.0)	(168.0)	(0.0784)	(69.8)	------	------	------	------
3	[1]	SG(3)	=+6463	−153.0	−49.34	−47.76	------	------	------	------	−615.8	−653.9	−0.3145	+349.5	+564.3	−443.0	+4796	433.7
		s.d.	= (454)	(14.9)	(5.68)	(18.17)	------	------	------	------	(203.1)	(164.0)	(0.0770)	(68.9)	(314.2)	(289.3)	(2007)	------
3A	[2]	SG(3) (odd)	=+6613	−128.7	−55.40	*−12.10	------	------	------	------	−420.0	−911.5	−0.4487	+426.3	+797.7	*−373.3	+5416	414.6
		s.d.	= (612)	(21.6)	(7.50)	(27.97)	------	------	------	------	(246.8)	(240.8)	(0.1202)	(100.8)	(458.3)	(456.1)	(2458)	------
3B	[2]	SG(3) (even)	=+6436	−164.3	−47.68	−58.70	------	------	------	------	−1043.2	−429.1	−0.2498	+320.5	+466.1	−609.6	+4429	454.9
		s.d.	= (706)	(22.4)	(9.35)	(26.20)	------	------	------	------	(360.2)	(254.3)	(0.1074)	(100.0)	(444.3)	(419.2)	(3741)	------
4	[1]	SG(3)	=+1632	------	------	------	+447.7	------	+209.4	−170.1	------	------	*−0.0038	------	------	------	------	501.4
		s.d.	= (2222)	------	------	------	(31.6)	------	(53.6)	(35.9)	------	------	(0.0758)	------	------	------	------	------
5	[1]	SG(3)	=+5191	------	------	------	+338.5	−159.6	+177.7	−169.6	------	------	−0.0856	------	------	------	------	496.4
		s.d.	= (2772)	------	------	------	(60.5)	(75.7)	(55.2)	(35.5)	------	------	(0.0846)	------	------	------	------	------
6	[1]	SG(3)	=+3834	------	------	------	+431.8	------	+196.3	−186.2	−617.7	−539.8	−0.2550	+372.9	------	------	------	447.0
		s.d.	= (2594)	------	------	------	(32.0)	------	(50.2)	(36.7)	(209.1)	(194.2)	(0.0772)	(74.6)	------	------	------	------
7	[1]	SG(3)	=+4506	------	------	------	+420.7	------	+198.5	−193.3	−623.8	−557.6	−0.2415	+377.7	+529.9	−534.8	+5300	432.7
		s.d.	= (2540)	------	------	------	(33.4)	------	(49.4)	(35.7)	(202.7)	(188.2)	(0.0752)	(72.8)	(312.1)	(288.0)	(2005)	------
7A	[2]	SG(3) (odd)	=+5223	------	------	------	+404.4	------	+247.1	−195.5	−359.3	−710.4	−0.3840	+445.1	+771.9	*−448.9	+5477	416.5
		s.d.	= (3501)	------	------	------	(46.1)	------	(67.6)	(48.7)	(251.1)	(269.5)	(0.1218)	(104.6)	(460.5)	(450.4)	(2440)	------
7B	[2]	SG(3) (even)	=+5847	------	------	------	+427.5	------	+161.5	−216.9	−1151.7	−381.5	−0.1659	+330.5	*+373.1	−644.4	+4737	455.8
		s.d.	= (3947)	------	------	------	(50.5)	------	(77.8)	(55.8)	(352.2)	(292.2)	(0.1021)	(109.6)	(443.5)	(421.3)	(3779)	------

[1] 178 cements; Avg=1191; S.D.=791.4. [2] 89 cements. *Coef./s.d. ratio less than 1.

TABLE 7–55. *Equations relating the compressive strength gain in psi from 28 days to 1 year of water-stored NAE cements to various independent variables*

Equation	Note		Const.	C_3A	C_3S	C_4AF	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	APF	Loss	P	Ti	V	S.D.
1	(1)	SG(3)	=+5931	−178.9	−42.87	−63.40							−0.1470					505.3
		s.d.	= (492)	(14.9)	(6.63)	(21.25)							(0.0828)					
2	(1)	SG(3)	=+6676	−156.2	−49.75	−55.76					−608.3	−638.0	−0.3403	+337.1				456.7
		s.d.	= (465)	(15.1)	(6.12)	(19.39)					(217.3)	(178.2)	(0.0823)	(73.1)				
3	(1)	SG(3)	=+6499	−150.1	−50.09	−48.90					−609.1	−653.7	−0.3195	+351.2	+558.9	−416.5	+4885	444.7
		s.d.	= (485)	(15.8)	(6.01)	(19.15)					(212.5)	(174.5)	(0.0809)	(72.2)	(324.1)	(306.6)	(2083)	
3A	(2)	SG(3) (odd)	=+6697	−145.2	−54.22	*−17.14					−567.4	−558.4	−0.4615	+418.0	+1047.1	*−263.6	+2946	411.6
		s.d.	= (625)	(21.8)	(7.43)	(25.60)					(251.0)	(240.8)	(0.1197)	(96.2)	(448.2)	(463.4)	(2607)	
3B	(2)	SG(3) (even)	=+6502	−155.4	−44.09	−77.16					−728.4	−745.3	−0.2962	+327.5	*+280.5	−514.8	+9012	478.0
		s.d.	= (766)	(23.8)	(10.63)	(29.66)					(435.6)	(276.9)	(0.1212)	(114.5)	(478.8)	(445.3)	(3659)	
4	(1)	SG(3)	=+2199				+444.5		+200.6	−176.5			*−0.0197					512.3
		s.d.	= (2379)				(33.1)		(56.9)	(37.9)			(0.0806)					
5	(1)	SG(3)	=+5953				+327.4	−170.3	+167.9	−175.2			−0.1046					506.6
		s.d.	= (2930)				(63.5)	(79.2)	(58.3)	(37.5)			(0.0890)					
6	(1)	SG(3)	=+4652				+428.6		+181.1	−196.2	−624.7	−553.8	−0.2671	+368.4				458.4
		s.d.	= (2766)				(33.6)		(53.7)	(38.8)	(218.6)	(205.6)	(0.0818)	(77.6)				
7	(1)	SG(3)	=+5188				+415.8		+186.0	−201.0	−622.6	−577.7	−0.2518	+373.8	+528.4	−510.3	+5459	443.9
		s.d.	= (2712)				(35.1)		(52.9)	(37.9)	(212.1)	(199.3)	(0.0796)	(75.9)	(322.1)	(305.1)	(2074)	
7A	(2)	SG(3) (odd)	=+5198				+425.5		+272.5	−204.3	−531.2	−413.6	−0.3863	+438.7	+1000.9	*−399.9	+3395	408.2
		s.d.	= (3970)				(47.0)		(68.3)	(54.3)	(250.5)	(291.0)	(0.1201)	(97.1)	(443.5)	(451.4)	(2528)	
7B	(2)	SG(3) (even)	=+6486				+397.5		*+86.8	−210.3	−895.1	−717.9	−0.2109	+326.2	*+195.3	−561.1	+9541	483.2
		s.d.	= (4112)				(54.8)		(87.4)	(58.7)	(436.1)	(301.2)	(0.1160)	(128.2)	(485.4)	(451.2)	(3730)	

[1] 166 cements; Avg=1218; S.D.=801.4. [2] 83 cements. *Coef./s.d. ratio less than 1.

Table 7–56. *Calculated contribution of independent variables to compressive strength in psi gain from 28 days to 1 year, SG(3), of 1:2.75 (cement to graded Ottawa sand) mortar cubes, water-stored, and the calculated ranges of such contributions*

Independent variable	Range of variable (percent)	Coefficients from eq (3) of table 7–54	Calculated contribution to SG(3)	Calculated range of contribution to SG(3)
			Const. =+6463	
C_3A	1 to 15	−153.0	−153 to −2295	2142
C_3S	20 to 65	−49.34	−987 to −3207	2220
C_4AF	1 to 16	−47.76	−48 to −764	716
Na_2O	0 to 0.7	=615.8	0 to −431	431
K_2O	0 to 1.1	−653.9	0 to −719	719
APF	*2500 to 5500	−0.3145	−786 to −1730	944
Loss	0.3 to 3.3	+349.5	+105 to +1153	1048
P**	0 to 0.5	+546.3	0 to +282	282
Ti**	0 to 1.0	−443.0	0 to −443	443
V	0 to 0.1	+4796	0 to +480	480

*cm^2/g.
**Doubtful significance. Coef./s.d. ratio less than 2.

Table 7–57. *Frequency distribution of cements with respect to strength-gain ratio from 28 days to 1 year of 1:2.75 (cement to graded Ottawa sand) mortar cubes stored in water*

[Strength-gain ratio, SGR(3) = (1-year–28-day)/28-day]

Type cement	Strength-gain ratio										Total
	−0.15 to 0	0 to 0.15	0.15 to 0.30	0.30 to 0.45	0.45 to 0.60	0.60 to 0.75	0.75 to 0.90	0.90 to 1.05	1.05 to 1.20	1.20 to 1.35	
	Number of cements										
I	1	37	31	11	---	1	---	---	---	---	81
IA	-----	1	5	2	---	---	---	---	---	---	1
II	-----	5	24	24	13	2	---	---	---	---	68
IIA	-----	---	1	1	1	---	---	---	---	---	3
III	6	9	3	2	---	---	---	---	---	---	20
IIIA	1	---	2	---	---	---	---	---	---	---	3
IV & V	-----	---	2	4	4	2	1	1	---	1	15
Total	8	52	68	44	18	5	1	1	---	1	198

reduction in the S.D. value. By using 3 additional commonly determined variables, Na_2O, K_2O and Loss in eq 2, a further highly significant reduction in the S.D. value was attained, and by use of the trace elements in eq 3, the S.D. value was again reduced by a significant amount, although 4 or 5 of the variables in eqs 3 and 7 do not show strong evidence of significance (see also table 7–75). A similar series of relationships using the oxides are presented in eqs 5, 6, and 7. Equations calculated for the "odds" and "evens," eqs 3A, 3B, 7A, and 7B, indicated that K_2O, APF, and each of the trace elements had coef./s.d. ratios less than 1 in one or the other of the smaller groups of cements. The use of the fineness values determined by the two methods, (eqs 3 and 4, or eqs 7 and 8) resulted in S.D. values which were nearly the same.

An analogous series of equations for the NAE cements are presented in table 7–63. The series of equations, 1, 2, and 3, or 6, 7, and 8 each indicate a progressive significant reduction in the S.D. values (see also table 7–75). Equatious calculated for the "odds" and "evens" in the array of cements indicated a number of independent variables with coef./s.d. ratios less than one, as may be noted in eqs 3A and 3B for Mn and eqs 8A and 8B for K_2O, where the ratio was less than one in both of the smaller groups, and for Zr, Cr and Ti in one or the other of the smaller groups. The use of the air content of the 1:4 mortar as an independent variable, as in eq 5, resulted in a slightly lower S.D. value than in eq 4. When this variable was used, the coefficient, and the coef./s.d. ratios of Na_2O, K_2O, and Loss were also affected.

The contributions of the variables to the 28-day to 10-year compressive-strength-gain values were calculated from eq 3 of table 7–62 and are presented in table 7–64 together with the calculated ranges of these contributions. Increases in C_2S, loss, and Ti with possibly Zr, Cr, Co, and Mn were associated with the higher compressive-strength-gain values, and increases in C_3A, Na_2O, and fineness, plus possibly K_2O, were associated with lower compressive-strength-gain values. Although C_2S and C_3A have a dominant role, other variables may also have an effect on the compressive-strength gain between 28 days and 10 years.

5.18. Compressive-Strength-Gain Ratio From 28 Days to 10 Years (STXY–ST28)/ST28

The frequency distributions of the 28-day to 10-year compressive-strength-gain-ratio values for the different types of cement are presented in table 7–65. There is overlapping of the values for the different types of cement, and in each of the types, as classified, there was a rather broad range of values.

Equations relating the compressive-strength-gain values to various independent variables are presented in table 7–66 for AE+NAE cements, and in table 7–67 for the NAE cements alone. In the series of equations 1, 2, 3, or 5, 6, 7, where additional variables were included, there was in every instance a significant reduction in the S.D. value obtained. Pb had a coef./s.d. ratio greater than 1 in eqs 3 and 4 where the major compounds were used, but not when used with the variables in eqs 7 and 8, where the major oxides were used. The equations for the "odds" and "evens" in the array of cements, (eqs 3A, 3B, 7A, and 7B) indicated that K_2O and all of the trace elements had coef./s.d. ratios less than 1 with one or the other or both of the smaller lots of cement. The only one of these variables that turned out to be consistently significant was Cr.

The observations relative to the results presented in table 7–66 for the AE+NAE cements in general are also applicable to table 7–67 for the NAE cements.

The contributions of the variables to the compressive-strength-gain-ratio values were calculated from eq 3 of table 7–66 and are presented in table 7–68 together with the calculated ranges of these contributions. Increases in C_3A, Na_2O, and fineness and possibly Cu were associated

Table 7–58. *Equations relating the compressive-strength-ratio, (1-year −28-day)/28-day, water-stored, for AE+NAE cements to various independent variables*

Equation	Note		Const.	C_3A	C_3S	C_4AF	CaO	SiO_2	Fe_2O_3	Na_2O	K_2O	APF	WAGN.	Air 1:4 mortar	Loss	P	Co	S.D.
1	(1)	SGR(3)	=+1.300	−0.0356	−0.0103	−0.0136	------	------	------	------	------	−0.000034	------	------	------	------	------	0.1090
		s.d.	= (0.105)	(0.0032)	(0.0014)	(0.0046)	------	------	------	------	------	(0.000017)	------	------	------	------	------	------
2	(1)	SGR(3)	=+1.423	−0.0315	−0.0113	−0.0106	------	------	------	−0.1401	−0.1417	−0.000079	------	+0.0031	+0.0740	------	------	0.0982
		s.d.	= (0.099)	(0.0033)	(0.0013)	(0.0042)	------	------	------	(0.0474)	(0.0388)	(0.000017)	------	(0.0022)	(0.0154)	------	------	------
3	(1)	SGR(3)	=+1.438	−0.0325	−0.0118	−0.0115	------	------	------	−0.1433	−0.1434	−0.000076	------	+0.0029	+0.0787	+0.1304	+8.504	0.0972
		s.d.	= (0.099)	(0.0033)	(0.0013)	(0.0042)	------	------	------	(0.0469)	(0.0384)	(0.000017)	------	(0.0021)	(0.0154)	(0.0691)	(5.547)	------
3A	(2)	SGR(3) (odd)	=+1.466	−0.0317	−0.0131	−0.0127	------	------	------	−0.0882	−0.2067	−0.000057	------	*+0.0026	+0.0717	+0.2409	*+4.601	0.0889
		s.d.	= (0.124)	(0.0046)	(0.0016)	(0.0058)	------	------	------	(0.0536)	(0.0531.	(0.000021)	------	(0.0028)	(0.0190)	(0.1074)	(8.379)	------
3B	(3)	SGR(3) (even)	=+1.392	−0.0310	−0.0106	*−0.0064	------	------	------	−0.2765	−0.0845	−0.000100	------	+0.0042	+0.0797	*+0.0856	+8.319	0.1050
		s.d.	= (0.161)	(0.0048)	(0.0022)	(0.0066)	------	------	------	(0.0882)	(0.0591)	(0.000029)	------	(0.0033)	(0.0262)	(0.0937)	(7.860)	------
4	(1)	SGR(3)	=+1.561	−0.0353	−0.0118	−0.0127	------	------	------	−0.1393	−0.1536	------	−0.000168	+0.0024	+0.0537	+0.1361	+6.987	0.0962
		s.d.	= (0.108)	(0.0033)	(0.0013)	(0.0042)	------	------	------	(0.0464)	(0.0383)	------	(0.000035)	(0.0021)	(0.0140)	(0.0684)	(5.530)	------
5	(1)	SGR(3)	=+1.061	------	------	------	−0.0456	+0.0927	+0.0357	------	------	*−0.000012	------	------	------	------	------	0.1092
		s.d.	= (0.484)	------	------	------	(0.0078)	(0.0072)	(0.0119)	------	------	(0.000016)	------	------	------	------	------	------
6	(1)	SGR(3)	=+1.345	------	------	------	−0.0465	+0.0893	+0.0378	−0.1436	−0.1296	−0.000066	------	+0.0036	+0.0766	------	------	0.0977
		s.d.	= (0.572)	------	------	------	(0.0081)	(0.0073)	(0.0114)	(0.0469)	(0.0433)	(0.000017)	------	(0.0022)	(0.0164)	------	------	------
7	(1)	SGR(3)	=+1.438	------	------	------	−0.0480	+0.0924	+0.0392	−0.1465	−0.1299	−0.000063	------	+0.0034	+0.0815	+0.1298	+8.947	0.0966
		s.d.	= (0.566)	------	------	------	(0.0080)	(0.0074)	(0.0114)	(0.0464)	(0.0429)	(0.000017)	------	(0.0021)	(0.0163)	(0.0686)	(5.492)	------
7A	(2)	SGR(3) (odd)	=+1.132	------	------	------	−0.0472	+0.0978	+0.0359	−0.0761	−0.1601	−0.000049	------	+0.0032	+0.0804	+0.2338	*+4.125	0.0890
		s.d.	= (0.769)	------	------	------	(0.0104)	(0.0098)	(0.0151)	(0.0539.	(0.0634)	(0.000020)	------	(0.0028)	(0.0207)	(0.1071)	(8.404)	------
7B	(3)	SGR(3) (even)	=+1.880	------	------	------	−0.0528	+0.0849	+0.0419	−0.2988	−0.0933	−0.000080	------	+0.0044	+0.0750	*+0.0859	+10.218	0.1039
		s.d.	= (0.880)	------	------	------	(0.0132)	(0.0115)	(0.0178)	(0.0859)	(0.0617)	(0.000028)	------	(0.0033)	(0.0270)	(0.0928)	(7.735)	------
8	(1)	SGR(3)	=+1.344	------	------	------	−0.0484	+0.0965	+0.0395	−0.1466	−0.1400	------	−0.000136	+0.0031	+0.0628	+0.1327	+7.891	0.0957
		s.d.	= (0.560)	------	------	------	(0.0079)	(0.0071)	(0.0113.	(0.0459)	(0.0429)	------	(0.000033)	(0.0021)	(0.0151)	(0.0679)	(5.465)	------

[1] 173 cements; Avg=0.2383; S.D.=0.1647. [2] 87 cements. [3] 86 cements. *Coef./s.d. ratio less than 1.

Table 7–59. *Equations relating the compressive-strength ratio, (1-year —28-day)/28-day, water-stored, for NAE cements to various independent variables*

Equation	Note		Const.	C_3A	C_3S	C_4AF	CaO	SiO_2	Fe_2O_3	Na_2O	K_2O	APF	WAGN.	Air 1:4 mortar	Loss	P	Co	S.D.
1	[1]	SGR(3)	=+1.291	−0.0356	−0.0101	−0.0132	--------	--------	--------	--------	--------	−0.000036	--------	--------	--------	--------	--------	0.1118
		s.d.	= (0.112)	(0.0034)	(0.0015)	(0.0048)	--------	--------	--------	--------	--------	(0.000018)	--------	--------	--------	--------	--------	-------
2	[1]	SGR(3)	=+1.403	−0.0306	−0.0114	−0.0104	--------	--------	--------	−0.1620	−0.1593	−0.000082	--------	+0.0085	+0.0730	--------	--------	0.1003
		s.d.	= (0.108)	(0.0034)	(0.0014)	(0.0044)	--------	--------	--------	(0.0516)	(0.0420)	(0.000018)	--------	(0.0050)	(0.0161)	--------	--------	-------
3	[1]	SGR(3)	=+1.422	−0.0315	−0.0118	−0.0113	--------	--------	--------	−0.1585	−0.1572	−0.000077	--------	+0.0064	+0.0776	+0.1209	+9.002	0.0995
		s.d.	= (0.108)	(0.0035)	(0.0014)	(0.0044)	--------	--------	--------	(0.0512)	(0.0416)	(0.000018)	--------	(0.0050)	(0.0161)	(0.0726)	(+5.877)	-------
3A	[2]	SGR(3) (odd)	=+1.412	−0.0321	−0.0134	−0.0100	--------	--------	--------	−0.0982	−0.1385	−0.000045	--------	*+0.0013	+0.0674	+0.1618	*+1.230	0.0894
		s.d.	= (0.134)	(0.0046)	(0.0017)	(0.0054)	--------	--------	--------	(0.0610)	(0.0546)	(0.000022)	--------	(0.0063)	(0.0204)	(0.1125)	(8.190)	-------
3B	[3]	SGR(3) (even)	=+1.428	−0.0298	−0.0104	−0.0110	--------	--------	--------	−0.2450	−0.1930	−0.000115	--------	+0.0122	+0.0971	*+0.0874	+14.360	0.1102
		s.d.	= (0.183)	(0.0054)	(0.0024)	(0.0077)	--------	--------	--------	(0.0943)	(0.0714)	(0.000031)	--------	(0.0084)	(0.0264)	(0.1026)	(8.748)	-------
4	[1]	SGR(3)	=+1.557	−0.0349	−0.0119	−0.0127	--------	--------	--------	−0.1468	−0.1589	--------	−0.000166	*+0.0036	+0.0522	+0.1334	+7.317	0.0990
		s.d.	= (0.120)	(0.0036)	(0.0013)	(0.0044)	--------	--------	--------	(0.0508)	(0.0415)	--------	(0.000037)	(0.0049)	(0.0150)	(0.0722)	(5.905)	-------
5	[1]	SGR(3)	=+1.018	--------	--------	--------	−0.0447	+0.0922	+0.0367	--------	--------	*−0.000014	--------	--------	--------	--------	--------	0.1120
		s.d.	= (0.521)	--------	--------	--------	(0.0083)	(0.0076)	(0.0127)	--------	--------	(0.000017)	--------	--------	--------	--------	--------	-------
6	[1]	SGR(3)	=+1.498	--------	--------	--------	−0.0484	+0.0877	+0.0355	−0.1684	−0.1525	−0.000070	--------	+0.0095	+0.0739	--------	--------	0.0996
		s.d.	= (0.600)	--------	--------	--------	(0.0084)	(0.0076)	(0.0119)	(0.0508)	(0.0466)	(0.000018)	--------	(0.0049)	(0.0170)	--------	--------	-------
7	[1]	SGR(3)	=+1.501	--------	--------	--------	−0.0496	+0.0904	+0.0347	−0.1648	−0.1494	−0.000066	--------	+0.0075	+0.0787	+0.1182	+9.228	0.0988
		s.d.	= (0.595)	--------	--------	--------	(0.0084)	(0.0077)	(0.0199)	(0.0504)	(0.0463)	(0.000018)	--------	(0.0050)	(0.0170)	(0.0719)	(5.813)	-------
7A	[2]	SGR(3) (odd)	=+1.238	--------	--------	--------	−0.0505	+0.0996	+0.0433	−0.0838	−0.1002	−0.000038	--------	*+0.0028	+0.0730	+0.1583	*−0.826	0.0883
		s.d.	= (0.863)	--------	--------	--------	(0.0117)	(0.0100)	(0.0143)	(0.0601)	(0.0661)	(0.000021)	--------	(0.0062)	,(0.0210)	(0.1107)	(8.080)	-------
7B	[3]	SGR(3) (even)	=+1.657	--------	--------	--------	−0.0477	+0.0823	+0.0291	−0.2694	−0.1926	−0.000099	--------	+0.0135	+0.0946	*+0.0850	+16.307	0.1094
		s.d.	= (0.901)	--------	--------	--------	(0.0134)	(0.0125)	(0.0215)	(0.0929)	(0.0744)	(0.000031)	--------	(0.0082)	(0.0280)	(0.1017)	(8.582)	-----
8	[1]	SGR(3)	=+1.475	--------	--------	--------	−0.0501	+0.0955	+0.0371	−0.1592	−0.1522	--------	−0.000137	+0.0055	+0.0594	+0.1259	+8.068	0.0983
		s.d.	= (0.592)	--------	--------	--------	(0.0083)	(0.0075)	(0.0119)	(0.0499)	(0.0461)	--------	(0.000035)	(0.0049)	(0.0160)	(0.0715)	(5.822)	-------

[1] 161 cements; Avg=0.2403; S.D.=0.1677. [2] 81 cements. [3] 80 cements. *Coef./s.d. ratio less than 1.

TABLE 7-60. *Calculated contribution of independent variables to compressive-strength-gain ratio (1-year—28-day)/28-day, SGR(3), of 1:2.75 (cement to graded Ottawa sand) mortar cubes, water-stored, and the calculated ranges of such contributions*

Independent variable	Range of variable (percent)	Coefficients from eq 3 of table 7-58	Calculated contribution to S G R(3)	Calculated range of contribution to SGR(3)
			Const. = +1.438	
C_3A	1 to 15	−0.0325	−0.032 to −0.488	0.456
C_3S	20 to 65	−0.0118	−0.236 to −0.767	0.531
C_4AF	1 to 16	−0.0115	−0.012 to −0.184	0.172
Na_2O	0 to 0.7	−0.1433	0 to −0.100	0.100
K_2O	0 to 1.1	−0.1434	0 to −0.158	0.158
APF	*2500 to 5500	−0.000076	−0.197 to −0.418	0.221
Air, 1:4 mortar**	1 to 21	+0.0029	+0.003 to +0.061	0.058
Loss	0.3 to 3.3	+0.0787	+0.024 to +0.260	0.236
P**	0 to 0.5	+0.1304	0 to +0.065	0.065
Co**	0 to 0.01	+8.504	0 to +0.085	0.085

*cm ^{2}/g.
**Doubtful significance. Coef./s.d. ratio less than 2.

with decreases in the compressive-strength ratio, and increases in the other variables which were significant with increases in the compressive-strength ratio. K_2O, Zr, Co, Ti, Mn, Pb were not highly significant.

5.19. Compressive-Strength Ratio of 1-Year (Water-Stored/Moist-Air-Stored) Specimens

The frequency distributions of the 1-year (water-stored/moist-air-stored) compressive-strength values for the different types of cement are presented in table 7-69. The median value for this group of cements was slightly less than 1. Of the 199 cements, 154 had lower compressive strength when stored in water than when stored in moist air. There was no great distinction between the different types of cement, either with respect to the range of values, or the actual values.

The results of plots of the 1-year compressive-strength ratio, (water-stored/moist-air-stored), versus various independent variables are presented in figure 7-5 together with plots of some other strength ratios. In plots for the strength-ratio versus the independent variables, SiO_2, Al_2O_3, CaO, MgO, SO_3, C_3A, C_3S, C_2S, A/F, S/(A+F), and APF, the absolute value of the quadrant sum was greater than 11, a value previously used to indicate that there is a relationship at the five percent probability level.

Equations relating the 1-year compressive strength ratio (water-stored/moist air-stored) to combinations of independent variables are presented in table 7-70 for the AE+NAE cements and in table 7-71 for the NAE cements. The reductions in the S.D. values resulting from the added independent variables were significant when comparing eqs 1 and 2, or 3 and 4 (see table 7-75). Most of the independent variables, other than the constant, the C_3S and Zr, had relatively low coef./s.d. ratios when the larger group of cements were used in the calculations, and P and Li were of doubtful significance both with compounds or oxides. When equations for the smaller groups, the "odds" and "evens," were calculated, the coef./s.d. ratios were often less than 1 in one or the other of these lots of cement.

No separate table was prepared indicating the calculated contributions of the different variables. However, it appears from tables 7-70 and 7-71 that increases in C_3A, and C_3S with possibly C_4AF, SO_3, Na_2O and P are associated with decreases in the strength ratios, and increases in MgO, Zr, V, and Rb, and plus possibly Li are associated with increases in the strength ratios.

TABLE 7-61. *Frequency distribution of cements with respect to compressive strength change from 28 days to 10 years of 1:2.75 (cement to graded Ottawa sand) mortar cubes, water-stored*

Type Cement	Compressive strength change, psi×10^{-3}													Total
	−2.0 to −1.5	−1.5 to −1.0	−1.0 to −0.5	−0.5 to 0	0 to +0.5	+0.5 to +1.0	+1.0 to +1.5	+1.5 to +2.0	+2.0 to +2.5	+2.5 to +3.0	+3.0 to +3.5	+3.5 to +4.0	+4.0 to +4.5	
	Number of cements													
I	-----	6	11	16	25	8	10	2	-----	-----	-----	-----	-----	78
IA	-----	-----	1	2	4	-----	1	-----	-----	-----	-----	-----	-----	8
II	-----	-----	2	3	9	8	20	5	5	4	-----	-----	-----	56
IIA	-----	-----	-----	-----	-----	2	-----	-----	-----	-----	-----	-----	-----	2
III	3	3	1	6	1	2	-----	-----	-----	-----	-----	-----	-----	16
IIIA	1	-----	-----	-----	1	-----	-----	-----	-----	-----	-----	-----	-----	2
IV & V	-----	-----	-----	-----	-----	-----	3	1	1	-----	-----	1	1	7
Total	4	9	15	27	40	20	34	8	6	4	-----	1	1	169

TABLE 7–62. *Equations relating the compressive strength gain in psi from 28 days to 10 years water-stored of AE+NAE cements to various independent variables*

Equation	Note		Const.	C_3A	C_2S	CaO	SiO_2	Fe_2O_3	Na_2O	K_2O	APF	WAGN.	Loss	Zr	Cr	Co	Mn	Ti	S.D.
1	(1)	SG(4)	=+1887	−153.0	+44.86						−0.3460								693.8
		s.d.	= (665)	(20.3)	(9.82)						(0.1248)								
2	(1)	SG(4)	=+2406	−128.8	+53.11				−1305	−649.8	−0.5779		+375.9						625.2
		s.d.	= (612)	(19.6)	(8.97)				(310)	(242.1)	(0.1226)		(105.4)						
3	(1)	SG(4)	=+1354	−122.3	+54.87				−1255	−482.6	−0.4539		+370.8	+1938	+19682	+56347	+466.2	+1067	594.6
		s.d.	= (639)	(18.9)	(8.80)				(304)	(242.2)	(0.1216)		(104.2)	(1206)	(12431)	(40616)	(391.9)	(436)	
3A	(2)	SG(4) (odd)	= +220	−115.5	+52.83				−1114	*−225.0	*−0.1425		+247.2	+17501	+19469	+45609	*+31.7	*+603	547.6
		s.d.	= (797)	(24.8)	(10.42)				(383)	(307.9)	(0.1720)		(170.2)	(9168)	(17029)	(43072)	(497.5)	(716)	
3B	(2)	SG(4) (even)	=+2204	−119.5	+55.77				−1429	−749.7	−0.6869		+446.5	*+1326	*+13155	*+102086	+931.5	+943	638.5
		s.d.	= (1134)	(30.9)	(16.66)				(558)	(439.3)	(0.1872)		(149.1)	(1469)	(20381)	(109251)	(629.8)	(700)	
	(1)	SG(4)	=+1610	−131.5	+56.87				−1278	−542.5		−0.8645	+218.6	+2517	+22927	+51744	*+374.3	+1056	595.9
		s.d.	= (710)	(19.6)	(8.66)				(305)	(245.7)		(0.2377)	(97.3)	(1196)	(12354)	(40926)	(392.8)	(437)	
5	(1)	SG(4)	=−4473			−102.4	+516.1	+342.3			−0.2219								694.5
		s.d.	= (3263)			(51.0)	(54.4)	(80.3)			(0.1172)								
	(1)	SG(4)	=−2193			−121.1	+514.5	+320.0	−1267	−470.1	−0.5136		+425.0						623.4
		s.d.	= (3728)			(51.8)	(53.7)	(75.3)	(309)	(280.1)	(0.1179)		(110.5)						
7	(1)	SG(4)	=−2270			−133.3	+519.4	+274.7	−1208	−319.6	−0.3987		+413.1	+1792	+16480	+65830	+595.5	+1020	594.3
		s.d.	= (3936)			(54.5)	(52.8)	(73.0)	(307)	(284.6)	(0.1165)		(110.3)	(1213)	(12754)	(40674)	(421.5)	(436)	
7A	(2)	SG(4) (odd)	=+420			−171.7	+464.7	+254.6	−1107	*−215.2	*−0.0900		+261.5	+18300	+18442	+50371	*+36.6	*+492	552.3
		s.d.	= (5966)			(82.1)	(77.1)	(99.8)	(388)	(393.0)	(0.1726)		(177.4)	(9211)	(18097)	(44479)	(557.2)	(720)	
7B	(2)	SG(4) (even)	=−1959			−128.4	+535.9	+240.9	−1354	−565.4	−0.6373		+498.7	*+1060	*+8713	*+95146	+1096.1	+984	636.0
		s.d.	= (5564)			(78.9)	(78.0)	(112.0)	(562)	(473.0)	(0.1689)		(159.4)	(14829)	(20710)	(109094)	(667.1)	(690)	
8	(1)	SG(4)	=−1901			−145.6	+545.5	+278.6	−1242	−381.1		−0.7387	+281.8	+2295	+19630	+63400	+506.4	+1010	595.4
		s.d.	= (3948)			(54.2)	(51.9)	(73.2)	(308)	(288.8)		(0.2208)	(102.4)	(1203)	(12679)	(40844)	(423.1)	(437)	

[1] 152 cements; Avg=400.0; S.D.=975.1. [2] 76 cements. *Coef/s.d. ratio less than 1.

TABLE 7–63. *Equations relating the compressive strength gain in psi from 28 days to 10 years water-stored of NAE cements to various independent variables*

Equation	Note		Const.	C_3A	C_2S	CaO	SiO_2	Fe_2O_3	Na_2O	K_2O	APF	WAGN.	Loss	Zr	Cr	Co	Mn	Ti	Air 1:4 Mortar	S.D.
1	(1)	SG(4)	=+1948	−150.6	+43.99						−0.3630									715.8
		s.d.	= (709)	(21.8)	(10.46)						(0.1345)									
2	(1)	SG(4)	=+2407	−122.8	+53.90				−1347	−697.6	−0.5914		+377.2							644.2
		s.d.	= (649)	(20.9)	(9.59)				(327)	(258.3)	(0.1305)		(111.5)							
3	(1)	SG(4)	=+1360	−118.8	+54.32				−1262	−475.2	−0.4695		+364.5	+2034	+20010	+67903	+577.8	+1131		608.0
		s.d.	= (666)	(20.1)	(9.33)				(321)	(260.5)	(0.1281)		(110.0)	(1244)	(13162)	(43667)	(421.8)	(462)		
3A	(2)	SG(4) (odd)	=+ 692	−104.4	+50.48				−1183	−639.6	−0.2430		+249.4	*+3072	+44029	+56452	*+550.6	*+556		621.2
		s.d.	= (938)	(29.2)	(11.88)				(436)	(385.0)	(0.2056)		(170.3)	(3292)	(20519)	(53990)	(552.0)	(721)		
3B	(2)	SG(4) (even)	=+1618	−116.7	+61.93				−1734	−428.3	−0.5804		+428.6	+1866	*+271	+116870	*+381.7	+1420		616.7
		s.d.	= (1110)	(31.7)	(17.22)				(557)	(394.5)	(0.1819)		(156.2)	(1453)	(18816)	(83575)	(794.6)	(666)		
4	(1)	SG(4)	=+1629	−129.5	+56.53				−1290	−520.4		−0.8952	+201.5	+2659	+23912	+60184	+489.5	+1145		610.4
		s.d.	= (751)	(21.0)	(9.20)				(322)	(263.7)		(0.2550)	(103.8)	(1235)	(13105)	(44239)	(422.9)	(464)		
5	(1)	SG(4)	=+2122	−133.0	+55.44				−974	−339.4		−0.8995	+249.3	+2167	+23128	+65681	+463.7	+992	−82.52	596.7
		s.d.	= (757)	(20.6)	(9.00)				(337)	(266.8)		(0.2493)	(103.0)	(1222)	(12813)	(43295)	(413.5)	(456)	(31.29)	
6	(1)	SG(4)	=−4403			−98.40	+502.4	+355.1			−0.2444									716.8
		s.d.	= (3539)			(54.62)	(58.3)	(86.3)			(0.1275)									
7	(1)	SG(4)	=−1492			−125.7	+500.9	+318.9	−1305	−536.7	−0.5355		+418.6							643.0
		s.d.	= (4003)			(55.3)	(57.4)	(81.1)	(326)	(298.5)	(0.1267)		(116.1)							
8	(1)	SG(4)	=−1612			−137.2	+503.2	+275.8	−1225	−339.9	−0.4181		+399.5	+1924	+17271	+75131	+672.6	+1079		609.0
		s.d.	= (4188)			(57.4)	(55.9)	(78.0)	(323)	(306.2)	(0.1239)		(115.6)	(1253)	(13469)	(43629)	(452.8)	(464)		
8A	(2)	SG(4) (odd)	=−4373			−88.9	+459.1	+273.1	−1065	*−384.0	−0.2106		+302.1	*+2678	+38976	+66610	+771.2	*+424		626.9
		s.d.	= (6515)			(87.7)	(85.5)	(128.0)	(448)	(489.4)	(0.2040)		(184.2)	(3352)	(21249)	(54134)	(636.6)	(731)		
8B	(2)	SG(4) (even)	=+2498			−200.3	+532.8	+238.5	−1714	*−426.1	−0.5488		+438.3	+1746	*−677	+120611	*+321.9	+1465		612.9
		s.d.	= (5882)			(83.1)	(78.5)	(109.8)	(554)	(437.5)	(0.1662)		(161.0)	(1458)	(18995)	(84470)	(812.8)	(661)		
9	(1)	SG(4)	=−1395			−149.1	+534.6	+281.3	−1265	−385.1		−0.7739	+259.3	+2465	+20785	+70361	+588.7	+1063		611.0
		s.d.	= (4208)			(57.4)	(55.0)	(78.4)	(325)	(310.2)		(0.2387)	(108.4)	(1245)	(13421)	(43980)	(454.9)	(466)		

[1] 140 cements; avg=422.1; S.D.=990.7. [2] 70 cements. *Coef./s.d. ratio less than 1.

Table 7–64. *Calculated contribution of independent variables to compressive strength gain from 28 days to 10 years, SG(4), of 1:2.75 (cement to graded Ottawa sand) mortar cubes, water-stored, and the calculated ranges of such contributions, psi*

Independent variable	Range of variable (percent)	Coefficients from eq 3 of table 7–62	Calculated contribution to SG(4)	Calculated range of contribution to SG(4)
			Const. =+1354	
C_3A	1 to 15	−122.3	−122 to −1834	1712
C_2S	5 to 50	+54.87	+274 to +2740	2466
Na_2O	0 to 0.7	−1255	0 to −878	878
K_2O**	0 to 1.1	−482.6	0 to −531	531
APF	*2500 to 5500	−0.4539	−1135 to −2496	1361
Loss	0.3 to 3.3	+370.8	+111 to +1224	1113
Zr**	0 to 0.5	+1938	0 to +969	969
Cr**	0 to 0.02	+19682	0 to +394	394
Co**	0 to 0.01	+56347	0 to +563	563
Mn**	0 to 1.0	+466.2	0 to +466	466
Ti	0 to 1.0	+1067	0 to +1067	1067

*cm ²/g.
**Doubtful significance. Coef./s.d. ratio less than 2.

Table 7–65. *Frequency distribution of cements with respect to strength-gain ratio from 28 days to 10 years of 1:2.75 (cement to graded Ottawa sand) mortar cubes stored in water*

[SGR(4)=(STXY−ST28)/ST28]

Type cement	Strength-gain ratio: −0.45 to −0.30	−0.30 to −0.15	−0.15 to 0	0 to 0.15	0.15 to 0.30	0.30 to 0.45	0.45 to 0.60	0.60 to 0.75	0.75 to 0.90	0.90 to 1.05	1.05 to 1.20	1.20 to 1.35	Total
	Number of cements												
I	2	11	20	32	10	4	---	---	---	---	---	---	79
IA	---	---	3	3	2	---	---	---	---	---	---	---	8
II	---	1	4	14	19	10	5	2	---	---	---	---	55
IIA	---	---	---	---	2	---	---	---	---	---	---	---	2
III	1	6	6	1	2	---	---	---	---	---	---	---	16
IIIA	---	1	---	1	---	---	---	---	---	---	---	---	2
IV & V	---	---	---	---	3	1	---	1	1	---	---	1	7
Total	3	19	33	51	38	15	5	3	1	---	---	1	169

Table 7–66. *Equations relating the compressive-strength-gain ratio, (10-year*

Equation	Note	Const.	C_3A	C_2S	CaO	SiO_2	Fe_2O_3	Na_2O	K_2O
1	(1)	SGR(4) =+0.3154	−0.0292	+0.0089	---	---	---	---	---
		s.d. = (0.1384)	(0.0043)	(0.0021)	---	---	---	---	---
2	(1)	SGR(4) =+0.4049	−0.0248	+0.0108	---	---	---	−0.2651	−0.1118
		s.d. = (0.1291)	(0.0041)	(0.0019)	---	---	---	(0.0657)	(0.0508)
3	(1)	SGR(4) =+0.1784	−0.0247	+0.0120	---	---	---	−0.2542	−0.0925
		s.d. = (0.1380)	(0.0041)	(0.0019)	---	---	---	(0.0645)	(0.0515)
3A	(2)	SGR(4) (odd)=+0.0210	−0.0239	+0.0135	---	---	---	−0.1876	−0.0728
		s.d. = (0.1784)	(0.0054)	(0.0024)	---	---	---	(0.0807)	(0.0656)
3B	(2)	SGR(4)(even)=+0.3311	−0.0265	+0.0100	---	---	---	−0.3224	*−0.0682
		s.d. = (0.2213)	(0.0064)	(0.0034)	---	---	---	(0.1246)	(0.0943)
4	(1)	SGR(4) =+0.2586	−0.0265	+0.0121	---	---	---	−0.2576	−0.1071
		s.d. = (0.1531)	(0.0042)	(0.0018)	---	---	---	(0.0642)	(0.0521)
5	(1)	SGR(4) =−0.6120	---	---	−0.0248	+0.1021	+0.0583	---	---
		s.d. = (0.6746)	---	---	(0.0105)	(0.0116)	(0.0167)	---	---
6	(1)	SGR(4) =−0.1090	---	---	−0.0297	+0.1028	+0.0531	−0.2630	−0.0872
		s.d. = (0.7880)	---	---	(0.0109)	(0.0116)	(0.0159)	(0.0655)	(0.0591)
7	(1)	SGR(4) =−0.1855	---	---	−0.0335	+0.1094	+0.0511	−0.2523	−0.0668
		s.d. = (0.8324)	---	---	(0.0116)	(0.0113)	(0.0158)	(0.0651)	(0.0605)
7A	(2)	SGR(4) (odd)=+0.8874	---	---	−0.0505	+0.1065	+0.0523	−0.1916	−0.0913
		s.d. = (1.2979)	---	---	(0.0178)	(0.0159)	(0.0211)	(0.0820)	(0.0877)
7B	(2)	SGR(4)(even)=−0.5612	---	---	−0.0256	+0.1059	+0.0508	−0.3191	*−0.0440
		s.d. = (1.2145)	---	---	(0.0173)	(0.0186)	(0.0254)	(0.1245)	(0.1002)
8	(1)	SGR(4) =−0.1269	---	---	−0.0349	+0.1129	+0.0528	−0.2585	−0.0812
		s.d. = (0.8299)	---	---	(0.0115)	(0.0110)	(0.0158)	(0.0650)	(0.612)

[1] 152 cements; Avg=0.08268; S.D.=0.1915. [2] 76 cements. *Coef./s.d. ratio less than 1.

DEPENDENT VARIABLE COMPRESSIVE STRENGTH RATIOS	NOTE *	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TOTAL ALKALI	C_3A	C_3S	C_2S	C_4AF	A/F	S/(A+F)	AIR P. FINE	WAGN. FINE	AIR 1:4 MORT
1 YEAR IN WATER / 7 DAYS IN WATER (STIY/STO7)	(1)	12/0	12/0	10/2	8/4	6/6	10/2	8/4	12/0	12/0	12/0	10/2	10/2	10/2	12/0	10/2	10/2	6/6	10/2
	(2)																		
	(3)	L	L	L	L	NO	NL	L?	L	L?	L	L	L	L?	L	L	NL	NO	L?
	(4)	+24	−24	+18	−11	−1	−18	+2	−24	−24	−24	−16	+19	+17	−24	+19	−11	+1	−11
1 YEAR IN AIR ** / 7 DAYS IN WATER (STIA/STO7)	(1)	10/2	10/2	10/2	10/2	8/4	10/2	6/6	6/6	8/4	10/2	10/2	12/0	9/1	10/2	10/2	8/4	6/6	8/4
	(2)																		
	(3)	L	L	L	L	L	NL	L?	L?	L?	L	L	L	L?	L	NL	NL	NO	L?
	(4)	+19	−14	+18	−17	+13	−17	+6	−5	−3	−16	−17	+24	+16	−17	+15	−11	−1	+5
1 YEAR IN WATER / 28 DAYS IN WATER (STIY/ST28)	(1)	12/0	12/0	12/0	8/4	6/6	10/2	8/4	12/0	10/2	12/0	10/2	12/0	10/2	12/0	10/2	10/2	6/6	8/4
	(2)																		
	(3)	L	L	NL	L?	NO	NL	L?	L	NL	L	L	L	NL	L	L	NL	NO	L?
	(4)	+24	−24	+24	−10	−4	−15	−4	−24	−15	−24	−18	+24	+14	−24	+15	−15	−3	−2
1 YEAR IN WATER / 1 YEAR IN AIR ** (STIY/STIA)	(1)	12/0	12/0	10/2	6/6	10/2	12/0	10/2	12/0	10/2	12/0	10/2	12/0	10/2	12/0	12/0	10/2	7/5	8/4
	(2)																		
	(3)	L	L	L	NO	L?	L	L?	NL	NL	L	L	L	L	L	L	NL	L?	NL
	(4)	+24	−24	+17	0	−15	−24	−15	−24	−20	−24	−16	+24	+15	−24	+24	−14	+5	−12
1 YEAR IN WATER / 1 YEAR IN MOIST AIR (STIY/STIM)	(1)	10/2	8/4	6/6	10/2	12/0	8/4	8/4	8/4	6/6	8/4	10/2	10/0	8/4	8/4	8/4	9/3	6/6	6/6
	(2)																		
	(3)	L	L	NO	NL	L	L?	L?	L?	NO	L	L?	L	L?	L	L	L?	NO	NO
	(4)	+16	−13	+6	−17	+24	−15	+2	+5	−2	−12	−12	+13	+9	−12	+12	+12	−1	−3

FIGURE 7–5. *Results of plotting ratios of compressive strength determined at different ages of 1:2.75 (cement to graded Ottawa sand) mortars on the "Y" axis versus various independent variables on the "X" axis.*

*Note (1) Ratio of number of plotted points in pairs of diametrically opposite quadrants.
Note (2) General trend of line drawn through plotted points.
Note (3) Apparent nature of relationship. L-linear; NL-nonlinear; NO-no apparent relationship; and L=-nature of relationship not determinable.
Note (4) Quadrant sum in corner test. (See reference [8].)

**Stored in moist air for 24 hours, then water for 6 days then in laboratory air at 23° C, 50 percent RH for 49 weeks, then water for 2 weeks.

—28-day)/28-day, water-stored, for AE+NAE cements to various independent variables

APF	WAGN.	Loss	Zr	Co	Cr	Ti	Mn	Pb	Cu	S.D.
−0.000053 (0.000026)										0.1441
−0.000096 (0.000026)		+0.0711 (0.0223)								0.1320
−0.000066 (0.000026)		+0.0713 (0.0221)	+0.3805 (0.2548)	+12.28 (8.61)	+5.494 (2.650)	+0.1989 (0.1087)	+0.0964 (0.0833)	+2.235 (2.066)	−2.829 (1.636)	0.1253
−0.000039 (0.000034)		+0.0595 (0.0305)	+3.9123 (1.8724)	+15.31 (9.20)	*+3.335 (3.542)	*+0.1505 (0.1559)	*+0.0024 (0.1022)	+2.875 (2.159)	−3.170 (1.754)	0.1135
−0.000097 (0.000042)		+0.0967 (0.0364)	*+0.3102 (0.3239)	*+24.55 (26.88)	+4.708 (4.603)	*+0.0563 (0.2111)	+0.2211 (0.1402)	*−0.430 (5.507)	*+0.042 (3.923)	0.1381
	−0.000142 (0.000050)	+0.0492 (0.0205)	+0.4614 (0.2506)	+11.30 (8.60)	+5.949 (2.615)	+0.1952 (0.1082)	*+0.0793 (0.0829)	+2.339 (2.056)	−3.170 (1.633)	0.1248
+0.000029 (0.000024)										0.1446
−0.000083 (0.000025)		+0.0773 (0.0234)								0.1320
−0.000058 (0.000025)		+0.0750 (0.0233)	+0.3645 (0.2568)	+14.14 (8.63)	+5.281 (2.711)	+0.1976 (0.1091)	+0.1193 (0.0898)		−2.627 (1.664)	0.1255
−0.000033 (0.000033)		+0.0549 (0.0322)	+4.1126 (1.8852)	+13.38 (9.25)	+4.515 (3.799)	*+0.1387 (0.1566)	−0.0084 (0.1159)		−3.418 (1.890)	0.1142
−0.000074 (0.000039)		+0.1029 (0.0386)	*+0.2823 (0.3250)	*+23.76 (23.80)	*+3.991 (4.670)	*+0.0386 (0.2096)	+0.2393 (0.1469)		*−0.464 (4.004)	0.1381
	−0.000117 (0.000047)	+0.0571 (0.0215)	+0.4320 (0.2529)	+13.57 (8.61)	+5.706 (2.680)	+0.1944 (0.1087)	+0.1030 (0.0896)		−2.884 (1.662)	0.1250

Table 7–67. *Equations relating the compressive-strength-gain ratio, (10-year*

Equation	Note	Const.	C_3A	C_2S	CaO	SiO_2	Fe_2O_3	Na_2O	K_2O
1	(1)	SGR(4) =+0.3300	−0.0288	+0.0085	----	----	----	----	----
		s.d. = (0.1475)	(0.0046)	(0.0022)	----	----	----	----	----
2	(1)	SGR(4) =+0.4100	−0.0237	+0.0107	----	----	----	−0.2716	−0.1254
		s.d. = (0.1369)	(0.0044)	(0.0020)	----	----	----	(0.0693)	(0.0542)
3	(1)	SGR(4) =+0.1820	−0.0239	+0.0118	----	----	----	−0.2552	−0.0961
		s.d. = (0.1440)	(0.0043)	(0.0020)	----	----	----	(0.0682)	(0.0556)
3A	(2)	SGR(4)(odd) =+0.1459	−0.0211	+0.0122	----	----	----	−0.2388	−0.1476
		s.d. = (0.2106)	(0.0065)	(0.0026)	----	----	----	(0.0912)	(0.0794)
3B	(2)	SGR(4)(even) =+0.2808	−0.0272	+0.0108	----	----	----	−0.3750	*−0.0436
		s.d. = (0.2230)	(0.0066)	(0.0034)	----	----	----	(0.1328)	(0.0936)
4	(1)	SGR(4) =+0.2557	−0.0259	+0.0120	----	----	----	−0.2597	−0.1077
		s.d. = (0.1619)	(0.0045)	(0.0020)	----	----	----	(0.0681)	(0.0561)
5	(1)	SGR(4) =−0.6160	----	----	−0.0235	+0.0982	+0.0615	----	----
		s.d. = (0.7325)	----	----	(0.0113)	(0.0125)	(0.0180)	----	----
6	(1)	SGR(4) =+0.0343	----	----	−0.0302	+0.0988	+0.0534	−0.2697	−0.1058
		s.d. = (0.8455)	----	----	(0.0116)	(0.0124)	(0.0172)	(0.0692)	(0.0630)
7	(1)	SGR(4) =−0.0608	----	----	−0.0339	+0.1052	+0.0517	−0.2553	−0.0759
		s.d. = (0.8879)	----	----	(0.0123)	(0.0120)	(0.0169)	(0.0688)	(0.0652)
7A	(2)	SGR(4)(odd) =−0.4588	----	----	−0.0279	+0.1068	+0.0459	−0.2293	*−0.0834
		s.d. = (1.3948)	----	----	(0.0186)	(0.0181)	(0.0260)	(0.0942)	(0.1046)
7B	(2)	SGR(4)(even) =+0.5683	----	----	−0.0425	+0.1031	+0.0557	−0.3854	*−0.0538
		s.d. = (1.3145)	----	----	(0.0187)	(0.0182)	(0.0261)	(0.1311)	(0.0989)
8	(1)	SGR(4) =−0.0194	----	----	−0.0354	+0.1096	+0.0534	−0.2624	−0.0874
		s.d. = (0.8867)	----	----	(0.0122)	(0.0117)	(0.0169)	(0.0689)	(0.0659)

[1] 140 cements; Avg=0.08582; S.D.=0.1942. [2] 70 cements. *Coef./s.d. ratio less than 1.

5.20. Compressive-Strength Ratio of 1-Year (Air-Stored) to 28-Day, Water-Stored Specimens

The frequency distributions of the ratios of the compressive strength values of the 1-year air-stored (7-day water-cured, then 49 weeks in laboratory air, then 2 weeks in water, and tested wet) to the compressive strength values of specimens stored in water until tested at 28 days are presented in table 7–72 for the different types of cement. Although the average compressive strength after the two types of storage are nearly equal, 5237 psi for ST1A, and 5037 psi for ST28 for the AE+NAE cements, there was a considerable spread of the ratios of the different cements. Of the 199 cements, 57 had lower compressive strength values for the 1-year air-stored specimens than for those cured 28 days in water.

Equations relating the compressive strength ratios for specimens tested after the two conditions of storage, to various independent variables are presented in table 7–73 for the AE+NAE cements, and in table 7–74 for the NAE cements. The independent variables used in eq 1, table 7–73 resulted in a significant reduction in the S.D. value. With the added variables in eqs 2 and 3, further significant reductions in the S.D. values were attained. A further significant reduction was not attained in eq 5 with the added variables (See also table 7–75.) The MgO had a coef./s.d. ratio less than one with the variables in eq 5 and 6 where the major oxides were used in the equations. The coef./s.d. ratio was less than one in one or both of the "odds" or "evens" groups for C_4AF, Fe_2O_3, SO_3, Mn, and Cr. The coefficients for Pb were negative in eqs 3B and 6B but they were positive in eqs 3, 3A, 6, and 6A. In table 7–74 the

—28-day)/28-day, water-stored, for NAE cements to various independent variables

APF	WAGN.	Loss	Zr	Co	Cr	Ti	Mn	Pb	Cu	S.D.
−0.000055 (0.000028)	----- -----	----- -----	----- -----	----- -----	----- -----	----- -----	----- -----	----- -----	----- -----	0.1487 -----
−0.000099 (0.000028)	----- -----	+0.0726 (0.0236)	----- -----	----- -----	----- -----	----- -----	----- -----	----- -----	----- -----	0.1359 -----
−0.000069 (0.000027)	----- -----	+0.0713 (0.0234)	+0.3931 (0.2636)	+15.84 (9.31)	+5.418 (2.807)	+0.2009 (0.1173)	+0.1137 (0.0899)	+2.229 (2.128)	−2.634 (1.696)	0.1286 -----
−0.000056 (0.000039)	----- -----	+0.0554 (0.0312)	*+0.3080 (0.6810)	+16.79 (11.36)	+8.841 (4.261)	*+0.1015 (0.1623)	*+0.1097 (0.1117)	+2.730 (2.388)	−5.204 (3.720)	0.1280 -----
−0.000086 (0.000042)	----- -----	+0.0832 (0.0396)	+0.4543 (0.3309)	+25.54 (23.38)	*+1.024 (4.580)	+0.3225 (0.2072)	*+0.1101 (0.1823)	*−1.888 (8.155)	*−0.892 (2.225)	0.1373 -----
----- -----	−0.000143 (0.000054)	+0.0476 (0.0220)	+0.4813 (0.2598)	+14.43 (9.35)	+5.977 (2.777)	+0.1987 (0.1171)	+0.0975 (0.0895)	+2.311 (2.122)	−2.962 (1.695)	0.1282 -----
−0.000031 (0.000027)	----- -----	----- -----	----- -----	----- -----	----- -----	----- -----	----- -----	----- -----	----- -----	0.1495 -----
−0.000087 (0.000027)	----- -----	+0.0775 (0.0246)	----- -----	----- -----	----- -----	----- -----	----- -----	----- -----	----- -----	0.1360 -----
−0.000059 (0.000027)	----- -----	+0.0735 (0.0245)	+0.3842 (0.2658)	+17.28 (9.31)	+5.284 (2.867)	+0.2009 (0.1181)	+0.1302 (0.0965)	----- -----	−2.488 (1.723)	0.1290 -----
−0.000055 (0.000039)	----- -----	+0.0626 (0.0342)	*+0.3180 (0.6905)	+15.62 (11.18)	+8.937 (4.361)	*+0.0902 (0.1641)	+0.1730 (0.1310)	----- -----	−5.091 (3.760)	0.1293 -----
−0.000069 (0.000042)	----- -----	+0.0847 (0.0405)	+0.4636 (0.3317)	+22.21 (18.83)	*+1.291 (4.490)	+0.3019 (0.2052)	*+0.0777 (0.1875)	----- -----	*−0.928 (2.232)	0.1368 -----
----- -----	−0.000120 (0.000051)	+0.0541 (0.0229)	+0.4584 (0.2624)	+16.40 (9.32)	+5.775 (2.841)	+0.1984 (0.1179)	+0.1146 (0.0964)	----- -----	−2.741 (1.722)	0.1287 -----

Table 7–68. *Calculated contributions of independent variables to compressive-strength-gain ratio, (10-year —28-day)/28-day, SGR(4), of 1:2.75 (cement to graded Ottawa sand) mortar cubes, water-stored, and the calculated ranges of such contributions*

Independent variable	Range of variable (percent)	Coefficients from eq 3 of table 7–66	Calculated contribution to SGR(4)	Calculated range of contribution to SGR(4)
			Const. = +0.1784	
C_3A	1 to 15	−0.0247	−0.0247 to −0.3705	0.3458
C_2S	5 to 50	+0.0120	+0.0600 to +0.6000	0.5400
Na_2O	0 to 0.7	−0.2542	0 to −0.1779	0.1779
K_2O**	0 to 1.1	−0.0925	0 to −0.1018	0.1018
APF	*2500 to 5500	−0.000066	−0.1650 to −0.3630	0.1980
Loss	0.3 to 3.3	+0.0713	+0.0214 to +0.2353	0.2139
Zr**	0 to 0.5	+0.3805	0 to +0.1902	0.1902
Co**	0 to 0.01	+12.28	0 to +0.1228	0.1228
Cr	0 to 0.02	+5.494	0 to +0.1099	0.1099
Ti**	0 to 1.0	+0.1989	0 to +0.1989	0.1989
Mn**	0 to 1.0	+0.0964	0 to +0.0964	0.0964
Pb**	0 to 0.05	+2.235	0 to +0.1118	0.1118
Cu**	0 to 0.05	−2.829	0 to −0.1415	0.1415

*cm^2/g.

**Doubtful significance. Coef./s.d. ratio less than 2.

Table 7–69. *Frequency distribution of cements with respect to compressive-strength ratio, STIY/STIM, of 1:2.75 (cement to graded Ottawa sand) mortar cubes*

Type cement	Compressive strength ratio								Total
	0.80 to 0.85	0.85 to 0.90	0.90 to 0.95	0.95 to 1.00	1.00 to 1.05	1.05 to 1.10	1.10 to 1.15	1.15 to 1.20	
	Number of cements								
I	6	19	26	18	7	3	1	1	81
IA	----	3	1	2	2	----	----	----	8
II	----	12	17	22	15	1	1	----	68
IIA	----	1	1	----	----	1	----	----	3
III	3	4	9	----	3	----	1	----	20
IIIA	1	----	----	1	----	1	----	----	3
IV & V	----	1	5	2	2	4	----	1	15
Total	10	40	59	45	29	10	3	2	198

Table 7–70. *Equations relating the 1-year compressive-strength ratio, (water-stored/moist-air-stored), for AE+NAE cements to various independent variables*

Equation	Note		Const.	C_3A	C_3S	C_4AF	CaO	SiO_2	SO_3	MgO	Na_2O	Zr	P	V	Rb	Li	S.D.
1	(1)	SR(1)	=+1.200	−0.00612	−0.00252	−0.00408			−0.0277	+0.00776	−0.0414						0.05781
		s.d.	= (0.057)	(0.00183)	(0.00072)	(0.00242)			(0.0139)	(0.00385)	(0.0270)						
2	(1)	SR(1)	=+1.129	−0.00430	−0.00192	−0.00324			−0.0272	+0.01033	−0.0691	+0.3120	−0.0457	+0.5352	+5.306	+2.295	0.05527
		s.d.	= (0.059)	(0.00198)	(0.00071)	(0.00236)			(0.0133)	(0.00396)	(0.0294)	(0.1075)	(0.0405)	(0.2653)	(2.344)	(1.463)	
2A	(2)	SR(1) (odd)	=+1.140	−0.00764	−0.00191	−0.00674			*−0.0091	+0.00978	*+0.0004	+1.0101	−0.0815	*+0.3475	+5.325	*−0.052	0.05377
		s.d.	= (0.081)	(0.00281)	(0.00089)	(0.00321)			(0.0207)	(0.00583)	(0.0499)	(0.4531)	(0.0661)	(0.4470)	(3.190)	(2.251)	
2B	(3)	SR(1) (even)	=+1.135	*−0.00169	−0.00239	*−0.00030			−0.0375	+0.00811	−0.1054	+0.2981	*−0.0215	+0.4402	*+3.774	+4.277	0.05779
		s.d.	= (0.091)	(0.00301)	(0.00124)	(0.00362)			(0.0184)	(0.00585)	(0.0403)	(0.1195)	(0.0555)	(0.3755)	(3.801)	(2.023)	
3	(1)	SR(1)	=+1.776				−0.0176	+0.0161	−0.0291		−0.0487						0.05743
		s.d.	= (0.261)				(0.0039)	(0.0041)	(0.0151)		(0.0264)						
4	(1)	SR(1)	=+1.382				−0.0107	+0.0125	−0.0257	+0.00797	−0.0708	+0.3087	−0.0441	+0.5474	+5.106	+2.266	0.05501
		s.d.	= (0.381)				(0.0053)	(0.0046)	(0.0150)	(0.00536)	(0.0285)	(0.1068)	(0.0400)	(0.2649)	(2.316)	(1.429)	
4A	(2)	SR(1) (odd)	=+0.681				*−0.0038	+0.0204	*+0.0040	+0.01401	*−0.0018	+0.9898	−0.0820	*+0.3152	+5.185	*+0.254	0.05348
		s.d.	= (0.492)				(0.0066)	(0.0065)	(0.0228)	(0.00745)	(0.0471)	(0.4497)	(0.0650)	(0.4447)	(3.156)	(2.200)	
4B	(3)	SR(1) (even)	=+2.357				−0.0228	*+0.0066	−0.0488	*−0.00273	−0.1090	+0.2733	*−0.0101	+0.4742	*+2.872	+4.253	0.05649
		s.d.	= (0.626)				(0.0090)	(0.0068)	(0.0207)	(0.00823)	(0.0389)	(0.1162)	(0.0541)	(0.3666)	(3.710)	(1.929)	

[1] 175 cements; Avg=0.9429; S.D.=0.06454. [2] 88 cements. [3] 87 cements. *Coef./s.d. ratio less than 1.

Table 7–71. *Equations relating the 1-year compressive strength ratio, (water-stored/moist-air-stored), for NAE cements to various independent variables*

Equation	Note		Const.	C_3A	C_3S	C_4AF	CaO	SiO_2	SO_3	MgO	Na_2O	Zr	P	V	Rb	Li	S.D.
1	(1)	SR(1)	=+1.182	−0.00570	−0.00244	−0.00359			−0.0256	+0.00840	−0.0371						0.05835
		s.d.	= (0.059)	(0.00188)	(0.00075)	(0.00249)			(0.0144)	(0.00399)	(0.0277)						
2	(1)	SR(1)	=+1.111	−0.00373	−0.00186	−0.00257			−0.0265	+0.01100	−0.0666	+0.3229	−0.0457	+0.5757	+5.091	+2.257	0.05561
		s.d.	= (0.061)	(0.00205)	(0.00074)	(0.00242)			(0.0138)	(0.00410)	(0.0302)	(0.1087)	(0.0409)	(0.2685)	(2.396)	(1.484)	
2A	(2)	SR(1) (odd)	=+1.019	−0.00283	*−0.00045	*−0.00274			−0.0276	+0.01313	*−0.0247	+0.2567	−0.0799	+0.7816	+7.524	*+1.740	0.05322
		s.d.	= (0.086)	(0.00276)	(0.00103)	(0.00361)			(0.0177)	(0.00591)	(0.0419)	(0.1162)	(0.0585)	(0.3617)	(3.469)	(2.194)	
2B	(2)	SR(1) (even)	=+1.171	−0.00494	−0.00285	*−0.00301			*−0.0148	+0.00858	−0.1189	+0.5760	*−0.0035	*+0.3206	+2.453	+3.419	0.05942
		s.d.	= (0.093)	(0.00331)	(0.00116)	(0.00353)			(0.0238)	(0.00646)	(0.0469)	(0.2913)	(0.0618)	(0.4428)	(3.512)	(2.192)	
3	(1)	SR(1)	=+1.815				−0.0178	+0.0150	−0.0279		−0.0441						0.05793
		s.d.	= (0.270)				(0.0040)	(0.0042)	(0.0156)		(0.0270)						
4	(1)	SR(1)	=+1.415				−0.0108	+0.0112	−0.0260	+0.00816	−0.0676	+0.3169	−0.0420	+0.5893	+4.930	+2.201	0.05532
		s.d.	= (0.393)				(0.0054)	(0.0048)	(0.0155)	(0.00556)	(0.0291)	(0.1079)	(0.0403)	(0.2681)	(2.366)	(1.449)	
4A	(2)	SR(1) (odd)	=+0.551				*+0.0029	+0.0082	*−0.0181	+0.01742	*−0.0238	+0.2661	−0.0805	+0.7453	+7.526	*+1.924	0.05272
		s.d.	= (0.617)				(0.0085)	(0.0067)	(0.0210)	(0.00831)	(0.0406)	(0.1147)	(0.0575)	(0.3640)	(3.310)	(2.146)	
4B	(2)	SR(1) (even)	=+1.953				−0.0201	+0.0145	*−0.0173	*+0.00125	−0.1248	+0.5482	*−0.0010	*+0.3222	*+1.771	+3.437	0.05833
		s.d.	= (0.539)				(0.0076)	(0.0070)	(0.0248)	(0.00825)	(0.0447)	(0.2848)	(0.0593)	(0.4319)	(3.487)	(2.104)	

[1] 164 cements; Avg=0.9440; S.D.=0.06439. [2] 82 cements. *Coef./s.d. ratio less than 1.

coef./s.d. ratio for Pb was less than one in the "evens" groups (eqs 3B and 6B). Comparing eqs 4 and 5 of table 7–74 it may be noted that the use of the added variables in eq 5 resulted in a reduction of the S.D. value significant only at the 5 percent probability level (see also table 7–75). Cr and SO_3 were not highly significant.

Tables 7–73 and 7–74 indicate that increases in C_3A, C_3S, C_4AF, and Ba are associated with lower compressive strength ratios and that increases in MgO, Loss, air content, CO, Pb, Mn, and V, and possibly SO_3 are associated with higher compressive strength ratios of the 1-year air-stored to 28-day water-stored specimens.

TABLE 7–72. *Frequency distribution of cements with respect to compressive strength ratios of 1-year air-stored to 28-day water-stored 1:2.75 (cement to graded Ottawa sand) mortar cubes*

Type cement	Compressive strength ratio										Total
	0.7 to 0.8	0.8 to 0.9	0.9 to 1.0	1.0 to 1.1	1.1 to 1.2	1.2 to 1.3	1.3 to 1.4	1.4 to 1.5	1.5 to 1.6	1.6 to 1.7	
	Number of cements										
I	1	7	16	42	14	1	1	---	---	---	82
IA	---	---	---	---	4	2	2	---	---	---	8
II	---	1	20	25	14	4	2	1	---	1	68
IIA	---	---	---	1	1	---	---	1	---	---	3
III	---	2	8	9	1	---	---	---	---	---	20
IIIA	---	---	---	3	---	---	---	---	---	---	3
IV & V	---	2	---	6	4	1	2	---	---	---	15
Total	1	12	44	86	38	8	7	2	---	1	199

6. Discussion

6.1. Compressive Strength of Different Types of Cement

By plotting the average compressive strength values of the different types of nonair-entraining cements versus the age of test on a semilog scale, as presented in figure 7–1, it was noted that the averages of the different types were different. The almost linear character of the relationship (on the log scale) at the early ages changed at different ages with the different types of cement, and as a result, some of the lines in the graph crossed.

The various tables presented to show the frequency distribution of the compressive strength values at the different test ages indicated that there was a considerable overlapping of the values for the cements as classified into the different types. This was found, not only for the strength values at a given age, but for the gain in strength between the various ages, or the percentage strength increase after some earlier test. The use of average values for predicting compressive strength or compressive strength gain for a cement of a given type may, therefore be inadequate and result in erroneous predicted values. The fact that there was such an overlapping and range of values for the cements of the different types as classified indicate that it is not sufficient, especially in research reports, to merely describe a cement as meeting the requirements of a certain type.

It was also noted in figure 7–1 that there was a retrogression of the average compressive strength values for each of the types of cement after 1-year water storage, which was, of course, not true for all of the cements within each group. Of the 189 cements for which values were obtained, 68 had higher compressive strength at 5 years than at 1 year, and, of 169 cements, 23 had higher compressive strength at 10 years than at 1 year, and 26 had higher strength at 10 years than at 5 years. It was also noted that 154 of the 199 cements had lower compressive strength when stored in water for 1 year than when stored in moist air for the same period.

The retrogression of compressive strength of small, relatively porous, water-stored specimens may be attributed to leaching, to some destructive action which causes strains within the specimens, or to possible other causes. If specimens made from all cements had shown this tendency of lower strength at 5 and 10 years, the effect could definitely be attributed to leaching. Mortars made of some cements may have this tendency to a greater extent than others.

The equations presented relating the compressive-strength values to combinations of variables indicated that an increase in the C_3A content was associated with lower compressive strength values at 1, 5 and 10 years, but was associated with higher compressive strength values at the earlier ages. The C_3A content may then be one of the contributing factors (others are indicated in the tables) that confirm previously published reports.

It was noted at one of the five laboratories that made these tests that the 5- and 10-year specimens were coated with a hard crust. (This condition was not found in the other 4 laboratories.) It was necessary to remove this coating with abrasive cloth, as required by specifications, a procedure which may by itself have resulted in lower compressive strengths.

6.2. Relationships of Compressive Strengths Determined at Different Ages

The relationships of the compressive strengths at various ages to those at earlier ages are presented in table 7–76. The equations were calculated with the dependent variable (the compressive strength at one age) as a function of a constant plus the compressive strength at an earlier age. The s.d., and the S.D. values are presented together with the reduction in variance, "F," resulting from the determination of the constant and coefficient of one independent variable. With the number of degrees of freedom in these equations, a value of 4.72 or above is significant at the one percent probability level, and a value of 3.05 or above, significant at the five percent level. The

TABLE 7–73. *Equations relating the compressive strength ratio, (1-year air-stored/*

Equation	Note	Const.	C_3A	C_3S	C_4AF	CaO	SiO_2	Fe_2O_3	MgO
1	(1)	SR(2) =+1.336 s.d. = (0.080)	−0.00841 (0.00253)	−0.00442 (0.00102)	−0.0092 (0.0036)				
2	(1)	SR(2) =+1.263 s.d. = (0.081)	−0.01073 (0.00261)	−0.00468 (0.00103)	−0.0096 (0.0036)				+0.0133 (0.0057)
3	(1)	SR(2) =+1.187 s.d. = (0.081)	−0.00916 (0.00262)	−0.00436 (0.00098)	−0.0102 (0.0034)				+0.0145 (0.0057)
3A	(2)	SR(2)(odd) =+1.243 s.d. = (0.092)	−0.00901 (0.00345)	−0.00501 (0.00108)	−0.0162 (0.0039)				+0.0196 (0.0078)
3B	(2)	SR(2)(even) =+1.179 s.d. = (0.149)	−0.00824 (0.00395)	−0.00380 (0.00191)	*−0.0032 (0.0060)				*+0.0064 (0.0090)
4	(1)	SR(2) =+2.747 s.d. = (0.398)				−0.0348 (0.0062)	+0.0230 (0.0052)	−0.0189 (0.0095)	
5	(1)	SR(2) =+2.340 s.d. = (0.432)				−0.0321 (0.0062)	+0.0296 (0.0060)	−0.0149 (0.0095)	
6	(1)	SR(2) =+2.370 s.d. = (0.430)				−0.0316 (0.0061)	+0.0256 (0.0061)	−0.0210 (0.0091)	
6A	(2)	SR(2)(odd) =+2.759 s.d. = (0.587)				−0.0367 (0.0078)	+0.0252 (0.0074)	−0.0424 (0.0115)	
6B	(2)	SR(2)(even) =+1.903 s.d. = (0.661)				−0.0241 (0.0097)	+0.0243 (0.0102)	*+0.0029 (0.0148)	

[1] 178 cements; Avg=1.049; S.D.=0.1032. [2] 89 cements. *Coef./s.d. ratio less than 1.

TABLE 7–74. *Equations relating the compressive strength ratio, (1-year air-stored/*

Equation	Note	Const.	C_3A	C_3S	C_4AF	CaO	SiO_2	Fe_2O_3	MgO
1	(1)	SR(2) =+1.324 s.d. = (0.086)	−0.00926 (0.00261)	−0.00422 (0.00106)	−0.0100 (0.0037)				
2	(1)	SR(2) =+1.258 s.d. = (0.086)	−0.01148 (0.00267)	−0.00445 (0.00107)	−0.0105 (0.0036)				+0.0132 (0.0059)
3	(1)	SR(2) =+1.188 s.d. = (0.085)	−0.00971 (0.00270)	−0.00416 (0.00102)	−0.0107 (0.0035)				+0.0143 (0.0059)
3A	(2)	SR(2)(odd) =+1.274 s.d. = (0.099)	−0.00863 (0.00342)	−0.00517 (0.00111)	−0.0115 (0.0043)				*+0.0066 (0.0072)
3B	(2)	SR(2) (even) =+1.065 s.d. = (0.156)	−0.00902 (0.00435)	−0.00278 (0.00197)	−0.0073 (0.0060)				+0.0195 (0.0102)
4	(1)	SR(2) =+2.627 s.d. = (0.415)				−0 0333 (0.0064)	+0.0238 (0.0054)	−0.0194 (0.0098)	
5	(1)	SR(2) =+2.187 s.d. = (0.449)				−0.0303 (0.0064)	+0.0306 (0.0061)	−0.0151 (0.0098)	
6	(1)	SR(2) =+2.246 s.d. = (0.452)				−0.0299 (0.0063)	+0.0262 (0.0063)	−0.0206 (0.0094)	
6A	(2)	SR(2) (odd) =+2.161 s.d. = (0.521)				−0.0291 (0.0070)	+0.0286 (0.0072)	−0.0217 (0.0120)	
6B	(2)	SR(2) (even) =+2.396 s.d. = (0.845)				−0.0311 (0.0120)	+0.0219 (0.0108)	−0.0172 (0.0156)	

[1] 166 cements; Avg=1.040; S.D.=0.0977. [2] 83 cements. *Coef./s.d. ratio less than 1.

28-day water-stored) for AE+NAE cements to various independent variables

SO_3	Loss	Air 1:4 mortar	Ba	Co	Pb	Mn	V	Cr	S.D.
—	—	+0.0112 (0.0018)	—	—	—	—	—	—	0.08797
+0.0316 (0.0211)	+0.0277 (0.0127)	+0.0094 (0.0018)	—	—	—	—	—	—	0.08490
+0.0326 (0.0202)	+0.0366 (0.0123)	+0.0096 (0.0017)	−0.4265 (0.2065)	+10.04 (4.43)	+2.187 (1.027)	+0.0995 (0.0523)	+0.8690 (0.4149)	+2.412 (1.617)	0.07935
*+0.0281 (0.0283)	+0.0439 (0.0159)	+0.0113 (0.0021)	−0.3884 (0.2373)	+13.85 (5.26)	+3.210 (1.019)	+0.1238 (0.0575)	+0.8585 (0.5980)	+2.297 (2.114)	0.06893
*+0.0175 (0.0293)	+0.0320 (0.0191)	+0.0072 (0.0027)	−0.6465 (0.3630	+ 9.21 (8.51)	−5.845 (3.676)	*+0.0516 (0.0969)	+1.0607 (0.6147)	*+1.247 (2.440)	0.08625
—	—	+0.0095 (0.0018)	—	—	—	—	—	—	0.08551
+0.0335 (0.0226)	+0.0189 (0.0127)	+0.0092 (0.0018)	—	—	—	—	—	—	0.08465
+0.0322 (0.0218)	+0.0266 (0.0121)	+0.0095 (0.0017)	−0.4157 (0.2058)	+10.20 (4.41)	+2.226 (1.022)	+0.1022 (0.0518)	+0.8671 (0.4133)	+2.225 (1.599)	0.07911
*+0.0265 (0.0314)	+0.0284 (0.0150)	+0.0112 (0.0021)	−0.3831 (0.2368)	+14.24 (5.18)	+3.373 (1.002)	+0.1342 (0.0569)	+0.8065 (0.5955)	*+1.983 (2.097)	0.06898
*+0.0215 (0.0312)	+0.0262 (0.0190)	+0.0070 (0.0027)	−0.6106 (0.3603)	+ 9.19 (8.34)	−5.777 (3.629)	*+0.0449 (0.0960)	+1.0528 (0.6073)	*+1.341 (2.405)	0.08538

28-day water-stored), for NAE cements to various independent variables

SO_3	Loss	Air 1:4 mortar	Ba	Co	Pb	Mn	V	Cr	S.D.
—	—	+0.0137 (0.0039)	—	—	—	—	—	—	0.08817
+0.0316 (0.0217)	+0.0291 (0.0131)	+0.0103 (0.0039)	—	—	—	—	—	—	0.08496
+0.0331 (0.0209)	+0.0373 (0.0128)	+0.0100 (0.0037)	−0.4358 (0.2095)	+10.33 (4.60)	+2.229 (1.038)	+0.0812 (0.0548)	+0.8594 (0.4206)	+1.954 (1.670)	0.07988
+0.0436 (0.0286)	+0.0437 (0.0165)	+0.0054 (0.0050)	−0.4784 (0.2381)	+12.24 (4.85)	+3.301 (1.065)	+0.1144 (0.0609)	+1.4902 (0.6056)	*−1.078 (2.141)	0.06808
*+0.0232 (0.0315)	+0.0364 (0.0213)	+0.0122 (0.0060)	*−0.3257 (0.3855)	+16.11 (10.75)	*−2.988 (3.451)	*+0.0225 (0.1004)	*+0.2991 (0.6278)	+4.259 (2.734)	0.09101
—	—	+0.0111 (0.0039)	—	—	—	—	—	—	0.08613
+0.0354 (0.0233)	+0.0221 (0.0130)	+0.0100 (0.0039)	—	—	—	—	—	—	0.08497
+0.0342 (0.0226)	+0.0289 (0.0125)	+0.0097 (0.0037)	−0.4273 (0.2096)	+10.60 (4.58)	+2.316 (1.036)	+0.0841 (0.0544)	+0.8601 (0.4201)	+1.735 (1.658)	0.07987
+0.0464 (0.0306)	+0.0364 (0.0159)	*+0.0048 (0.0050)	−0.4833 (0.2355)	+11.85 (4.71)	+3.269 (1.025)	+0.1178 (0.0597)	+1.5147 (0.5977)	*−1.026 (2.057)	0.06734
*+0.0214 (0.0343)	+0.0281 (0.0205)	+0.0125 (0.0060)	*−0.2783 (0.3886)	+15.65 (10.78)	*−3.111 (3.458)	*+0.0157 (0.1014)	*−0.2827 (0.6286)	+4.529 (2.760)	0.09129

TABLE 7–75. *"F" value for significance of reduction of variance due to added variables.*

Table	Equations	"F" ratio	D.F.	Critical "F" ratio	
				α=0.01	α=0.05
7–2	1, 2	5.06	3:165	3.90	2.67
	3, 4	4.88	3:165	3.90	2.67
	5, 6	4.54	3:162	3.90	2.67
	7, 8	5.69	3:163	3.90	2.67
7–3	1, 2	5.08	3:153	3.90	2.68
	3, 4	4.95	3:153	3.91	2.68
	5, 6	4.43	4:150	3.91	2.68
	7, 8	5.34	3:151	3.91	2.68
7–6	1, 2	4.61	4:164	3.42	2.43
	5, 6	5.85	3:166	3.90	2.67
	7, 8	3.26	4:162	3.42	2.43
	9, 10	3.78	4:163	3.42	2.43
7–7	1, 2	4.67	4:152	3.43	2.44
	4, 5	5.54	3:154	3.91	2.68
	6, 7	3.35	4:150	3.43	2.44
	8, 9	3.52	4:151	3.43	2.44
	8, 10	3.55	4:151	3.43	2.44
7–10	1, 3	8.38	5:165	3.12	2.27
	2, 4	3.37	1:165	6.78	3.90
	5, 6	0.50	1:165	6.78	3.90
7–11	1, 3	8.57	5:153	3.15	2.28
	2, 4	4.00	1:153	6.78	3.90
	5, 6	1.15	1:153	6.78	3.90
7–14	1, 4	6.45	5:164	3.12	2.27
	2, 3	4.41	3:165	3.90	2.67
	5, 6	3.86	4:165	3.42	2.43
7–15	1, 4	7.13	4:153	3.43	2.44
	2, 3	3.78	3:153	3.91	2.68
	5, 6	3.37	4:153	3.43	2.44
7–18	1, 4	4.27	5:167	3.12	2.27
	2, 3	3.15	5:167	3.12	2.27
	6, 7	3.25	4:166	3.42	2.43
7–19	1, 4	3.99	5:155	3.15	2.28
	2, 3	3.01	5:155	3.15	2.28
	5, 8	4.06	4:154	3.43	2.44
	6, 7	3.29	4:154	3.43	2.44
7–22	1, 2	4.82	5:162	3.13	2.28
	4, 5	4.31	6:161	2.91	2.15
7–23	1, 2	4.26	6:150	2.92	2.15
	4, 5	4.39	6:150	2.92	2.15
7–26	1, 3	7.81	4:167	3.42	2.43
	2, 4	4.77	3:167	3.90	2.67
	5, 6	5.00	3:166	3.90	2.67
7–27	1, 3	6.93	4:155	3.43	2.44
	2, 4	4.41	3:155	3.91	2.68
	5, 6	5.53	3:154	3.91	2.68
7–30	1, 2	3.51	5:160	3.13	2.28
7–31	1, 2	3.13	5:149	3.14	2.27
7–34	*0, 1	55.78	4:151	3.43	2.44
	1, 3	11.00	4:147	3.44	2.44
	3, 4	4.50	5:142	3.14	2.28
	2, 5	4.64	4:143	3.44	2.44
	6, 7	17.50	2:148	4.73	3.05
	7, 8	3.40	6:142	2.93	2.16
7–35	0, 1	51.86	4:139	3.45	2.45
	1, 2	6.59	4:135	3.45	2.45
	2, 5	4.30	4:131	3.45	2.45
	1, 3	7.41	4:135	3.45	2.45
	3, 4	4.19	5:130	3.15	2.28
	6, 7	13.40	2:136	4.76	3.91
	7, 8	4.42	4:132	3.45	2.45
7–38	0, 1	15.07	4:168	3.42	2.43
	1, 2	13.51	4:164	3.42	2.43
	2, 3	6.99	5:159	3.13	2.27
	5, 6	15.88	4:164	3.42	2.43
	6, 7	7.72	4:160	3.42	2.43
7–39	0, 1	14.80	4:156	3.43	2.44
	1, 2	7.64	4:152	3.43	2.44
	2, 3	6.26	5:147	3.14	2.28
	5, 6	10,00	4:152	3.43	2.44
	6, 7	5.83	5:147	3.14	2.28
7–42	0, 1	48.18	4:165	3.42	2.43
	1, 2	10.22	3:162	3.90	2.67
	2, 3	7.99	5:157	3.13	2.27
	5, 6	12.55	3:161	3.90	2.67
	6, 7	8.40	4:157	3.43	2.44
7–43	0, 1	43.47	4:153	3.43	2.44
	1, 2	8.43	3:150	3.91	2.68
	2, 3	7.04	5:145	3.14	2.28
	5, 6	10.58	3:149	3.91	2.68
	6, 7	7.48	4:145	3.42	2.43
7–46	0, 1	83.76	4:174	3.42	2.43
	1, 2	19.29	3:171	3.89	2.66
	2, 4	4.59	4:167	3.42	2.43
	6, 7	17.30	3:170	3.90	2.67
	7, 8	4.83	4:166	3.42	2.43
7–47	0, 1	81.50	4:162	3.42	2.43
	1, 2	15.91	3:159	3.91	2.68
	2, 4	5.27	4:155	3.43	2.44
	6, 7	14.82	3:158	3.91	2.68
	7, 8	5.33	4:154	3.43	2.44
7–50	0, 1	102.19	4:170	3.43	2.43
	1, 2	12.37	4:166	3.42	2.43
	2, 3	5.16	5:161	3.13	2.27
	5, 6	12.18	4:165	3.42	2.43
	6, 7	4.47	5:160	3.13	2.27
7–51	0, 1	94.72	4:158	3.43	2.44
	1, 2	10.49	4:154	3.43	2.44
	2, 3	5.49	5:149	3.14	2.28
	5, 6	10.77	4:153	3.43	2.44
	6, 7	4.10	5:148	3.14	2.28
7–54	0, 1	56.03	5:173	3.13	2.27
	1, 2	14.68	3:130	3.89	2.66
	2, 3	4.23	3:167	3.89	2.66
	4, 6	15.89	3:170	3.89	2.66
	6, 7	4.81	3:167	3.89	2.66
7–55	0, 1	51.31	5:161	3.13	2.27
	1, 2	13.03	3:158	3.90	2.67
	2, 3	3.88	3:155	3.90	2.67
	4, 6	14.36	3:158	3.90	2.67
	6, 7	4.50	3:155	3.90	2.67
7–58	0, 1	45.40	5:168	3.13	2.27
	1, 2	10.75	4:164	3.42	2.43
	2, 3	2.70	2:162	4.72	3.05
	5, 6	11.47	4:164	3.42	2.43
	6, 7	2.88	2:162	4.72	3.05
7–59	0, 1	41.25	5:156	3.13	2.27
	1, 2	10.46	4:152	3.43	2.44
	2, 3	2.23	2:150	4.73	3.05
	5, 6	11.32	4:152	3.43	2.44
	7, 8	2.24	2:150	4.73	3.05
7–62	0, 1	38.06	4:148	3.43	2.44
	1, 2	12.43	3:145	3.91	2.68
	2, 3	4.06	5:140	3.15	2.28
	5, 6	12.81	3:144	3.91	2.68
	6, 7	3.89	5:139	3.15	2.28
7–63	0, 1	33.05	4:136	3.46	2.45
	1, 2	11.64	3:133	3.98	2.69
	2, 3	4.26	5:128	3.16	2.29
	6, 7	11.92	3:132	3.98	2.69
	7, 8	4.03	5:127	3.16	2.29
7–66	0, 1	30.11	4:148	3.43	2.44
	1, 2	10.46	3:145	3.91	2.68
	2, 3	3.27	7:138	2.77	2.07
	5, 6	10.80	3:144	3.91	2.68
	6, 7	3.55	6:138	2.93	2.16
7–67	0, 1	25.70	4:136	3.46	2.45
	1, 2	9.94	3:133	3.98	2.69
	2, 3	3.22	7:126	2.79	2.09
	5, 6	10.38	3:132	3.98	2.69
	6, 7	3.45	6:126	2.95	2.16
7–70	0, 1	7.16	7:168	2.75	2.07
	1, 2	4.16	5:163	3.13	2.27
	0, 3	10.20	5:170	3.13	2.27
	3, 4	3.55	6:164	2.91	2.15
7–71	0, 1	6.10	7:157	2.76	2.07
	1, 2	4.17	5:152	3.14	2.27
	0, 3	8.73	5:159	3.14	2.27
	3, 4	3.56	6:153	2.92	2.16
7–73	0, 1	14.39	5:173	3.13	2.27
	1, 2	5.25	3:170	3.90	2.67
	2, 3	5.10	6:164	2.91	2.15
	4, 5	2.77	2:171	4.72	3.04
	5, 6	5.13	6:165	2.91	2.15
7–74	0, 1	8.56	5:161	3.13	2.27
	1, 2	5.13	3:158	3.90	2.67
	2, 3	4.46	6:152	2.92	2.16
	0, 4	10.52	5:161	3.13	2.27
	4, 5	3.21	2:159	4.72	3.05
	5, 6	4.49	6:153	2.92	2.16

*Equation 0 refers to the variance for the values themselves with no fitted equation.

reduction resulting from the use of the variables was not significant at the one percent level in eq 10, and the five percent level in eq 11. The reduction in variance values were highly significant in all the other equations.

These equations were calculated on the assumption that the relationship of strength at later ages to that at earlier ages is linear. This assumption may not be true in all cases, especially when cements of different types are combined.

TABLE 7–76. *Relationships of compressive strengths at different ages, to compressive strengths at earlier ages and comparisons with S.D. values from previous equations*

Eq. No.	Equation	S.D.	"F"	S.D. from equations derived with chemical and physical properties
1	ST28 =+2991 +0.955 ST03 s.d. = (127) (0.056)	554	147	554 eq 3 table 7–14
2	ST1Y =+5393 +0.389 ST03 s.d. = (185) (0.081)	809	11	535 eq 3 table 7–18
3	ST1M =+5400 +0.565 ST03 s.d. = (190) (0.083)	828	23	572 eq 2 table 7–22
4	ST1A =+3668 +0.737 ST03 s.d. = (110) (0.048)	479	117	447 eq 3 table 7–26
5	ST5Y =+5368 +0.335 ST03 s.d. = (216) (0.094)	941	6.3	508 eq 2 table 7–30
6	ST28 =+2507 +0.779 ST07 s.d. = (135) (0.039)	507	194	554 eq 3 table 7–14
7	ST1Y =+5373 +0.263 ST07 s.d. = (218) (0.063)	821	8.5	535 eq 3 table 7–18
8	ST1M =+5200 +0.435 ST07 s.d. = (221) (0.065)	830	23	572 eq 2 table 7–22
9	ST1A =+3388 +0.572 ST07 s.d. = (127) (0.037)	479	117	447 eq 3 table 7–26
10	ST5Y =+5431 +0.202 ST07 s.d. = (254) (0.074)	954	3.7	508 eq 2 table 7–30
11	STXY=+5036 +0.161 ST07 s.d. = (303) (0.087)	1035	1.7	562 eq 4 table 7–34
12	ST1Y =+3383 +0.564 ST28 s.d. = (293) (0.057)	695	49	535 eq 3 table 7–18
13	ST1M =+3123 +0.692 ST28 s.d. = (292) (0.057)	690	74	572 eq 2 table 7–22
14	ST1A =+2026 +0.640 ST28 s.d. = (186) (0.036)	448	156	447 eq 3 table 7–26
15	ST5Y =+3592 +0.494 ST28 s.d. = (367) (0.071)	867	24	508 eq 2 table 7–30
16	STXY=+3036 +0.495 ST28 s.d. = (432) (0.083)	948	18	562 eq 4 table 7–34
17	ST1M =+754 +0.941 ST1Y s.d. = (243) (0.038)	452	298	572 eq 2 table 7–22
18	ST1A =+2351 +0.467 ST1Y s.d. = (321) (0.051)	598	42	447 eq 3 table 7–26
19	ST5Y =+8977 +0.963 ST1Y s.d. = (276.5) (0.044)	515	240	508 eq 2 table 7–30
20	STXY=−353 +0.949 ST1Y s.d. = (337) (0.053)	611	158	562 eq 4 table 7–34
21	STXY=+808 +0.719 ST1M s.d. = (423) (0.063)	781	65	562 eq 4 table 7–34
22	STXY=−181 +0.956 ST5Y s.d. = (218) (0.036)	452	357	562 eq 4 table 7–34

6.3. Early Strength Versus Composition of the Cement, and the Prediction of Strength at Later Ages

In order to evaluate the relative merits of the use of the compressive strength at an earlier age versus the use of the physical and chemical properties of the cements in making predictions of the compressive strength of cement mortars at a later age, a comparison was made of the S.D. values obtained by the two methods. The S.D. values obtained from the strength relations discussed in the previous subsection and those obtained by use of the combinations of chemical and physical independent variables are both presented in table 7–76.

Referring to table 7–76 it may be noted that the S.D. value for eq 1 was the same as that obtained in eq 3 of table 7–14. From this it may be inferred that the 28-day compressive strength values can be predicted equally well by either method. Equations 6, 14, 17, and 22 of table 7–76 had lower values than those obtained in corresponding previously calculated equations. Equation 6 related the 28 to 7-day strengths, eq 22 the 10 to 5-year strengths, eq 17 the 1-year moist-air to water-stored strengths. All of these test ages were adjacent to each other. Equation 14 related the 1 year strength of the air-stored specimens to the 28-day compressive strength. The 1-year air-stored specimens were cured 3 weeks in water, 1 week at the start and 2 weeks before the compression tests, and were therefore hydrated for approximately the same time as those cured in water for 28 days.

All of the other equations of table 7–76 had higher S.D. values than when the compressive-strength values were fitted to combinations of independent variables—the chemical and physical properties of the cements. Many of these pairs of S.D. values were approximately equal, but information which would indicate statistical significance is not available. However, since the equation derived from chemical and physical properties include many more variables, their S.D. values would have to be considerably lower than those for the equations in table 7–76 to indicate the same prediction value.

The fact that the S.D. values of so many of the equations derived with the use of the chemical and physical properties of the cement were lower than those derived from the relation to earlier strength results indicates, that in many instances it might be possible to use the chemcial and physical properties to make a rough prediction of the compressive strength at the later test ages.

6.4. Coefficients, and Their Significance, of the Major Potential Compounds, of Other Commonly Determined Variables and of the Trace Elements at Different Test Ages

A series of tables has been presented indicating the variables found to be significant for the compressive strength at each of the test ages from 1 day to 10 years. In view of the fact that it is difficult to follow the trends of the coefficients with the age of test, a summary, Table 7–77, has been prepared. For this comparison, a single equation was selected from each of the tables previously presented for the NAE cements at the various test ages and now presented in table 7–77. The equation selected was, in each case, one in which one or more of the potential compounds, air permeability fineness, and trace elements were included as independent variables.

The equations are presented *vertically* instead of *horizontally* as was done in the previous tables. For example,

$$\begin{gathered} Y \\ = \\ \text{constant} \\ + \\ c_1X_1 \\ + \\ c_2X_2 \\ + \\ c_nX_n \end{gathered}$$

Under each coefficient is presented the coef./s.d. ratio instead of the s.d. value in the original equations.

TABLE 7–77. *Coefficients, coef./s.d. ratios, and calculated ranges of contributions of independent variables associated with compressive strength values at different ages for NAE cements*

Equation	2	2	3	4	4	3	5	3	4
Table	7–3	7–7	7–11	7–15	7–19	7–31	7–35	7–23	7–27
	ST01	ST03	ST07	ST28	ST1Y	ST5Y	STXY	ST1M	ST1A
	=	=	=	=	=	=	=	=	=
Constant	−2071	−2935	−2813	+1010	+6820	+6505	+7774	+6502	+2130
C_3A, coef.	----------	+40.7	+70.2	+74.1	−82.7	−85.4	−126.2	−57.9	----------
Coef./s.d.	----------	3.6	5.3	3.6	5.4	5.0	5.4	3.2	----------
Calculated ranges*	----------	570	983	1037	1158	1196	1767	811	----------
C_3S, coef.	+19.2	+39.5	+55.2	+45.5	----------	----------	----------	----------	+29.5
Coef./s.d.	8.2	8.6	9.9	5.7	----------	----------	----------	----------	4.8
Calculated range	864	1778	2484	2048	----------	----------	----------	----------	1328
C_2S, coef.	----------	----------	----------	----------	----------	+17.8	+19.6	----------	----------
Coef./s.d.	----------	----------	----------	----------	----------	2.5	2.5	----------	----------
Calculated range	----------	----------	----------	----------	----------	801	882	----------	----------
C_4AF, coef.	----------	----------	----------	+42.0	----------	----------	−53.7	----------	----------
Coef./s.d.	----------	----------	----------	1.6	----------	----------	2.0	----------	----------
Calculated range	----------	----------	----------	630	----------	----------	806	----------	----------
APF, coef.	+0.55	+0.78	+0.89	+0.71	+0.37	+0.47	+0.31	+0.51	+0.43
Coef./s.d.	14.5	10.8	10.2	6.5	4.3	5.4	2.9	4.7	4.7
Calculated range	4350	3248	2670	2130	1110	1410	930	1530	1290
Air 1:4 Mortar, coef.	−18.8	−70.3	−75.5	−101.5	−95.0	−170.2	−224	−139	−89.6
Coef./s.d.	2.2	4.4	3.9	3.8	3.6	6.9	8.1	4.8	4.0
Calculated range	376	1406	1510	2030	1900	3404	4480	2780	1792
SO_3, coef.	+257	+446	+313	----------	----------	----------	----------	+270	+494
Coef./s.d.	4.6	4.1	2.5	----------	----------	----------	----------	1.5	3.8
Calculated range	463	802	563	----------	----------	----------	----------	486	889
Loss, coef.	−188	−252	−362	−460	−713	----------	----------	----------	----------
Coef./s.d.	6.2	4.5	5.2	4.6	2.0	----------	----------	----------	----------
Calculated range	564	756	1086	1380	2139	----------	----------	----------	----------
Insol., coef.	−216	----------	----------	----------	----------	−928	−985	----------	−655
Coef./s.d.	1.8	----------	----------	----------	----------	2.7	2.5	----------	2.2
Calculated range	216	----------	----------	----------	----------	928	985	----------	655
MgO, coef.	----------	----------	−26.1	----------	----------	−64.7	----------	−82.9	+80.3
Coef./s.d.	----------	----------	0.9	----------	----------	1.8	----------	2.0	2.3
Calculated range	----------	----------	131	----------	----------	324	----------	414	402
K_2O, coef.	+399	+376	+524	----------	----------	----------	----------	----------	----------
Coef./s.d.	5.4	2.6	2.9	----------	----------	----------	----------	----------	----------
Calculated range	439	414	576	----------	----------	----------	----------	----------	----------
Na_2O, coef.	----------	----------	----------	----------	−858	−1030	−1256	----------	----------
Coef./s.d.	----------	----------	----------	----------	3.0	3.8	4.1	----------	----------
Calculated range	----------	----------	----------	----------	601	721	879	----------	----------
Ba, coef.	----------	----------	----------	----------	----------	----------	----------	----------	−3540
Coef./s.d.	----------	----------	----------	----------	----------	----------	----------	----------	3.1
Calculated range	----------	----------	----------	----------	----------	----------	----------	----------	708
Co, coef.	----------	----------	----------	−71700	−58500	----------	----------	−49700	----------
Coef./s.d.	----------	----------	----------	2.0	1.8	----------	----------	1.3	----------
Calculated range	----------	----------	----------	717	585	----------	----------	497	----------
Cr, coef.	----------	+7480	----------	−22000	----------	----------	+18300	----------	----------
Coef./s.d.	----------	1.1	----------	2.0	----------	----------	1.7	----------	----------
Calculated range	----------	150	----------	440	----------	----------	366	----------	----------

See footnote at end of table.

TABLE 7–77. *Coefficients, coef./s.d. ratios, and calculated rauges of contributions of independent variables associated with compressive strength values at different ages for NAE cements*—Continued

Equation	2	2	3	4	4	3	5	3	4
Table	7–3	7–7	7–11	7–15	7–19	7–31	7–35	7–23	7–27
Cu, coef	---	---	---	---	---	---	---	−7190	−6226
Coef./s.d	---	---	---	---	---	---	---	1.2	1.4
Calculated range	---	---	---	---	---	---	---	340	311
Mn, coef	---	−537	---	---	−576	---	---	−500	---
Coef./s.d	---	2.2	---	---	1.6	---	---	1.2	---
Calculated range	---	537	---	---	576	---	---	500	---
Ni, coef	+5960	---	---	---	---	+19300	---	---	---
Coef./s.d	1.4	---	---	---	---	1.5	---	---	---
Calculated range	119	---	---	---	---	386	---	---	---
P, coef	−275	---	---	---	---	---	---	+990	---
Coef./s.d	2.1	---	---	---	---	---	---	2.2	---
Calculated range	137	---	---	---	---	---	---	445	---
Pb, coef	---	---	---	---	---	---	---	---	+9260
Coef./s.d	---	---	---	---	---	---	---	---	1.5
Calculated range	---	---	---	---	---	---	---	---	463
Rb, coef	---	---	---	---	−63000	−60000	---	−99800	---
Coef./s.d	---	---	---	---	2.7	2.7	---	3.9	---
Calculated range	---	---	---	---	630	600	---	998	---
SrO, coef	−394	−911	−558	−1130	---	---	−990	−1460	---
Coef./s.d	2.3	2.7	1.4	1.8	---	---	1.6	2.5	---
Calculated range	234	541	331	671	---	---	588	867	---
Zn, coef	---	---	---	---	---	+1990	+3730	---	---
Coef./s.d	---	---	---	---	---	1.5	1.6	---	---
Calculated range	---	---	---	---	---	398	746	---	---
Zr, coef	---	---	---	+1720	+2220	+1740	+2590	---	---
Coef./s.d	---	---	---	1.5	2.1	1.7	2.2	---	---
Calculated range	---	---	---	860	1110	870	1245	---	---
V, coef	---	+3200	---	---	---	---	---	---	---
Coef./s.d	---	1.9	---	---	---	---	---	---	---
Caclulated range	---	320	---	---	---	---	---	---	---

*The calculated range was computed from the range of values for the cements times the coefficient for each independent variable.

Also presented in this table are values called "calculated range." These values were obtained by multiplying the coefficient for each of the variables by the difference between the high and low value for each of the respective variables found with the cements used in this investigations. In some instances, as for SO_3, insoluble residue and ignition loss, the values found were less than are permitted by present specifications for portland cements.

The first seven equations in table 7–77 are for the compressive strength of water-stored specimens from 1 day to 10 years. The coefficients for C_3A were positive and highly significant at 3, 7 and 28 days, but at 1, 5 and 10 years, the coefficients were negative, and again highly significant. The coefficients for C_3S were positive with an increase of the coef./s.d. ratio to 7 days,—then a decrease at 28 days, after which the coef./s.d. ratio was less than one. In this series of tests, the C_2S did not show any evidence of significance until the 5- and 10-year tests. The coefficient for C_4AF was positive but of doubtful significance at 28 days but the sign was negative in the equation for the 10-year tests.

The coefficients for fineness were positive at all ages. The variable was most significant at the early ages, but less significant at later ages. On the other hand, the air content of the 1:4 mortar, with a negative coefficient became more highly significant at the later test ages,—5 and 10 years. The SO_3 was significant only up through 7 days, but Loss was significant up through 1 year, and Insoluble residue only at the later ages. The MgO was of doubtful significance at 5 years for the water-stored specimens, and more significant at 1 year for the moist-air-stored, and the air-stored specimens. The coefficient was negative in the ST5Y and ST1M equations, and positive in the ST1A equation.

The coefficients for K_2O were positive and were significant only at 1, 3, and 7 days. The coefficients for Na_2O were not significant at the early ages but were at 1, 5, and 10 years and the coefficients were negative. (It should be noted, however, that in equations for SG(1), SGR(1),

SG(2), SGR(2), SG(3), SGR(3), SG(4), SGR(4), in previous tables, the coefficients for both Na_2O and K_2O were significant and were negative in all the strength-gain, and the strength-gain-ratio equations. No explanation can be offered for these differences, but the alkalies will be discussed further in a later subsection.

In table 7–77 there were only two instances where the coef./s.d. ratios for the other trace elements, Ba, Co, Cr, Cu, Mn, Ni, P, Pb, Rb, SrO, V, Zn, and Zr were greater than 3. The signs of the coefficients were consistent where the variable occurred and was significant in more than one equation. The coefficients for SrO were significant in equations for one and three days and 1-year moist cured and possibly significant at 7 and 28 days. (SrO was not significant in the SG nor the SGR equations.) The coefficients for Zr were significant at 1 and 10 years, and possibly at 28 days and 5 years but not at the earlier ages, and the coefficient for Zn was not highly significant at any age. The coefficients of the rest of the trace elements did not show strong evidence of significance.

The use of trace elements found to be significant in the equations for compressive strength resulted in a significant reduction in the S.D. values at all ages except for the 7-day tests. There is no apparent reason for the difference in behavior at the 7-day test age.

6.5. Coefficients, and Their Significance, of the Major Oxides at Different Test Ages

Equations were presented for the compressive strength at various test ages as related to the major potential compounds with other variables, and to the major oxides with other variables. There were only a few instances where the other variables were not the same or had different coefficients or coef./s.d. ratios when the oxides were used than when the compounds were used in the calculations. The S.D. values were approximately the same in both cases in comparable equations for each of the test ages.

As in subsection 6.4 the coefficients and coef./s.d. ratios for the oxides were different at different ages. The coefficient for CaO was positive and the coef./s.d. ratio increased from 1 to 3 to 7 days,—decreased some at 28 days and was not significant at 1, 5, and 10 years. The coefficient for SiO_2 was negative up through 28 days,—was not significant at 1 year,—then became positive at 5 and 10 years. The coefficient for Al_2O_3 was negative at 1 and 3 days, and at 1 year, but was not significant at the other ages for the water-stored specimens. The Fe_2O_3 was significant at 1 and possibly 3 days with a negative coefficient,—was not significant at 7 and 28 days,—then the coefficient became positive with increasing significance at 1, 5, and 10 years. The trends of the coefficients, and changes of the signs of the coefficients for SiO_2 between 28 days and 5 years, or for Fe_2O_3 between 3 days and 1 year are of interest and value in indicating the dominant oxides associated with early strength differences of mortars made of the various portland cements, and those stored in water for an extended period of time.

6.6. The Effect of Alkalies in Portland Cement on Compressive Strength

It was previously noted that the coefficient for K_2O was significant in equations for the 1-, 3-, and 7-day compressive strengths with positive coefficients, and Na_2O in the equations for the 1-, 5-, and 10-year compressive strengths with negative coefficients. It has been reported, and is generally accepted, that the K_2O may be in the substituted C_2S, ($KC_{23}S_{12}$), and also in solid solution as a sulfate. Some Na_2O is generally believed to be in a substituted C_3A, (NC_8A_3), with any excess in a solid solution, possibly in the form of a sulfate.

Of the other elements in this group, Li was possibly significant in equations for SR(1). Rb was significant in equations for ST1Y, ST1M, ST5Y, and SR(1) and possibly for SG(1), SG(2), and SGR(2). Information is not available on the compounds these elements are associated with or if they also occur in the solid solutions. No statistical tests were made to determine possible interaction of the different alkalies with the other independent variables in the equations. It does appear, however, that more attention should be given to the effect of the individual alkalies on properties other than the alkali-aggregate expansion.

6.7. Compressive Strength and Heat of Hydration

It was indicated in a previous section of this series of articles [13] dealing with the heat of hydration that there was a significant relationship between the 7- and 28-day heat of hydration and compressive strength, but no relation between strength and the 1-year heat of hydration.

At 7 and 28 days C_3A and C_3S were important among the compounds associated with both heat of hydration and compressive strength. In equations for the 1-year heat of hydration, the coefficient for C_3A was positive, but it was negative in the equations for 1-year compressive strength. The C_3S and C_2S, although contributing to the 1-year heat of hydration, did not appear to affect the 1-year compressive strength values obtained with the different cements. The C_4AF content contributed to the heat of hydration at 28 days and 1 year, but showed a significant effect on strength only at one day (eq 3, tables 7–2 and 7–3).

Of the other commonly determined variables, the loss on ignition had a relatively large effect at all ages through one year in both the heat of hydration tests and the strength tests. The fineness of the cement was a contributing factor in both heat of hydration and strength, but it appeared to have a more dominant role in the compressive strength tests. The coefficient for SO_3 was positive and significant in equations for both the 7-day heat of hydration and strength but in neither test was the coefficient significant at the later ages.

The coefficient for K_2O was positive and significant in equations for both 7-day heat of hydration and strength, but was not significant at 28 days or 1 year in equations for these two properties. The coefficient for Na_2O was significant and had a negative sign in both the 1-year heat of hydration equations and the 1-year compressive strength equations, but was not significant at the earlier ages. The air in the 1:4 mortars was associated with the compressive strength of the 1:2.75 mortars at all ages, but this variable was not significant in equations for heat of hydration.

Some trace elements were also associated with the heat of hydration and with the compressive strength. The signs of the coefficients were generally the same in equations for both properties, but in many instances the effect of some trace elements were masked at some ages. For example an increase in Cu was associated with lower heat of hydration at 7 and 28 days and 1 year but was not highly significant in any of the strength equations. The Zr content appeared to make a significant contribution to the 7- and 28-day heat of hydration, but not to the 1-year heat of hydration. The Zr content was possibly also associated with the compressive strength values of the water-stored specimens at 28 days and later ages. An increase in Zr when significant was associated with an increase in strength. The coefficient for SrO was significant and negative in equations for the 28-day heat of hydration.

In the equations for compressive strength, the coefficient for SrO was significant and negative at one and three days water-stored and 1-year moist-air-stored and was possibly significant at 7 and 28 days and 10-years water-stored but not significant for the 1-year air-stored specimens. An increase in P was associated with lower heat of hydration values at all ages. The coefficient for P was negative in equations for 1-day compressive strength, and positive in equations for the compressive strength at 1 year for the moist-air-stored specimens. At other ages there was no evidence for any effect of P. (The number of cements with reported values for P was small and, as previously indicated, values below the lower reporting limit were listed as having 0% of the element. This makes any values for P doubtful.)

Of the other trace elements, the coefficient for Cr was significant in equations for the 7-day heat of hydration and 28-day compressive strength. The coefficient for Co was significant in equations for both 28-day heat of hydration and compressive strength and possibly also in equations for the 1-year compressive strength. The coefficients for V and Ba were significant in equations for 1-year heat of hydration, but not in equations for 1-year compressive strength. The coefficients for Rb and Mn were not significant in equations for heat of hydration, but Rb was significant and Mn was possibly significant in equations for 1-year compressive strength.

There appear then to be a number of instances where the effect of a variable on compressive strength is also significant in the equations for the heat of hydration. There are also differences, for example the sign change of the coefficient for C_3A in the equations for compressive strength, and the lack of significance of C_3S and C_2S in the equations for 1-year compressive strength. Another large factor affecting the compressive strength is the air entraining characteristics of the cements.

6.8. Air Permeability and Turbidimeter Fineness Values and Compressive Strength

The importance of the fineness of grinding of portland cement clinkers has been recognized in specification requirements for many years. In the present investigation it was also found to be one of the important variables associated with the compressive strength of cements of different compositions especially at the earlier test ages. It was noted that in relating the compressive strength at the different ages to the combinations of independent variables, that the equations using the turbidimeter fineness values usually had lower S.D. values than comparable equations using the air-permeability fineness values. Equations for strength-gain, strength-gain ratios, and strength ratios had smaller differences in the S.D. values when using the fineness values obtained by the two methods in the equations.

The average ratio of the fineness values determined by the two methods was 1.88 with an estimated standard deviation of 0.16. It has been reported (Lea-Desch p 331) [7] that the APF/WAGN ratio varies with the fineness of the cement and the gypsum content. It is commonly known also, that the ratio for types II, IV and V cements may differ appreciably from the ratio obtained with type I cements.

Using the same statistical techniques employed in the rest of this series of articles, 2 equations were obtained as follows:

$$(1)\ \mathrm{APF/WAGN} = \underset{(0.043)}{+1.422} \ \underset{(0.0027)}{+0.0129\ C_3A} \ \underset{(0.0254)}{+0.0776\ SO_3} \ \underset{(0.0155)}{+0.1670\ \mathrm{Loss}}$$

s.d.= (0.043) (0.0027) (0.0254) (0.0155)

$$(2)\ \mathrm{APF} = \underset{(136)}{-621} \ \underset{(0.068)}{+1.720\ \mathrm{WAGN}} \ \underset{(5.39)}{+17.79\ C_3A} \ \underset{(50.9)}{+207.9\ SO_3} \ \underset{(28.9)}{+305.2\ \mathrm{Loss}}$$

s.d.= (136) (0.068) (5.39) (50.9) (28.9)

An S.D. value of 0.105 was obtained for the first equation. The reduction of variance resulting from the use of the added variables was 57 with 4:175 degrees of freedom. In the second equation the S.D. value was 198, the "F" value 221 with 5:174 degrees of freedom. The coef./s.d. ratios for all of the independent variables in the two equations were highly significant. Other equations, not presented, indicated that the trace elements Zr, Cr, and Rb may also be associated with the fineness and fineness ratio. The C_3A, SO_3, and Loss were, however, the most significant variables.

High values of C_3A, SO_3, or loss on ignition are all associated with low specific gravity of the portland cements. A specific gravity less than the assumed value of 3.15 would result in a specific surface value somewhat greater than would be obtained if the correct specific gravity value were used with both the turbidimeter and air-permeability apparatus.[11]

When the independent variables C_3A, SO_3, and loss on ignition were significant in equations relating the compressive strength at the different ages to the various independent variables, it was noted that numerical differences in coefficient and coef./s.d. ratios occurred when Wagner turbidimeter fineness values were substituted for air permeability values. In the case of Loss these differences were large and highly significant at ages less than 1 year. For the other two variables, the differences were much smaller, but may possibly indicate a significant effect at some ages.

6.9. Compressive Strength and Other Independent Variables

The previous subsection presented information relative to the interrelation between fineness values and other determined variables, C_3A, SO_3, and loss on ignition. It is probable that some of the so-called independent variables are not truly "independent." Although the water-requirement for the mortars of the different cements, for instance, was not found to be a significant variable in the compressive strength tests, it was previously shown in section 2 of this series of articles that this property is also dependent on many of the variables associated with compressive strength. (See table 2–6 p 18, 19) [9].

Also in table 7–63 of this article, there was some indication (on the basis of one pair of equations) that the "air in the 1:4 mortar" may be a variable which may interact with other independent variables. The air content was not determined for the 1:2.75 mortars used for the compressive strength tests and it was necessary to use the values for the percentage air entrained in 1:4 mortars. The correlation between the air content values of the two mortars is far from perfect, and better knowledge of the air content of the test mortars may have resulted in better fit of the test data to the calculated relationships. The air-entraining characteristics are apparently of great importance, even with the nonair-entraining cements, and should be recorded in any future work of this nature.

There are also other interrelations in the portland cement composition, as, for example, the C_3S and C_2S, or the C_4AF and C_3A. When the potential C_3S content in a portland cement is increased, it is usually at the expense of the potential C_2S content. When used in a multivariable regression equation, one or the other may have a dominant effect. If both are used in an equation, the significance of one or both may disappear.

Previous studies of the strength-producing characteristics of laboratory-prepared compounds of C_3S and C_2S have established the fact that both contribute to a major extent to the compressive strengths although the rates of strength contributions are different. It may seem unusual, therefore, that neither the C_3S nor the C_2S were significant in multivariable equations relating the different independent variables to the compressive strength at 1 year for the water-stored specimens, for example.

One way of getting around difficulties mentioned above is the interpretation of the relationships of the various "independent" variables to *differences* in the compressive strength values attained by the portland cements. This interpretation does not detract from the usefulness of the equations presented. It does help to explain why different cements attain greater strength than others. It also indicates that the extension of research on the modifying effects of certain trace elements on such properties as compressive strength may be fruitful.

7. Summary and Conclusions

(1) Compressive strength tests were made on 1:2.75 (cement to graded Ottawa sand) mortar cubes of standard consistency at ages from 24 hr to 10 years. The tests were made on 199 portland cements of different types and from different mills. All specimens were stored in water until time of testing, except that 1-year tests were also made on specimens stored at 95 to 100 percent relative humidity and on specimens stored in laboratory air at 50 percent relative humidity for 49 of the 52 weeks.

(2) The average compressive strength values for water-stored specimens for the different types of cement increased up through the 1-year tests, but the averages were somewhat lower at the time of the 5- and 10-year tests.

[11] The rate of settling of the particles is a function of the difference in density of the cement and the liquid in which it is dispersed in the tubidimeter test. The permeability function, $e^{3/2}/(1-e)$, where e=porosity, in the air permeability test for fineness is probably more sensitive to differences in the specific gravity of the cements. With the turbidimeter test, a low-specific-gravity cement would settle more slowly and result in a "high" fineness value. With the air-permeability fineness test, the actual porosity of the test bed would be less than the calculated value which would also result in a "high" fineness value.

(3) The average compressive strength of the 1-year air-stored specimens, tested after resaturation, was near that of the 28-day water stored specimens. The average compressive strengths of the 1-year moist-air stored and the 1-year water-stored specimens were also nearly the same.

(4) The frequency distributions of the compressive strength values at the different test ages indicated that a range of values was obtained for each of the types of cement, and there was considerable overlapping of the values obtained for the different types.

(5) Computations of multivariable equations by a least-squares method were used to determine the chemical and physical properties of the cements which were associated with the compressive strength values at the various ages, the strength gain between various ages, the compressive-strength-gain ratios, and various strength ratios. The equations were computed for all cements for which minor constituents and trace elements had been determined, and for the nonair-entraining cements within this group. The equations were computed using as independent variables, either the major potential compounds, or the major oxides, each with other commonly determined variables found to be significant.

The following observations relate to the equations for water-stored specimens made of nonair-entraining cements as summarized in table 7–77.

(5.1) The major potential compounds found to be associated with differences in compressive strength were not the same at the different test ages or after different storage conditions.

An increase in the C_3A was associated with higher compressive-strength values at 3, 7, and 28 days, and with lower compressive-strength values at 1, 5 and 10 years.

An increase in the C_3S was associated with higher compressive-strength values up to 28 days, but the coefficient for C_3S was not significant at the later ages.

An increase in the C_2S was associated with higher compressive-strength values only at 5 and 10 years. (At 1 year neither C_3S nor C_2S had significant coefficients.)

An increase in the C_4AF showed a barely significant association with lower strength values at 10 years.

(5.2) Other commonly determined variables were also associated with the compressive-strength values at the different test ages, and the contribution and significance of these variables were different at different test ages.

An increase in fineness was associated with higher compressive-strength values at all test ages but to a greater extent at the early ages.

An increase in the air content of the 1:4 mortar (the air contents of the 1:2.75 mortars were not determined), was associated with lower compressive strength values at all ages, and most significantly at the later test ages, 5 and 10 years.

An increase in SO_3 was associated with higher compressive strength values only at 1, 3, and 7 days.

An increase in loss on ignition was associated with lower compresisve-strength values at all test ages up to 1 year.

An increase in the insoluble residue was associated with lower compressive-strength values at 5 and 10 years, and possibly at 1 day.

An increase in MgO was associated with a higher compressive strength with the 1-year air-stored specimens and possibly with a lower compressive strength for the 1-year moist-air-stored specimens and the 5-year water-stored specimens.

An increase in K_2O was associated with higher compressive strengths only at 1, 3, and 7 days.

An increase in Na_2O was associated with lower compressive strength values at 1, 5, and 10 years, but not at early ages. (An increase in both Na_2O and K_2O was associated with lower strength gain and strength-gain-ratios in all equations.)

(5.3) The use of other minor constituents and trace elements resulted, in most equations, in significant reductions in the estimated standard deviation values. The one exception was in equations for the 7-day compressive-strength values. The coefficients for the trace elements were generally not highly significant, and, in equations calculated for the "odds" and "evens" in the array of cements, many were not significant in the smaller groups.

In general, increases in Mn, Rb, and SrO were associated with lower compressive-strength values at one or more of the test ages, and an increase in Zr with higher values at some later test ages. There were also indications of a possibility that Ba, Co, Cu, Ni, Pb, V, and Zn might also have some effect.

(6) Equations calculated using the major oxides, other commonly determined variables and trace elements resulted in estimated standard deviation values of about the same magnitude as obtained with the use of the major potential compounds. There were a number of exceptions, but in general, the same other commonly determined variables and trace elements were significant as when the major compounds were used in the equations. As was found for the major compounds, the coefficients of the major oxides as well as the significance of the coefficients were not the same for the compressive strength values determined at different ages.

An increase in CaO was associated with higher compressive strength values at 1, 3, 7, and 28 days, but not at later ages.

An increase in SiO_2 was associated with lower compressive strength values up through the 28-day tests and with higher compressive strength values at 5 and 10 years.

An increase in the Al_2O_3 was associated with lower compressive strength at 1 and 3 days, but was not significant for the water-stored specimens at other test ages.

An increase in Fe_2O_3 was associated with lower compressive strength values at 1 and 3 days and with higher compressive strength values at 5 and 10 years and possibly at 1 year.

(7) Variables associated with the compressive-strength values of nonair-entraining cements were also associated in equations for the combined air-entraining and nonair-entraining cements. The significance of the coefficients of the air-content variable was greater when the air-entraining cements were included. Some differences were noted in the values of the coefficients of corresponding variables in the equations for the AE+NAE cements and those in equations for the NAE cements alone, but they were usually small compared to the estimated standard deviations of the respective coefficients.

(8) The equations for gain in compressive strength between different test ages, for the strength-gain ratios, and strength ratios did not have the same significant independent variables as in the equations for the compressive strength at the corresponding test ages. Some independent variables found to be significant in one or both of the equations relating the variables to the strength at each of two ages were not significant in ratios or differences of the strength values. It was noted, however, that in some equations for ratios etc., other variables, not significant in the equations for the strength at two test ages were significant in the equations for ratios or differences.

(9) Although the average compressive-strength values of 1-year water-stored and moist-air-stored specimens were nearly the same, the specimens of a majority of the cements stored in water had lower compressive strength values than those stored at a high humidity. Equations were computed for the ratio of the compressive-strength values after water storage to those after moist air storage, as related to combinations of independent variables. Increases in C_3A, C_3S, C_4AF, SO_3, and Na_2O and possibly P were associated with lower strength ratios, and increases in MgO, Zr, V, and Rb and possibly Ti were associated with higher strength ratios.

(10) Although the average 1-year compressive strength of the air-stored specimens was about equal to the average 28-day compressive strength of water-stored specimens, this relationship was not true for all cements. The compressive strengths of the air-stored specimens were lower for 57 of the 199 cements. Increases in C_3A, C_3S, C_4AF, and Ba were associated with lower (1-year-air/28-day-water) strength ratios, and increases in MgO, Loss, air content, Co, Pb, Mn, and V, and possibly SO_3 and Cr with increases in the strength ratio.

(11) The use of various independent variables associated with the chemical and physical properties of the cements in equations resulted, in many instances, in lower estimated standard-deviation values than were obtained by relating the compressive-strength values at a later age to those at an earlier age.

(12) A comparison was made of the variables associated with the heat of hydration at 7 and 28 days, and 1 year, and the variables associated with the compressive-strength values at these ages. There were a large number of instances where the independent variables had parallel effects in the two tests at the respective test ages. Some of the more important factors which may cause a lack of agreement between the 1-year heat of hydration and the 1-year compressive-strength differences are the change of sign for the coefficient for C_3A, and the fact that C_3S and C_2S contribute to heat of hydration, but not to compressive strength differences. The air-entraining characteristics of the cements were associated with the compressive-strength values at all ages, but not with the heat of hydration.

(13) The use of the Wagner-turbidimeter-fineness values rather than the air-permeability-fineness values usually resulted in lower estimated standard-deviation values in the multivariable equations for compressive-strength values at the different ages. The effect was not so pronounced in equations for strength-gain or for strength-gain ratios. The differences in ratios of the two fineness values are dependent to a large extent on the C_3A and SO_3 content and on the loss-on-ignition values, all of which may have an effect on the specific gravity of the cement. The interrelations of these "independent" variables were reflected to some extent in the coefficients of these variables when used in the equations.

Acknowledgments are made to the former heads of branch laboratories of the National Bureau of Standards at Allentown, Pa., Denver, Colo., San Francisco, Calif., and Seattle, Wash., G. Stiller, O. H. Cox, O. C. Marek, and Frank Winblade, respectively, as well as their associates, and to D. N. Evans, former head of the Washington Laboratory and his associates for collecting the cements, making the many tests, collecting, checking, and compiling the data.

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Section 8. Compressive Strength of Steam-cured Portland Cement Mortars

R. L. Blaine, H. T. Arni, and M. R. DeFore

The relationships between the chemical and physical characteristics of 161 portland cements and the compressive strengths of 2-inch mortar cubes made from those cements after both low- and high-pressure steam, as well as moist-air curing, were studied by computing multivariable regression equations with the aid of a digital computer, and determining which of the independent variables appeared to have a significant relationship to the compressive-strength values. An increase in C_3A, SO_3, and K_2O each appeared associated with higher compressive strengths with the low-pressure-steam-cured specimens but not with 28-day strengths of the 23 °C moist-air-cured specimens. Increases of C_3A, C_3S, C_2S, SO_3 and fineness were all associated with higher strength values when autoclave curing was started after 5 hours, but when started after 24 hours, variations of neither C_3A nor C_3S appear to have any effect. The use of certain of the trace elements in the equations together with commonly determined variables resulted in a reduction in variance although the coefficients of the individual trace elements were, in most instances, not highly significant.

Key Words: Accelerated curing of cements, autoclave curing of portland cement mortars, chemical composition, compressive strength of portland cement, compressive strength of steam-cured cements, mortars, steam curing of portland cement mortars, trace elements.

Contents

1. Introduction

The first reported commercial use of hydrothermal means to obtain a more rapid strength development of concrete was, according to one report [1],[1] by James Rowland in 1868. Since that time a great many investigations have been made, and reports published, relative to the strength and other properties of steam-cured concrete. Among the early contributors were Wig [2], Wig and Davis [3], Woodworth [4], Pearson and Brickett [5], and Thorvaldson [6]. The comprehensive investigation by Menzel [7] helped to establish better commercial application of high-pressure-steam-curing of concrete products.

Shideler and Chamberlin [8], Nurse [9], and Saul [10] were among the early contributors to a systematized knowledge of the effects of steam curing at atmospheric pressures.

Along with the practical aspects of the commercial use of steam curing, there has been a great amount of investigation of the chemical reaction

[1] Figures in brackets indicate the literature references at the end of this section.

involved and the hydrates formed under the different conditions. Studies by Kalousek [11] and by Aitken and Taylor [12] as well as many others have contributed greatly to our knowledge both of the reactions and reaction products formed. It would not be possible in this article to give reference to, nor evaluate all the contributions which have been made. The many contributions to both the practical and theoretical aspects of hydrothermal or steam-curing of cement and concrete products have been listed and discussed in the international symposia [6, 11, 12] as well as in books on the chemistry of cement by Bogue [13], Lea and Desch [14], and more recently by Taylor [15].

Accelerated curing of concrete in steam at atmospheric pressure, or at elevated temperatures and pressures is being used more extensively than ever before. The ACI report previously cited [1] summarized the knowledge in the field of high-pressure-steam curing and presented recommended procedures for commercial production. Another ACI report [16] presented similar information relative to low-pressure-steam curing. Both reports also present a large number of references.

Many of the variables involved have been studied but there does not appear to be much information available on the effect of cement composition on the properties of the steam-cured products, especially those cured in high-pressure steam. One of the objectives of the present study was to determine, by statistical means, some of the commonly determined variables associated with the relative compressive strengths of cements of different compositions when cured with both low- and high-pressure steam. Included also was a study of the possible effects of the trace elements in the cements.

A second objective in this series of tests relates to accelerated strength tests of portland cement mortars. Curing of the mortar and concrete at higher than normal temperatures has been proposed (according to Taylor [15] by King [17] and Ackroyd [18]) as a means for forecasting the long-term strength of normally cured concrete. A recent symposium [19] by correspondence conducted by RILEM (The International Union of Testing and Research Laboratories for Materials and Structures) has a series of eight articles by different authors relative to the use of "accelerated hardening of concrete with a view to rapid control test." Further information appeared desirable before such a method of testing can be adopted.

The recommended practices, both for low-pressure-steam curing [16], and high-pressure-steam curing [1] have suggested time-schedules for the various commercial operations which are difficult to carry out in a laboratory normal work day. These time schedules were followed as closely as possible in some series of tests. Additional specimens were made and cured using time schedules more easily accommodated in a laboratory in an attempt to develop a test method for evaluating different cements.

This article is limited in scope to the study of the variables associated with the differences in compressive strength obtained with different cements. It is recognized that other properties such as reduced shrinkage, or better sulfate resistance, or manufacturing problems such as the green strength, color, and time schedules are also of importance. The study and discussion of these are, however, outside the scope of the present investigation.

Although a number of variables were considered in the present study, they were limited in scope compared with those in commercial practice where changes may be made in mix design, cement content, aggregate and aggregate gradation, admixtures, water-cement ratio as well as curing schedule and temperature in order to achieve the desired quality of the manufactured product or products.

2. Materials

The portland cements used for the series of tests reported in this section have previously been described [20, 21, 22]. Some of the cements were not tested as will be indicated in the next subsection. The samples of cement had been stored in air-tight containers approximately 10 years before these present tests were made. Loss-on-ignition tests, made on the cements just prior to the present study, indicated a close agreement of values with those obtained in the original analyses. A further verification of the cement-sample identities was made by determining the Na_2O and K_2O by means of a flame photometer and comparing these values with those of the original analyses.

A mixture of Ottawa silica sand, Gopher silica sand, and silica flour was used in all mortars. The mix-proportion was 1 part of cement to 3.525 parts of silica by weight. A water-cement ratio of 0.5 by weight was used with all cements. The mix proportions of the cements, sand, silica flour and water are presented in table 8–1 for both the 9-cube and 6-cube batches. The particle-size distribution of sand plus silica flour is presented in table 8–2. Tests made by means of a Coulter

Table 8–1. *Mix proportions for 9-cube and 6-cube batches of mortar*

Materials	9-Cube batch	6-Cube batch
20–30 Ottawa sand ....g..	900	600
Graded Ottawa sand ....g..	870	580
Gopher #0 sand ....g..	240	160
Silica flour ....g..	105	70
Cement ....g..	600	400
Water ....ml..	300	200

counter indicated that 93 percent of the silica flour was finer than 5μ, and 43 percent was finer than 2μ.

Preliminary tests had indicated that mortars made with these proportions were plastic, and had percentage flow values on the standard 10-in flow table of about 100 with 25 drops. It was reported by some operators as being more sticky and somewhat more difficult to trowel the specimens than the standard 1:2.75 (cement to graded Ottawa sand) mortars.

TABLE 8–2. *Size distribution of sand plus silica flour mixture used for all mortars*

Sieve No.	Opening Microns	Percentage passing
20	841	100
30	595	57.0
40	420	40.4
50	297	25.4
70	210	18.9
100	149	12.2
140	105	5.7
200	74	5.4

3. Tests and Nomenclature

The cement-sand-water mortars were mixed, and the 2-in cubes compacted in accordance with the requirements of Federal Test Method Standard, SS–C–158 [23]. After troweling, monel identification-tags were imbedded in each cube. Compressive-strength tests were made after steam curing at both atmospheric pressure and 10 atm gage pressure, as well as after moist curing at 23 ± 1.7 °C for 28 days. The time, temperature, and curing procedures, as well as the condition of the 8 sets of specimens at the time of the compression test are summarized in table 8–3, and will also be described more fully in this subsection. The time at which specimens were removed from the molds and placed in steam or autoclave are approximate, as nearly 2½ hr were required to make the specimens of each test group.

3.1. Series I, Curing Started at 5 Hr

Three batches of test specimens were made with each of the available cements.[2] Additional duplicate batches were made with some cements as will be discussed later. For the first series of tests "9-cube" batches were made using 161 cements. Of these batches, 3 cubes from each cement were stored at 23 °C, 95–100 percent RH for 28 days and tested in compression when moist. These are identified as *WAGR* in both tables and illustrations. Six of the cubes from each cement were carefully removed from the molds at about 5 hr after making.[3]

Three of these specimens were placed on racks in a container and subjected to live steam at atmospheric pressure. The temperature, as indicated by a recording thermometer having the sensing bulb near the center of the container, was raised to 66 °C (150 °F) in 4 to 4½ hr. This temperature was then maintained for 12 to 13 hr. The cubes were then removed and placed on shelves in the laboratory with 5 sides exposed to the laboratory air at 23 °C, 50 ± 5 percent RH until tested in compression at 28 days. These specimens are identified as *STGR*, and the procedure used simulated to some extent the commercial practice of low-pressure-steam curing of specimens when still "green," i.e., not fully hardened.

The other 3 cubes from each batch of the first series, removed from the molds at about 5 hr, were placed on racks in an autoclave and the steam pressure raised to about 10 atm (actually 150 psi gage pressure) in 3 to 3½ hr. This included the time required to vent the air from the autoclave. The steam pressure was maintained for approximately 11 hr. About 3 hr were required for the autoclave to cool. The specimens were then placed in a forced-draft oven at approximately 105 °C for 24 hr after which they were placed in laboratory air at 23 °C and 50 percent RH for 2 or 3 days and tested in compression.[4] These specimens are identified at AUGR and the procedure used simulated to some extent the commercial practice of starting the autoclave curing of the products when they are still "green."

[2] Samples of some of the other cements had been used up in earlier tests or were not available in quantities sufficient for these series of tests.

[3] Preliminary tests had indicated that removal from the molds prior to 5 hr resulted in excessive breakage of the relatively weak specimens. Specimens from a few of the cements could not be removed without damage.

[4] It was necessary to abrade adhering sand grains from the STGR and AUGR specimens with aluminum oxide cloth on a steel plate prior to the compressive-strength tests.

TABLE 8–3. *Summary of curing conditions, and condition at time of test of the different specimens*

	Series 1				Series 2		Series 3	
Identification	STGR	AUGR	WAGR	STMA	AUMA	WAMA	WETS	DRYS
Time in molds at 23 °C, hr	5	5	24	24	24	24	24	24
Time to reach temp or pres, hr	4–4½	3–3½	----------	½	3½	----------	½	½
Temperature, °C	66	----------	23	71	----------	23	66	66
Pressure, atmospheres, atm	1	10	1	1	10	1	1	1
Time at temp or pres, hr	12–13	11	----------	7½	4	----------	24	24
Time to cool, do	1	3	----------	2–3	3	----------	1	1
Temp of drying, °C	23	105	----------	----------	105	23	----------	23
Time for drying, days	27	1	----------	----------	1	14	----------	12
Time at 100% RH, do	----------	----------	28	----------	----------	14	----------	----------
Age at test, do	28	4	28	2	4	28	2	14
Condition at test	dry	dry	wet	wet	dry	dry	wet	dry

The time in the autoclave was, however, longer than that used in commercial practice

Duplicate batches were made with some of the cements in this series. Four different days were required to make this series of cement mortars. Of 21 of the cements placed under test the first day, tests of seven of these cements were repeated on the second day, seven others on the third day, and seven others on the fourth day. Six laboratory personnel (plus other helpers) made specimens each day they were fabricated. The duplicates were made to evaluate differences in time temperature-curing cycles of the different days as well as possible other differences in the making of the test specimens.

3.2. Series II, Curing Started After 24 Hr

A second series of mortars was made using the same cements. Both nine- and six-cube batches were made because of the limited supply of some of the samples. The mortar proportions and preparation of the specimens were the same as in the first series. The specimens were removed from the molds at 22 to 24 hr. A third of the specimens from each cement were cured at 100 percent RH, 23 °C for two weeks, then placed in laboratory air for two weeks and tested in compression without rewetting. These specimens are identified as *WAMA* in the various tables and illustrations. A third of the specimens were placed in a container and live steam admitted. The recording thermometer (with sensing bulb near the center of the container) indicated that about ½ hr was required to raise the temperature to 71 °C (160 °F). This temperature was maintained for about 7½ hr, after which the steam was turned off. About 3 hr were required for the specimens (as indicated by the recording thermometer) to come to room temperature. The specimens were allowed to remain in the container overnight (an additional 12 to 14 hr), then placed in water and tested in compression at the age of about 50 hr. These specimens, which were steam cured when more mature but for a shorter period of time and slightly higher temperature than the STGR specimens in series I, are identified at STMA in tables and illustrations.

The other third of the specimens cured for 24 hr at normal temperatures were placed in an autoclave and the pressure raised to 10 atm (after the bleeding period) for about 3½ hr. The temperature and pressure were maintained for 3½ hr, after which the electric heaters were turned off. About 3 to 4 hr were required to cool the autoclave but the specimens remained in the vessel overnight (about 12 to 14 hr), after which they were dried at 105 °C for 24 hr, then removed to the 23 °C, 50 percent RH room where they were tested in compression after 2 more days. These specimens, autoclaved after they were mature, are identified as *AUMA* in both tables and illustrations.

The specimens were made on four different days. Duplicate tests were made on 21 of the cements in the same manner as in the first series.

3.3. Series III, Normally Cured Specimens

The third series of mortars was made on 65 of the portland cements having sufficient quantities of samples available. The batches were of the six-cube size, and all specimens were cured in steam at 150 °F (66 °C) for 24 hr after the first 24 hr in the moist room. Three of the specimens were then placed in water and cooled for a few hours and tested in compression when still wet. These specimens are identified as *WETS*. The other three specimens were allowed to dry in laboratory air at 23 °C, 50 percent RH for two weeks and tested without rewetting. These specimens are identified as *DRYS*. The mortars in the third series were made on three different days and duplicate mortars were made with 10 of the cements.

3.4. Other Notations and Comparisons

In addition to the use of WAGR, WAMA, STGR, STMA, AUGR, AUMA, WETS, and DRYS as indicated above to identify the different curing conditions, reference will also be made to ST01, ST03, ST07, ST28, ST1Y, ST5Y, for compressive strength after moist curing of the 1:2.75 mortars at 1, 3, 7, 28 days, 1 year, and 5 years respectively as in the previous section. The notations ST1M and ST1A, which are also used, refer to the 1 year moist-air cured and the 1 year laboratory-air cured specimens. (See page 2). Also used are ISET for initial time of set and FSET for final time of set of neat portland cement pastes of normal consistency. Other notations and abbreviations are consistent with those used in previous sections in this series of articles.[5]

4. Statistical Treatment

The statistical treatment of the compressive strength data obtained was the same as that used in previous sections of this series of articles. It was described in detail in Part 1 section 1 [20]. Briefly it consisted of determining which of the available independent variables appeared to have a significant relation to the dependent variable, and should be tried in the equations. Equations were calculated by the least-squares methods to determine which of the variables and combinations of variables appeared to have a significant effect in

[5] Included among these notations etc. are the use of C_3A, C_3S, C_2S, and C_4AF for the calculated potential compound composition of the cements, viz, tricalcium aluminate, tricalcium silicate, dicalcium silicate, and tetracalcium aluminoferrite. Also used are Loss for loss-on-ignition, Insol for insoluble residue, APF for air-permeability fineness and WAGN for fineness determined by means of the Wagner turbidimeter. AE+NAE is used to designate air-entraining plus nonair-entraining cements and NAE for the nonair-entraining cements.

improving the agreement of the actual values and those calculated by the equation. As in previous sections, the equations were computed for both the AE+NAE and the NAE cements, for commonly determined variables, and these together with trace elements all of which had coef./s.d. ratios [6] greater than one when used in the various combinations. Equations were also calculated for the "odds" and "evens" in the array of cements.

Some of the limitations of the statistical treatment and the interpretations of the results have been discussed in previous sections.

No attempt was made to calculate equations relating various independent variables to the compressive strengths of the specimens "WETS" and "DRYS" because of the limited number of cements involved.

5. Results of Tests

5.1. Compressive Strength at 28 Days of Moist-Air-Cured Specimens (WAGR)

The frequency distributions of the different types of cements with respect to the compressive-strength values of the moist-air-cured specimens, WAGR, are presented in table 8–4. There was considerable overlapping of the values of the cements of the different types as classified, and a spread of values within each group. The frequency distribution is also presented in figure 8–1 together with the frequency distributions obtained with these cements after other curing procedures.

Equations selected from those computed to determine the various independent variables associated with the 28-day compressive strength values for the moist-cured specimens of the AE+NAE cements are presented in table 8–5. Commonly determined variables associated with the compressive strength values are presented in eq 1. The air contents of these mortars were not

[6] The statistical terms used in this section are consistent with those used in previous sections. For example, S.D. refers to the estimated standard deviation calculated from the residuals of a fitted equation, or the estimated standard deviation about the average. Also as, in previous sections, s.d. refers to the estimated standard deviation of a coefficient of an independent variable used in a fitted equation. The coef./s.d. is the ratio of the estimated coefficient (of an independent variable used in an equation) to its estimated standard deviation. "F" = Fisher's ratio of variances. As indicated in previous sections, a coef./s.d. ratio greater than 1 was considered to be of sufficient significance to warrant further investigation. The one- and five-percent probability levels refer to $\alpha=0.01$ and $\alpha=0.05$ as used in table 8-28.

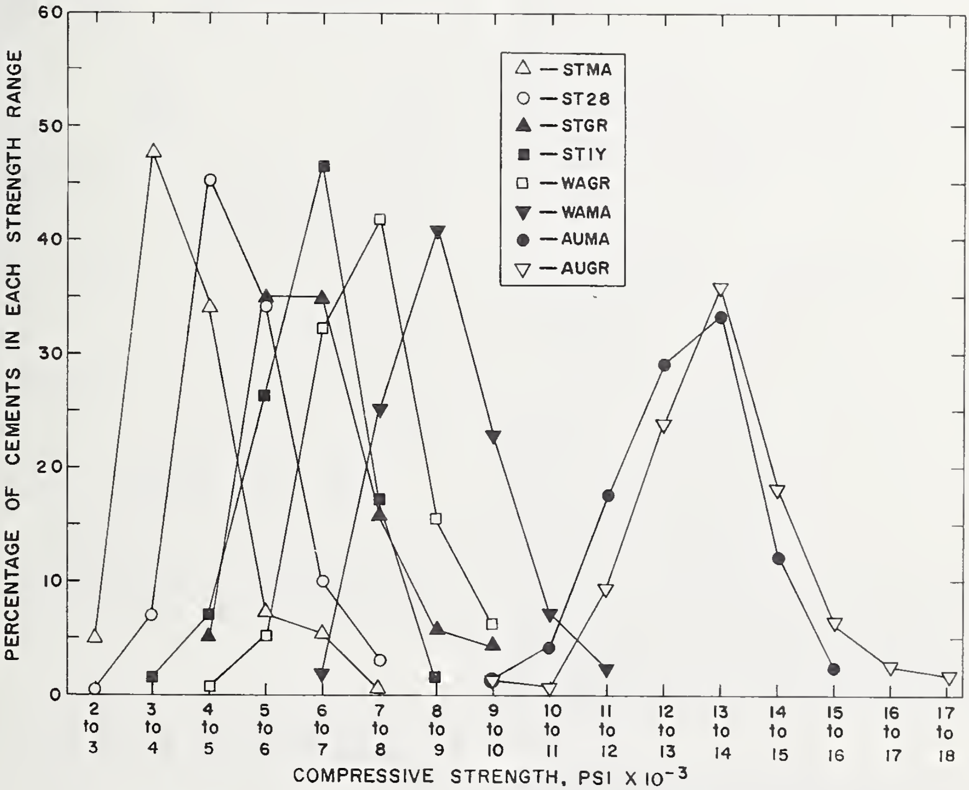

FIGURE 8–1. *Frequency distribution curves for the strength of cements when the mortar cubes were tested in compression after the different curing conditions.*

STMA, steam cured at 71 °C for 7.5 hr after 24 hr at 23 °C, and tested wet. ST28, water cured 28 days (1:2.75 mortar): STGR, steam cured at 66 °C for 12 hr after 5 hr at 23 °C, and tested after air drying. ST1Y, water cured 1 year (1:2.75 mortar). WAGR, moist air cured for 28 days and tested wet. WAMA, moist air cured for 14 days then air-dried for 14 days, and tested dry. AUMA, after 24 hr at 23 °C, the cubes were autoclaved at 10 atm for 4 hr, then oven dried, and tested dry. AUGR, after 5 hr at 23 °C, the cubes were autoclaved at 10 atm, then oven dried, and tested dry.)

TABLE 8–4. *Frequency distribution of cements with respect to compressive strengths of 28 day moist-air-stored mortar cubes (WAGR)*

Type cement	Compressive strength, psi×10⁻³											Total
	4.5 to 5.0	5.0 to 5.5	5.5 to 6.0	6.0 to 6.5	6.5 to 7.0	7.0 to 7.5	7.5 to 8.0	8.0 to 8.5	8.5 to 9.0	9.0 to 9.5	9.5 to 10.0	
	Number of cements											
I	---	---	4	9	16	13	8	11	---	1	---	62
IA	1	---	1	1	2	1	---	---	---	---	---	6
II	---	---	2	3	12	21	16	4	1	---	---	59
IIA	---	---	---	1	1	---	---	---	---	---	---	2
III	---	---	---	---	---	1	3	2	5	6	1	18
IIIA	---	---	---	---	---	---	1	---	---	---	---	1
IV, V	---	1	---	4	3	1	2	1	1	---	---	13
Total	1	1	7	18	34	37	30	18	7	7	1	161

determined and it was necessary to use the air-content values of the 1:4 (cement to sand) mortars as an independent variable. The addition of Insol, Cu, and Ba in eq 2 resulted in a highly significant reduction in the S.D. value (see table 8–28).[7] However, the equations calculated for the "odds" and "evens" in the array of cements, eqs 2A and 2B, indicated that Insol and Loss each had coef./s.d. ratios less than 1 in one of the smaller groups of cements.[8]

The use of the air-permeability-fineness values in place of Wagner fineness in eq 3 together with the other independent variables, and the additional variable, Rb, resulted in an S.D. of a higher value than was obtained in eq 2. In fact, the S.D. in eq 3 was almost the same as for eq 1 where only four independent variables were included.

Equations 4 through 6 present a similar series of relationships using the major oxides instead of the potential compounds. Al_2O_3 has a coef./s.d. ratios less than 1 in eq 4 and is probably not significant. The ratio was somewhat greater than 2 in eq 6 where WAGN was used as an independent variable. The coefficient for the insoluble residue is also of questionable significance. The reduction in variance resulting from the use of Cu and Ba in eq 5 was highly significant. (See table 8–28.)

Equations calculated for the NAE cements are presented in table 8–6. The coef./s.d. ratio for Insol was greater than 2 in eqs 2, 3, 5, and 6. The coefficients and the coef./s.d. ratios of the independent variables were not greatly different from those in the previous tab'e, 8–5, where the air-entraining cements were included.

The estimated contributions of the various independent variables calculated from the coefficients of eq 2 of table 8–6 are presented in table 8–7 [9] together with the calculated ranges of such contributions. The ranges of the independent

[7] A tabulation of the reduction in variance, "F" values, for all equations compared is presented in table 8-28. Presented also are the critical values for "F" which must be exceeded for significance at the α=one- and five-percent levels for the number of degrees of freedom (D.F.) involved in each comparison.

[8] As has been indicated in previous sections, chance occurrence of two or more extreme values in one of the two groups may cause such anomalous results. Another possible contributing factor was the assignment of zero to values for trace elements having less than the lowest reported value.

[9] As in previous sections, these values must be added to the constant. Attention is called to the fact that the constant and coefficients must be multiplied by 1000 to obtain values in terms of psi.

TABLE 8–5. *Coefficients for equations relating the 28 day compressive strength of moist-air-cured mortars of AE+NAE cements to various independent variables (WAGR)*

Equation	Note	psi×10⁻³	Const	C_3S	CaO	SiO_2	Al_2O_3	APF	WAGN	Air 1:4 mortar	Loss	Insol	Cu	Rb	Ba	S.D.
1	(1)	WAGR	= +2.709	+0.0432	---	---	---	---	+0.00187	−0.0862	−0.2443	---	---	---	---	0.5704
		s.d.	= (0.463)	(0.0079)	---	---	---	---	(0.00020)	(0.0131)	(0.0878)	---	---	---	---	---
2	(1)	WAGR	= +3.179	+0.0393	---	---	---	---	+0.00187	−0.0854	−0.2089	−0.5676	−20.46	---	−3.85	0.5316
		s.d.	= (0.4[illegible]3)	(0.0075)	---	---	---	---	(0.00019)	(0.0124)	(0.0847)	(0.3241)	(5.29)	---	(1.39)	---
2A	(2)	WAGR (odd)	= +3.637	+0.0369	---	---	---	---	+0.00184	−0.1089	−0.3262	*−0.4000	−26.26	---	−2.65	0.5442
		s.d.	= (0.695)	(0.0099)	---	---	---	---	(0.00029)	(0.0190)	(0.1123)	(0.4638)	(7.58)	---	(1.98)	---
2B	(3)	WAGR (even)	= +2.939	+0.0375	---	---	---	---	+0.00193	−0.0708	*−0.0218	−0.8260	−16.77	---	−5.52	0.5160
		s.d.	= (0.582)	(0.0119)	---	---	---	---	(0.00026)	(0.0167)	(0.1367)	(0.4902)	(7.49)	---	(2.01)	---
3	(1)	WAGR	= +4.489	+0.0362	---	---	---	+0.00082	---	−0.0975	−0.5009	−0.7186	−20.89	−68.06	−3.73	0.5648
		s.d.	= (0.442)	(0.0082)	---	---	---	(0.00010)	---	(0.0132)	(0.0958)	(0.3449)	(5.63)	(25.06)	(1.49)	---
4	(1)	WAGR	= −3.931	---	+0.2177	−0.2221	*−0.0915	---	+0.00195	−0.0816	−0.1797	−0.3689	---	---	---	0.5634
		s.d.	= (3.208)	---	(0.0425)	(0.0810)	(0.1030)	---	(0.00021)	(0.0133)	(0.0979)	(0.3536)	---	---	---	---
5	(1)	WAGR	= −5.085	---	+0.2302	−0.1851	−0.1098	---	+0.00189	−0.0807	−0.1439	−0.5988	−21.80	---	−4.19	0.5182
		s.d.	= (2.959)	---	(0.0395)	(0.0751)	(0.0955)	---	(0.00020)	(0.0123)	(0.0903)	(0.3289)	(5.18)	---	(1.40)	---
5A	(2)	WAGR (odd)	= −10.61	---	+0.2625	*−0.0414	*−0.0167	---	+0.00191	−0.1058	−0.1851	*−0.2497	−30.31	---	−3.27	0.5012
		s.d.	= (3.81)	---	(0.0487)	(0.0973)	(0.1240)	---	(0.00028)	(0.0175)	(0.1111)	(0.4448)	(7.22)	---	(1.95)	---
5B	(3)	WAGR (even)	= −0.103	---	+0.1807	−0.2597	−0.1783	---	+0.00193	−0.0694	*−0.0442	−0.9015	−18.05	---	−5.65	0.5199
		s.d.	= (4.697)	---	(0.0668)	(0.1213)	(0.1525)	---	(0.00030)	(0.0175)	(0.1540)	(0.5289)	(7.54)	---	(2.07)	---
6	(1)	WAGR	= −1.886	---	+0.2168	−0.2080	−0.2164	+0.00079	---	−0.0924	−0.4427	−0.6003	−22.60	−57.22	−4.46	0.5556
		s.d.	= (3.201)	---	(0.0434)	(0.0817)	(0.0991)	(0.00011)	---	(0.0132)	(0.1006)	(0.3535)	(5.56)	(25.92)	(1.50)	---

[1] 147 cements; Avg=7.323×10³ psi; S.D.=0.907×10³ psi. [2] 74 cements. [3] 73 cements. *Coef./s.d. ratio less than 1.

TABLE 8-6. *Coefficients for equations relating the 28 day compressive strength of moist-air-cured mortars of NAE cements to various indpendent variables (WAGR)*

Equation	Note	psi×10^{-3}	Const	C_3S	CaO	SiO_2	Al_2O_3	APF	WAGN	Air 1:4 mortar	Loss	Insol	Cu	Rb	Ba	S.D.
1	(1)	WAGR s.d.	=+3.139 = (0.487)	+0.0458 (0.0079)					+0.00181 (0.00020)	−0.1536 (0.0265)	−0.2410 (0.0879)					0.5592
2	(1)	WAGR s.d.	=+3.609 = (0.474)	+0.0413 (0.0075)					+0.00180 (0.00019)	−0.1420 (0.0252)	−0.2000 (0.0852)	−0.7850 (0.3465)	−17.81 (5.31)		−3.71 (1.38).	0.5240
2A	(2)	WAGR (odd) s.d.	=+4.361 = (0.720)	+0.0336 (0.0102)					+0.00190 (0.00027)	−0.2130 (0.0389)	−0.3010 (0.1229)	*−0.4285 (0.4702)	−22.84 (7.65)		−2.59 (1.99)	0.5410
2B	(3)	WAGR (even) s.d.	=+3.408 = (0.661)	+0.0440 (0.0118)					+0.00166 (0.00026)	−0.0920 (0.0324)	−0.1377 (0.1221)	−1.0660 (0.5510)	−15.91 (7.32)		−5.13 (1.92)	0.4926
3	(1)	WAGR s.d.	=+4.933 = (0.452)	+0.3719 (0.0081)				+0.00082 (0.00010)		−0.1676 (0.0266)	−0.4759 (0.0947)	−1.0600 (0.3623)	−17.86 (5.59)	−52.74 (24.91)	−3.46 (1.46)	0.5486
4	(1)	WAGR s.d.	=−2.004 = (3.210)		+0.2195 (0.0416)	−0.2714 (0.0815)	−0.1415 (0.1027)		+0.00187 (0.00021)	−0.1539 (0.0266)	−0.1844 (0.0969)	−0.6169 (0.3732)				0.5488
5	(1)	WAGR s.d.	=−3.646 = (3.011)		+0.2315 (0.0392)	−0.2225 (0.0769)	−0.1439 (0.0963)		+0.00182 (0.00020)	−0.1337 (0.0252)	−0.1548 (0.0905)	−0.7993 (0.3503)	−19.08 (5.23)		−4.04 (1.39)	0.5112
5A	(2)	WAGR (odd) s.d.	=−6.413 = (4.279)		+0.2269 (0.0524)	−0.1101 (0.1036)	*−0.0080 (0.1226)		+0.00199 (0.00028)	−0.1950 (0.0385)	−0.2060 (0.1251)	*−0.4513 (0.4612)	−23.96 (7.50)		−2.33 (2.02)	0.5114
5B	(2)	WAGR (even) s.d.	=+0.911 = (4.386)		+0.2167 (0.0629)	−0.3394 (0.1301)	−0.3081 (0.1690)		+0.00157 (0.00030)	−0.0879 (0.0329)	−0.1703 (0.1418)	−0.9624 (0.6030)	−17.16 (7.37)		−5.42 (1.98)	0.4963
6	(1)	WAGR s.d.	=−0.514 = (3.185)		+0.2135 (0.0426)	−0.2327 (0.0823)	−0.2393 (0.0986)	+0.00077 (0.00010)		−0.1596 (0.0266)	−0.4331 (0.0992)	−0.9229 (0.3717)	−19.54 (5.54)	−44.28 (25.68)	−4.16 (1.47)	0.5405

[1] 139 cements; Avg=7.377×10^3 psi; S.D.=0.879×10^3 psi. [2] 70 cements. [3] 69 cements. *Coef./s.d. ratio less than 1.

variables of these cements were assumed to be the same as for all 199 cements previously described in sections 2 and 3 of this series. The increase in C_3S and fineness was associated with an increase in compressive strength; and an increase in air content of the 1:4 (cement to sand) mortar, Ba, Cu, and possibly also Loss and Insol, with lower compressive strength values.

Somewhat different values may be obtained by use of other equations in this table for NAE cements, and also by use of equations presented in table 8-5 for the AE+NAE cements. Other tables of the "estimated contributions" will, for the sake of consistency, also be presented for the NAE cements only. In all instances, an equation having potential compounds and all other independent variables having coef./s.d. ratios greater than one will be used.

TABLE 8-7. *Calculated contributions of independent variables to compressive strength of mortar cubes (WAGR), moist-air-cured for 28 days at 23 °C, and the calculated ranges of such contributions*

Independent variable	Range of variable (percent)	Coefficients from eq (2) table 8-6	Calculated contribution to WAGR (×10^{-3})	Calculated range of contribution to WAGR (×10^{-3})
			Const=+3.609	
C_3S	20 to 65	+0.0413	+0.826 to +2.685	1.859
WAGN	*1200 to 3000	+0.00180	+2.160 to +5.400	3.240
Air, 1:4 mortar	1 to 21	+0.1420	+0.142 to −2.982	2.840
Loss	0.3 to 3.3	−0.2000	−0.060 to −0.660	0.600
Insol	0 to 1.0	−0.7850	0 to −0.785	0.785
Cu	0 to 0.05	−17.81	0 to −0.890	0.890
Ba	0 to 0.2	−3.71	0 to −0.742	0.742

*cm^2/g

5.2. Compressive Strength of Specimens Moist-Cured for 2 Weeks Then Air-Dried for 2 Weeks, (WAMA)

The frequency distribution of the cements with respect to compressive strength of specimens. WAMA, cured for the first 14 days at 23 °C and 100 percent RH and then air-dried at 23 °C and 50 percent RH are presented in table 8-8. There was a fairly broad spread of results within each of the types and considerable overlapping of the values for the different types. (See also fig. 8-1.)

Equations relating the compressive-strength values of the air-dried specimens to various independent variables are presented in table 8-9 for the AE+NAE cements and in table 8-10 for the NAE cements alone. The use of commonly determined variables in eq 1 of table 8-9 resulted in a significant reduction of the S.D. value. With additional variables, Insol, and SO_3, and the trace of elements, Ba, Cu, and SrO in eq 2, a further significant reduction in the S.D. value was attained (see table 8-28) although the coefficients for Insol, SO_3, Cu, and SrO were each of questionable significance. The use of the air-permeability-fineness values in eq 3 together

Table 8–8. *Frequency distribution of cements with respect to compressive strength of mortars, moist-cured 14 days, then air-dried 14-days (WAMA)*

Type cement	Compressive strength, psi×10⁻³												Total
	6.0 to 6.5	6.5 to 7.0	7.0 to 7.5	7.5 to 8.0	8.0 to 8.5	8.5 to 9.0	9.0 to 9.5	9.5 to 10.0	10.0 to 10.5	10.5 to 11.0	11.0 to 11.5	11.5 to 12.0	
	Number of cements												
I	-------	1	6	9	17	10	6	11	4	-------	-------	-------	64
IA	1	-------	2	3	-------	1	-------	-------	-------	-------	-------	-------	7
II	-------	-------	5	8	16	19	8	5	1	-------	-------	-------	62
IIA	-------	-------	-------	1	-------	1	-------	-------	-------	-------	-------	-------	2
III	-------	-------	-------	-------	-------	-------	3	3	3	4	2	2	17
IIIA	-------	-------	-------	-------	-------	-------	-------	1	-------	-------	-------	-------	1
IV, V	1	-------	4	4	1	3	-------	1	-------	-------	-------	-------	14
Total	2	1	17	25	34	34	17	21	8	4	2	2	167

Table 8–9. *Coefficients for equations relating the 28 day compressive strength of mortars (moist-cured*

Equation No.	Note	psi×10⁻³	Const	C_3A	C_3S	C_4AF	CaO	SiO_2	SO_3
1	(1)	WAMA s.d.	= +1.663 = (0.786)	+0.0961 (0.0232)	+0.0564 (0.0102)	+0.0589 (0.0301)	-------	-------	-------
2	(1)	WAMA s.d.	= +2.133 = (0.777)	+0.0899 (0.0288)	+0.0548 (0.0100)	+0.0629 (0.0305)	-------	-------	+0.2461 (0.1957)
2A	(2)	WAMA (odd) s.d.	= +4.488 = (1.026)	+0.1068 (0.0419)	*+0.0138 (0.0140)	+0.0492 (0.0383)	-------	-------	*+0.2273 (0.2770)
2B	(2)	WAMA (even) s.d.	= +1.138 = (1.103)	+0.0682 (0.0376)	+0.0841 (0.0139)	*+0.0278 (0.0448)	-------	-------	+0.2720 (0.2614)
3	(1)	WAMA s.d.	= +3.620 = (0.747)	+0.0405 (0.0281)	+0.0579 (0.0106)	+0.0470 (0.0319)	-------	-------	*+0.1830 (0.2198)
4	(1)	WAMA s.d.	= −2.713 = (3.217)	-------	-------	-------	+0.2496 (0.0500)	−0.3393 (0.0487)	-------
5	(1)	WAMA s.d.	= −3.444 = (3.148)	-------	-------	-------	+0.2633 (0.0480)	−0.3232 (0.0517)	-------
5A	(2)	WAMA (odd) s.d.	=+10.150 = (4.146)	-------	-------	-------	*+0.0366 (0.0668)	−0.2545 (0.0701)	-------
5B	(2)	WAMA (even) s.d.	=−16.825 = (3.981)	-------	-------	-------	+0.4584 (0.0593)	−0.3160 (0.0642)	-------
6	(1)	WAMA s.d.	= −4.007 = (3.343)	-------	-------	-------	+0.2552 (0.0515)	−0.2342 (0.0559)	-------

[1] 146 cements; Avg=8.653×10³ psi; S.D.=1.037×10³ psi. [2] 73 cements. *Coef./s.d. ratio less than 1.

Table 8–10. *Coefficients for equations relating the 28 day compressive strength of mortars (moist-cured*

Equation No.	Note	psi×10⁻³	Const	C_3A	C_3S	C_4AF	CaO	SiO_2	SO_3
1	(1)	WAMA s.d.	=+1.948 = (0.852)	+0.0919 (0.0240)	+0.0594 (0.0105)	+0.0570 (0.0312)	-------	-------	-------
2	(1)	WAMA s.d.	=+2.691 = (0.838)	+0.0823 (0.0293)	+0.0569 (0.0102)	+0.0509 (0.0314)	-------	-------	+0.4116 (0.2095)
2A	(2)	WAMA (odd) s.d.	=+3.393 = (1.187)	+0.0497 (0.0460)	+0.0597 (0.0150)	+0.0789 (0.0473)	-------	-------	+0.5015 (0.3243
2B	(3)	WAMA (even) s.d.	=+1.935 = (1.087)	+0.1298 (0.0358)	+0.0414 (0.0132)	*+0.0204 (0.0405)	-------	-------	*−0.0771) (0.2680)
3	(1)	WAMA s.d.	=+4.202 = (0.781)	+0.0524 (0.0268)	+0.0560 (0.0107)	+0.0431 (0.0316)	-------	-------	-------
4	(1)	WAMA s.d.	=−2.426 = (3.273)	-------	-------	-------	+0.2549 (0.0505)	−0.3474 (0.0499)	-------
5	(1)	WAMA s.d.	=−3.084 = (3.233)	-------	-------	-------	+0.2671 (0.0486)	−0.3325 (0.0535)	-------
5A	(2)	WAMA (odd) s.d.	=−0.309 = (4.774)	-------	-------	-------	+0.2284 (0.0723)	−0.3309 (0.0822)	-------
5B	(3)	WAMA (even) s.d.	=−5.577 = (4.863)	-------	-------	-------	+0.2841 (0.0710)	−0.3215 (0.0675)	-------
6	(1)	WAMA s.d.	=−3.011 = (3.375)	-------	-------	-------	+0.2511 (0.0513)	−0.2445 (0.0567)	-------

[1] 137 cements; Avg=8.699×10³ psi; S.D.=1.028×10³ psi. [2] 69 cements. [3] 68 cements. *Coef./s.d. ratio less than 1.

with the other variables of eq 2 resulted in a higher value for the S.D., and the SO_3 and SrO had coef./s.d. ratios less than 1. In this case the S.D. for eq 3 was even higher than that for eq 1.

A similar series of relationships calculated using the major oxides instead of the potential compounds are presented in eqs 4, 5, and 6. The SO_3 did not have a coef./s.d. ratio greater than 1 and was not included.

In the equations for the "odds" and "evens" in the array of cements, there were instances where the coef./s.d. ratios for C_3S, C_4AF, CaO, Na_2O, SO_3, Loss, Insol, Cu, and SrO were less than 1 in the smaller groups. The Loss-on-ignition was more highly significant in eqs 3 and 6 where APF was used than in eqs 2 and 5 where the Wagner fineness was used.

Comments relative to the relationship indicated in table 8–9 for AE+NAE cements, are in general, also applicable to the relationships in table 8–10 for the NAE cements alone.

The estimated contributions of the various independent variables to the compressive strength of the air-dried nonsteamed specimens were calculated from the coefficients of eq 2 of table 8–10 and are presented in table 8–11 together with the calculated ranges of these contributions. Increased values of C_3A, C_3S, fineness, and possibly also

2 weeks then air-dried 2 weeks) of AE+NAE cements to various independent variables (WAMA)

Na_2O	WAGN	APF	Loss	Insol	Air 1:4 mortar	Ba	Cu	SrO	S.D.
−0.7758 (0.3372)	+0.00208 (0.00025)		−0.2718 (0.1090)		−0.0686 (0.0159)				0.6719
−0.6750 (0.3508)	+0.00190 (0.00027)		−0.2962 (0.1154)	−0.6207 (0.4212)	−0.0699 (0.0161)	−4.734 (1.789)	−12.88 (6.77)	−1.101 (0.705)	0.6441
−1.2135 (0.4597)	+0.00186 (0.00033)		−0.1961 (0.1568)	−2.4421 (0.6517)	−0.0402 (0.0200)	−9.891 (4.238)	*−4.93 (9.81)	−1.747 (0.920)	0.5937
*−0.3653 (0.4957)	+0.00184 (0.00045)		−0.2152 (0.1578)	*+0.2727 (0.5253)	−0.0960 (0.0228)	−4.471 (1.974)	−18.42 (8.69)	*−0.847 (0.987)	0.5987
−0.6378 (0.3697)		+0.000827 (0.000151)	−0.5397 (0.1222)	−0.5545 (0.4436)	−0.0768 (0.0168)	−5.115 (1.889)	−14.61 (7.17)	*−0.736 (0.742)	0.6786
−0.8535 (0.3362)	+0.00210 (0.00023)		−0.2227 (0.1119)	−0.5788 (0.4124)	−0.0625 (0.0158)				0.6666
−0.7008 (0.3436)	+0.00201 (0.00022)		−0.2141 (0.1107)	−0.6513 (0.4032)	−0.0626 (0.0151)	−4.773 (1.736)	−14.93 (6.41)	−1.059 (0.671)	0.6362
−1.1056 (0.4471)	+0.00186 (0.00028)		−0.2393 (0.1415)	−2.2409 (0.5898)	−0.0426 (0.0195)	−9.582 (3.973)	*−6.92 (8.93)	−1.567 (0.877)	0.5851
*−0.3971 (0.4411)	+0.00225 (0.00030)		*−0.0044 (0.1478)	*+0.1726 (0.4771)	−0.0786 (0.0188)	−4.805 (1.747)	−24.19 (7.82)	*−0.657 (0.850)	0.5515
−0.6883 (0.3658)		+0.000934 (0.000123)	−0.4597 (0.1247)	−0.7251 (0.4285)	−0.0709 (0.0161)	−4.917 (1.846)	−16.00 (6.82)	−0.935 (0.714)	0.6762

2 weeks then air-dried 2 weeks) of NAE cements to various independent variables (WAMA)

Na_2O	WAGN	APF	Loss	Insol	Air 1:4 mortar	Ba	Cu	SrO	S.D.
−0.5250 (0.3645)	+0.00205 (0.00026)		−0.2639 (0.1136)		−0.1230 (0.0351)				0.6794
−0.3843 (0.3801)	+0.00174 (0.00028)		−0.3200 (0.1176)	−0.8495 (0.4576)	−0.1407 (0.0371)	−4.772 (1.798)	−9.37 (6.99)	−1.325 (0.735)	0.6434
−0.5636 (0.5040)	+0.00128 (0.00037)		−0.3410 (0.1531)	−0.9731 (0.6344)	−0.1354 (0.0557)	−14.971 (6.676)	−26.27 (11.03)	*−0.586 (1.121)	0.6675
−0.6996 (0.5752)	+0.00291 (0.00042)		*−0.0777 (0.1887)	−1.0354 (0.6393)	−0.1181 (0.4049)	−4.956 (1.809)	*+6.74 (8.89)	−2.152 (0.875)	0.5445
*−0.3871 (0.3883)		+0.000905 (0.000129)	−0.5038 (0.1213)	−0.9354 (0.4774)	−0.1518 (0.0355)	−4.426 (1.857)	−12.52 (7.14)	−0.896 (0.758)	0.6711
−0.6399 (0.3575)	+0.00207 (0.00024)		−0.2080 (0.1156)	−0.8222 (0.4524)	−0.1217 (0.0342)				0.6697
−0.5369 (0.3673)	+0.00197 (0.00023)		−0.2169 (0.1143)	−0.8835 (0.4403)	−0.1065 (0.0333)	−4.679 (1.776)	−13.45 (6.57)	−1.190 (0.709)	0.6404
−0.6741 (0.4986)	+0.00156 (0.00032)		−0.2623 (0.1507)	−1.1903 (0.6120)	−0.1094 (0.0524)	−11.227 (6.282)	−26.77 (10.23)	*−0.829 (1.095)	0.6729
*−0.4536 (0.5529)	+0.00255 (0.00031)		*−0.0417 (0.1848)	*−0.5815 (0.6211)	−0.1109 (0.0402)	−5.818 (1.914)	*+0.40 (8.38)	−1.630 (0.872)	0.5498
−0.4332 (0.3854)		+0.000936 (0.000123)	−0.4528 (0.1253)	−1.0768 (0.4585)	−0.1435 (0.0350)	−4.606 (1.857)	−13.86 (6.86)	−1.143 (0.740)	0.6683

C_4AF and SO_3 appeared associated with higher compressive-strength values. Increased values of Loss, (air, 1:4 mortar), Ba, and possibly Na_2O, Insol, Cu, and SrO appeared associated with lower compressive-strength values.

TABLE 8–11. *Calculated contributions of independent variables to compressive strength of mortars (WAMA), moist-air-cured for 14 days then air-dried 14 days at 23° C, and the calculated ranges of such contributions*

Independent variable	Range of variable (percent)	Coefficient from eq (2) table 8–10	Calculated contribution to WAMA (×10⁻³)	Calculated range of contribution to WAMA (×10⁻³)
			Const. = +2.691	
C_3A	1 to 15	+0.0823	+0.082 to +1.234	1.152
C_3S	20 to 65	+0.0569	+1.138 to +3.698	2.560
C_4AF**	1 to 16	+0.0509	+0.051 to +0.814	0.763
SO_3**	1.2 to 3.0	+0.4166	+0.500 to +1.250	0.750
Na_2O**	0 to 0.7	−0.3843	0 to −0.269	0.269
WAGN	*1200 to 3000	+0.00174	+2.088 to +5.220	3.132
Loss	0.3 to 3.3	−0.3200	−0.096 to −1.056	0.960
Insol**	0 to 1.0	−0.8495	0 to −0.850	0.850
Air, 1:4 mortar	1 to 21	−0.1407	−0.141 to −2.955	2.814
Ba	0 to 0.2	−4.772	0 to −0.954	0.954
Cu**	0 to 0.05	−9.37	0 to −0.468	0.468
SrO**	0 to 0.4	−1.325	0 to −0.530	0.530

*cm²/g.
**Coefficient of doubtful significance as coef./s.d. was less than 2.

5.3. Compressive Strength of Mortars Cured With Low-Pressure Steam After 5 Hr Moist Curing and Later Dried in Laboratory Air (STGR)

The frequency distributions of the cements with respect to compressive strengths of the mortars, STGR, steam cured at 66° C for 12 hr after about 5 hr in the fog room are presented in table 8–12. The specimens were air dried for 27 days after the steam-curing, prior to the compressive-strength tests. There was a fairly broad distribution of values within each of the types as classified, and an overlapping of the values for the different types of cement. (See also fig. 8–1.)

Selected equations relating various independent variables to the compressive-strength values are presented in table 8–13 for the AE+NAE cements and in table 8–14 for the NAE cements. The re-

TABLE 8–12. *Frequency distribution of cements with respect to compressive strength of mortars, steam-cured after 5 hrs, then air-dried (STGR)*

Type cement	Compressive strength, psi×10⁻³												Total
	4.0 to 4.5	4.5 to 5.0	5.0 to 5.5	5.5 to 6.0	6.0 to 6.5	6.5 to 7.0	7.0 to 7.5	7.5 to 8.0	8.0 to 8.5	8.5 to 9.0	9.0 to 9.5	9.5 to 10.0	
	Number of cements												
I	1	1	4	17	12	12	7	6	2	---	---	---	62
IA	1	---	1	4	---	---	---	---	---	---	---	---	6
II	---	1	5	17	17	10	6	2	1	---	---	---	59
IIA	---	---	1	---	---	1	---	---	---	---	---	---	2
III	---	---	---	1	---	1	2	1	2	4	3	4	18
IIIA	---	---	---	---	---	---	---	1	---	---	---	---	1
IV, V	1	3	4	2	3	---	---	---	---	---	---	---	13
Total	3	5	15	41	32	24	15	10	5	4	3	4	161

TABLE 8–13. *Coefficients for equations relating the compressive strength of mortars of AE+NAE cements cured with low-pressure steam after 5 hrs, then air-dried, to various independent variables (STGR)*

Equation	Note	psi×10⁻³	Const	C_3A	C_3S	CaO	SiO_2	SO_3	K_2O	WAGN	APF	Loss	Insol	Air 1:4 Mortar	Ba	Cu	P	S.D.
1	(1)	STGR	= −2.555	+0.0616	+0.0795	-------	-------	+0.3473	+0.6955	+0.00246	-------	−0.2723	-------	−0.0757	-------	-------	-------	0.5840
		s.d.	= (0.510)	(0.0190)	(0.0085)	-------	-------	(0.1767)	(0.2589)	(0.00025)	-------	(0.1017)	-------	(0.0138)	-------	-------	-------	-------
2	(1)	STGR	= −2.093	+0.0486	+0.0839	-------	-------	+0.4408	+0.5746	+0.00224	-------	−0.3027	-------	−0.0768	−5.54	−8.57	−1.506	0.5333
		s.d.	= (0.496)	(0.0187)	(0.0079)	-------	-------	(0.1641)	(0.2424)	(0.00023)	-------	(0.0931)	-------	(0.0126)	(1.46)	(5.55)	(0.421)	-------
2A	(2)	STGR(odd)	= −2.329	+0.0527	+0.0770	-------	-------	+0.5119	+1.0187	+0.00237	-------	−0.3661	-------	−0.0824	−6.14	+13.62	−3.071	0.4943
		s.d.	= (0.646)	(0.0275)	(0.0106)	-------	-------	(0.2340)	(0.3389)	(0.00028)	-------	(0.1211)	-------	(0.0163)	(3.54)	(7.81)	(0.626)	-------
2B	(2)	STGR(even)	= −2.018	+0.0446	+0.0907	-------	-------	+0.4386	+0.4162	+0.00208	-------	−0.2348	-------	−0.0766	−5.37	−23.71	−0.648	0.5255
		s.d.	= (0.770)	(0.0261)	(0.0115)	-------	-------	(0.2319)	(0.3453)	(0.00040)	-------	(0.1397)	-------	(0.0183)	(1.69)	(7.56)	(0.546)	-------
3	(1)	STGR	= −0.531	*+0.0096	+0.0854	-------	-------	+0.3591	+0.3569	-------	+0.001016	−0.6112	-------	−0.0799	−5.74	−12.70	−1.372	0.5738
		s.d.	= (0.463)	(0.0190)	(0.0085)	-------	-------	(0.1879)	(0.2562)	-------	(0.000131)	(0.1005)	-------	(0.0135)	(1.58)	(5.96)	(0.453)	-------
4	(1)	STGR	= −10.37	-------	-------	+0.3270	−0.4126	-------	+0.8048	+0.00288	-------	−0.1146	−0.6079	−0.0596	-------	-------	-------	0.6075
		s.d.	= (3.30)	-------	-------	(0.0474)	(0.0490)	-------	(0.2921)	(0.00021)	-------	(0.1036)	(0.3732)	(0.0142)	-------	-------	-------	-------
5	(1)	STGR	= −12.18	-------	-------	+0.3581	−0.3974	-------	+0.7491	+0.00277	-------	−0.1004	−0.7415	−0.0583	−4.68	−15.02	−1.572	0.5550
		s.d.	= (3.07)	-------	-------	(0.0443)	(0.0461)	-------	(0.2743)	(0.00020)	-------	(0.0959)	(0.3440)	(0.0130)	(1.50)	(5.69)	(0.435)	-------
5A	(2)	STGR(odd)	= −7.16	-------	-------	+0.2925	−0.4390	-------	+1.0850	+0.00279	-------	−0.1691	−1.0767	−0.0664	−4.23	*−1.76	−3.032	0.4889
		s.d.	= (4.02)	-------	-------	(0.0614)	(0.0565)	-------	(0.3649)	(0.00023)	-------	(0.1139)	(0.4878)	(0.0161)	(3.30)	(7.86)	(0.612)	-------
5B	(2)	STGR(even)	= −19.58	-------	-------	+0.4327	−0.2961	-------	+0.8551	+0.00288	-------	*−0.0184	*−0.2649	−0.0576	−4.76	−29.83	−0.716	0.5686
		s.d.	= (4.67)	-------	-------	(0.0634)	(0.0759)	-------	(0.4205)	(0.00032)	-------	(0.1590)	(0.4731)	(0.0192)	(1.77)	(8.02)	(0.589)	-------
6	(1)	STGR	= −10.99	-------	-------	+0.3266	−0.2991	-------	+0.4469	-------	+0.001295	−0.4738	−0.8082	−0.0673	−4.68	−17.92	−1.498	0.1696
		s.d.	= (3.43)	-------	-------	(0.0500)	(0.0529)	-------	(0.3023)	-------	(0.000113)	(0.1132)	(0.3842)	(0.0145)	(1.68)	(6.35)	(0.486)	-------

(1) 146 cements; Avg = 6.491×10³ psi; S.D. = 1.141×10³ psi. (2) 73 cements. *Coef./s.d. ratio less than 1.

Table 8–14. *Coefficients for equations relating the compressive strength of mortars of NAE cements, cured with low pressure steam after 5 hrs, then air-dried, to various independent variables (STGR)*

Equation	Note	psi×10⁻³	Const	C_3A	C_3S	CaO	SiO_2	SO_3	K_2O	WAGN	APF	Loss	Insol	Air 1:4 Mortar	Ba	Cu	P	S.D.
1	(1)	STGR =	−2.428	+0.0580	+0.0817	-----	-----	+0.4290	+0.7229	+0.00242	-----	−0.2754	-----	−0.1174	-----	-----	-----	0.5923
		s.d. =	(0.553)	(0.0197)	(0.0088)	-----	-----	(0.1853)	(0.2682)	(0.00026)	-----	(0.1052)	-----	(0.0297)	-----	-----	-----	-----
2	(1)	STGR =	−2.094	+0.0475	+0.0853	-----	-----	+0.4949	+0.5892	+0.00223	-----	−0.3111	-----	−0.0967	−5.64	−6.98	−1.46	0.5436
		s.d. =	(0.531)	(0.0194)	(0.0082)	-----	-----	(0.1734)	(0.2539)	(0.00024)	-----	(0.0969)	-----	(0.0284)	(1.50)	(5.87)	(0.43)	-----
2A	(2)	STGR(odd) =	−2.027	+0.0573	+0.0896	-----	-----	+0.4651	+0.9787	+0.00214	-----	−0.3618	-----	−0.1293	−6.66	−17.76	−2.80	0.5036
		s.d. =	(0.694)	(0.0278)	(0.0107)	-----	-----	(0.2482)	(0.3324)	(0.00028)	-----	(0.1125)	-----	(0.0380)	(4.87)	(7.94)	(0.62)	-----
2B	(3)	STGR(even) =	−2.219	+0.0581	+0.0779	-----	-----	*+0.1075	*+0.1505	+0.00254	-----	*+0.0460	-----	*−0.0342	−7.65	*+1.23	−0.76	0.4998
		s.d. =	(0.754)	(0.0256)	(0.0112)	-----	-----	(0.2387)	(0.3788)	(0.00038)	-----	(0.1662)	-----	(0.0396)	(1.59)	(8.13)	(0.54)	-----
3	(1)	STGR =	−0.381	*+0.0072	+0.0886	-----	-----	+0.4249	+0.4235	-----	+0.000997	+0.6083	-----	−0.1232	−5.72	−9.83	−1.29	0.5826
		s.d. =	(0.485)	(0.0195)	(0.0088)	-----	-----	(0.1968)	(0.2691)	-----	(0.000134)	(0.1037)	-----	(0.0302)	(1.61)	(6.29)	(0.47)	-----
4	(1)	STGR =	−10.29	-----	-----	+0.3317	−0.4231	-----	+0.8438	+0.00290	-----	−0.1125	−0.6620	−0.0866	-----	-----	-----	0.6171
		s.d. =	(3.38)	-----	-----	(0.0484)	(0.0509)	-----	(0.3049)	(0.00022)	-----	(0.1079)	(0.4168)	(0.0303)	-----	-----	-----	-----
5	(1)	STGR =	−12.35	-----	-----	+0.3631	−0.4053	-----	+0.7424	+0.00278	-----	−0.1189	−0.7423	−0.0542	−4.83	−14.78	−1.60	0.5643
		s.d. =	(3.15)	-----	-----	(0.0452)	(0.0480)	-----	(0.2885)	(0.00021)	-----	(0.1000)	(0.3830)	(0.0286)	(1.54)	(5.96)	(0.45)	-----
5A	(2)	STGR(odd) =	−12.25	-----	-----	+0.3865	−0.4533	-----	+1.3206	+0.00260	-----	−0.1535	−1.0394	−0.0957	−8.82	−24.33	−3.02	0.5052
		s.d. =	(3.87)	-----	-----	(0.0557)	(0.0599)	-----	(0.3512)	(0.00024)	-----	(0.1173)	(0.4564)	(0.0377)	(4.70)	(7.58)	(0.61)	-----
5B	(3)	STGR(even) =	−11.16	-----	-----	+0.3248	−0.3631	-----	*+0.3016	+0.00283	-----	*+0.1186	*−0.3762	*−0.0080	−6.87	*−8.41	−0.87	0.5388
		s.d. =	(5.16)	-----	-----	(0.0729)	(0.0695)	-----	(0.4655)	(0.00032)	-----	(0.1626)	(0.6034)	(0.0404)	(1.82)	(9.03)	(0.57)	-----
6	(1)	STGR =	−10.99	-----	-----	+0.3287	−0.2964	-----	+0.5496	-----	+0.001290	−0.4640	−1.0085	−0.0976	−4.77	−16.25	−1.47	0.6284
		s.d. =	(3.51)	-----	-----	(0.0509)	(0.0549)	-----	(0.3191)	-----	(0.000116)	(0.1168)	(0.4264)	(0.0321)	(1.72)	(6.64)	(0.50)	-----

[1] 137 cements; Avg=6.535×10³ psi; S.D.=1.140×10³ psi. [2] 69 cements. [3] 68 cements. *Coef./s.d. ratio less than 1.

lationships with commonly determined variables are presented in eqs 1 and 4 of table 8–13. SO_3 had a coef./s.d. ratio greater than one in eqs 1, 2, and 3, where the potential compounds were included but not with the variables in eqs 4, 5, and 6 where the oxides were used. The opposite was found for Insol. The addition of the 3 trace elements, Ba, Cu, and P, in eqs 2 and 5 resulted in significant reductions in the S.D. values (see table 8–28). The use of the APF values in eqs 3 and 6 resulted in higher values for the S.D. than were obtained in eqs 2 and 5. In eq 3 the coef./s.d. ratio for C_3A was less than one and the coefficient for Loss was of somewhat greater significance than when the Wagner fineness values were used. The relationship between the fineness values determined by the two methods and other variables such as C_3A, SO_3, and loss on ignition have previously been discussed in section 7 of this series.

Equations calculated for the "odds" and "even" (eqs 2A, 2B, 5A, and 5B) indicated instances where Loss, Insol, and Cu had coef./s.d. ratios less than one and in eq 2A the sign of the coefficient for Cu was positive instead of negative as in eq 2.

The equations for the NAE cements presented in table 8–14 present somewhat the same trend as in table 8–13. There were, however, also instances where the SO_3, K_2O and (air, 1:4 mortar) had coef./s.d. ratios less than 1 in the equations for the "odds" and "evens."

The estimated contributions of the independent variables to the compressive strength of the steam-cured specimens were calculated from the coefficients of eq 2 of table 8–14 and are presented in table 8–15 together with the calculated ranges of these contributions. Increases in C_3A, C_3S, SO_3, K_2O, and fineness were associated with an increase in the strength values, and increases in Loss, air content, Ba, P, and possibly Cu, associated with the lower compressive strength values. Differences in C_3S, fineness, and air content had the greatest effect.

Table 8–15. *Calculated contributions of independent variables to compressive strength of mortar cubes, steam-cured after 5 hrs, then air-dried, and the calculated ranges of such contributions (STGR)*

Independent variable	Range of variable (percent)	Coefficient from eq (2) table 8–14	Calculated contribution to STGR (×10⁻³)	Calculated range of contribution to STGR (×10⁻³)
			Const. = −2.094	
C_3A	1 to 15	+0.0475	+0.048 to +0.712	0.664
C_3S	20 to 65	+0.0853	+1.706 to +5.544	3.838
SO_3	1.2 to 3.0	+0.4949	+0.594 to +1.485	0.891
K_2O	0 to 1.1	+0.5892	0 to +0.648	0.648
WAGN	*1200 to 3000	+0.00223	+2.676 to +6.690	4.014
Loss	0.3 to 3.3	−0.3111	−0.093 to −1.027	0.934
Air, 1:4 mortar.	1 to 21	−0.0967	−0.097 to −2.031	1.916
Ba	1 to 0.2	−5.64	0 to −1.128	1.128
Cu**	0 to 0.05	−6.98	0 to −0.349	0.349
P	0 to 0.5	−1.46	0 to −0.730	0.730

* cm²/g.
** Coefficient of doubtful significance as coef./s.d. ratio was less than 2.

5.4. Compressive Strength of Specimens Cured With Low-Pressure Steam After 24 Hr, Tested Wet (STMA)

The frequency distributions of the different types of cements with respect to the compressive strength of specimens STMA, steam-cured for 7½ hr at 71° C after an initial 22 to 24 hr at normal temperature are presented in table 8–16. The specimens were tested while moist after cooling to laboratory temperature. There was a considerable range of values for each of the types and considerable overlapping of the values for the different types. The type III cements generally had the higher values, and the types IV and V the lower values (see also fig. 8–1).

Selected equations relating the compressive strength values obtained with the different cements to various independent variables are presented in table 8–17 for the AE+NAE cements, and the table 8–18 for the NAE cements. The use of commonly determined variables as in eqs 1 and 4 of table 8–17, each resulted in a significant reduction in the S.D. value (see table 8–28). The addition of 4 additional variables MgO, Ba, Cu, and Li, in eq 2 resulted in a slightly lower S.D. value but the reduction was significant only at the 5 percent probability level. MgO and Li of the added variables in eq 2 were of doubtful significance. A similar comparison cannot be made for eqs 4 and 5. However, there was only a slight reduction in the S.D. value. Al_2O_3 had a coef./s.d. ratio less than one in eq 4, but was probably significant in eq 5.

TABLE 8–16. *Frequency distribution of cements with respect to compressive strength of mortars, steam-cured after 24 hr and tested when wet (STMA)*

Type cement	Compressive strength, psi×10⁻³											Total
	2.0 to 2.5	2.5 to 3.0	.0 to 3.5	3.5 to 4.0	4.0 to 4 5	4.5 to 5.0	5.0 to 5.5	5.5 to 6.0	6.0 to 6.5	6.5 to 7.0	7.0 to 7.5	
	Number of cements											
I	---	1	7	18	18	12	5	2	---	---	---	63
IA	---	---	4	2	1	---	---	---	---	---	---	7
II	---	2	15	23	17	4	---	---	---	---	---	61
IIA	---	---	1	---	1	---	---	---	---	---	---	2
III	---	---	---	1	---	2	2	2	6	3	1	17
IIIA	---	---	---	---	---	---	---	1	---	---	---	1
IV, V	1	4	5	3	1	---	---	---	---	---	---	14
Total	1	7	32	47	38	18	7	5	6	3	1	165

Equations 2A, 2B, 5A, and 5B calculated for the "odds" and "evens" in the array of cements indicated that there were instances where the MgO, SO_3, Cu, and Li had coef./s.d. ratios less than 1 in one or both of the smaller groups.

The use of the air-permeability-fineness values in eqs 3 and 6 instead of the turbidimeter fineness values in eqs 2 and 5 resulted in S.D. values which were higher. Here again, the S.D. was higher than for eq 1.

The relationship of the "STMA" compresssive strength values of the NAE cements to various independent variables are presented in table 8–18. The coefficients differ only slightly from those presented in the previous table where the AE cements were included. Although some of the coefficients were not highly significant, there was no instance where the coef./s.d. ratios of the variables in the equations for the "odds" and "evens" (eqs 2A, 2B, 5A, and 5B) were less than 1.

Using the independent variables and their coefficients in eq 2 of table 8–18, and the ranges of these variables, values were calculated for their contributions to the STMA compressive-strength values. These calculated values are presented in table 8–19 together with the calculated ranges of these values. Increased values for C_3S, C_3A, SO_3, K_2O, fineness, and possibly Li were associated with higher strength values. Increased values for, Loss (air, 1:4 mortar), and possibly Ba, Cu, and MgO, were associated with lower compressive strength values. Of these variables, differences in C_3S and fineness appear to have the greatest effect.

5.5. Compressive Strength of Mortars Cured With High-Pressure Steam After 5 Hr Moist Storage (AUGR)

The frequency distribution of the compressive-strength values of mortars made of the different cements and autoclaved after about 5 hrs (AUGR), is presented in table 8–20 (after the autoclave treatment, the mortar specimens were oven dried, then stored for 2 days in laboratory air before the compression tests). There was a considerable spread of values for each of the types of cement and an overlapping of the cements of the different types. As mentioned above, these specimens attained the highest average strength level of all those tested. (See also fig. 8–1.)

Selected equations indicating the relationship of various independent variables to the compressive strength of the autoclaved mortars are presented in table 8–21 for the AE+NAE cements, and in table 8–22 for the NAE cements. The relationship to commonly determined variables are presented in eqs 1 and 4. Equations 2 and 5, table 8–21, show the effect of the trace elements found to have coef./s.d. ratios greater than 1. The reductions in the S.D. values were, in both instances, highly significant. (See table 8–28.) In eq 3, where APF was used instead of WAGN, the S.D. is higher than in eq 1.

There were instances in the equations for the "odds" and "evens" in the array of cements where SO_3, SiO_2, and V had coef./s.d. ratios less than 1. The coefficients for SiO_2 and V were probably not significant with the larger group.

A similar set of equations is presented in table 8–22 for the NAE cements alone. Again, the use of the 5 trace elements Ba, Cu, Li, Cr, and V in

TABLE 8–17. *Coefficients for equations relating the compressive strength of mortars of AE+NAE cements, cured with low pressure steam after 24 hrs, and tested wet, to various independent variables (STMA)*

Equation	Note	psi×10^{-3}	Const.	C_3S	C_3A	CaO	SiO_2	Al_2O_3	SO_3	K_2O	MgO	APF	WAGN	Loss	Air 1:4 mortar	Ba	Cu	Li	S.D.
1	(1)	STMA	= −3.638	+0.0726	+0.0652				+0.4206	+0.5454			+0.00184	−0.3679	−0.0433				0.4267
		s.d.	= (0.381)	(0.0062)	(0.0139)				(0.1374)	(0.1901)			(0.00018)	(0.0710)	(0.0101)				
2	(1)	STMA	= −3.240	+0.0720	+0.0526				+0.4663	+0.5435	−0.0447		+0.00179	−0.3827	−0.0431	−2.998	−12.07	+15.61	0.4128
		s.d.	= (0.402)	(0.0062)	(0.0143)				(0.1356)	(0.2007)	(0.0332)		(0.00019)	(0.0689)	(0.0100)	(1.148)	(4.59)	(10.71)	
2A	(2)	STMA (odd)	= −3.085	+0.0648	+0.0684				+0.2242	+0.3321	*−0.0192		+0.00207	−0.4000	−0.0435	−2.225	*−7.28	+20.91	0.3981
		s.d.	= (0.544)	(0.0085)	(0.0210)				(0.2023)	(0.3189)	(0.0478)		(0.00026)	(0.0948)	(0.0123)	(1.646)	(8.03)	(18.92)	
2B	(3)	STMA (even)	= −3.315	+0.0780	+0.0437				+0.6311	+0.6081	*−0.0435		+0.00159	−0.3468	−0.0455	−5.017	−20.40	*+3.19	0.4205
		s.d.	= (0.594)	(0.0098)	(0.0204)				(0.1904)	(0.2777)	(0.0492)		(0.00028)	(0.1031)	(0.0183)	(1.714)	(6.40)	(15.07)	
3	(1)	STMA	= −2.245	+0.0727	+0.0243				+0.4438	+0.3535	*−0.0299	+0.00086		−0.6480	−0.0455	−2.886	−13.50	*+10.64	0.4357
		s.d.	= (0.380)	(0.0066)	(0.0143)				(0.1471)	(0.2071)	(0.0349)	(0.00010)		(0.0747)	(0.0105)	(1.218)	(4.85)	(11.25)	
4	(1	STMA	= −2.414			+0.4953	−0.3351	*−0.0784	+0.4054	+0.7083	+0.1794		+0.00185	−0.1709	−0.0406				0.4222
		s.d.	= (0.452)			(0.0489)	(0.0770)	(0.0842)	(0.1479)	(0.2075)	(0.0501)		(0.00018)	(0.0823)	(0.0102)				
5	(1)	STMA	= −13.03			+0.3870	−0.4518	−0.2229	+0.3387	+0.6444			+0.00181	−0.2913	−0.0363	−3.230	−16.07	+20.71	0.4115
		s.d.	= (2.90)			(0.0340)	(0.0653)	(0.0750)	(0.1449)	(0.2128)			(0.00019)	(0.0734)	(0.0098)	(1.145)	(4.39)	(10.66)	
5A	(2)	STMA (odd)	= −13.88			+0.3700	−0.3798	−0.1679	*+0.1915	+0.5887			+0.00200	−0.2854	−0.0379	−3.100	−12.91	+27.96	0.4101
		s.d.	= (4.51)			(0.0516)	(0.0968)	(0.1080)	(0.2242)	(0.3436)			(0.00026)	(0.1055)	(0.0128)	(1.781)	(8.13)	(19.39)	
5B	(3)	STMA (even)	= −12.45			+0.4024	−0.5068	−0.2632	+0.4586	+0.6237			+0.00167	−0.2757	−0.0359	−5.092	−23.48	*+9.75	0.4129
		s.d.	= (4.06)			(0.0466)	(0.1010)	(0.1146)	(0.1993)	(0.2892)			(0.00028)	(0.1078)	(0.0175)	(1.672)	(5.99)	(14.89)	
6	(1)	STMA	= −17.40			+0.4442	−0.3924	−0.2496	+0.3797	+0.4767	+0.1062	+0.00086		−0.5046	−0.0445	−2.883	−13.38	+12.51	0.4312
		s.d.	= (4.85)			(0.0530)	(0.0795)	(0.0856)	(0.1594)	(0.2189)	(0.0550)	(0.00010)		(0.0865)	(0.0105)	(1.214)	(4.91)	(11.17)	

(1) 147 cements; Avg=4.119×10^3 psi; S.D.=0.904×10^3 psi. (2) 74 cements. (3) 73 cements. *Coef./s.d. ratio less than 1.

TABLE 8–18. *Coefficients for equations relating the compressive strength of mortars of NAE cements, cured with low-pressure steam after 24 hrs, and tested wet, to various independent variables (STMA)*

Equation	Note	psi×10^{-3}	Const.	C_3S	C_3A	CaO	SiO_2	Al_2O_3	SO_3	K_2O	MgO	APF	WAGN	Loss	Air 1:4 mortar	Ba	Cu	Li	S.D.
1	(1)	STMA	= −3.398	+0.0748	+0.0599				+0.4776	+0.5771			+0.00177	−0.3753	−0.0861				0.4301
		s.d.	= (0.415)	(0.0063)	(0.0143)				(0.1421)	(0.1961)			(0.00019)	(0.0727)	(0.0217)				
2	(1)	STMA	= −3.092	+0.0749	+0.0512				+0.5280	+0.6548	−0.0524		+0.00175	−0.3954	−0.0951	−3.021	−10.31	+26.97	0.4140
		s.d.	= (0.422)	(0.0064)	(0.0145)				(0.1396)	(0.2108)	(0.0340)		(0.00019)	(0.0703)	(0.0238)	(1.159)	(4.67)	(11.70)	
2A	(2)	STMA (odd)	= −2.311	+0.0758	+0.0493				+0.3663	+0.8624	−0.0835		+0.00163	−0.4151	−0.1405	−2.508	−13.12	+23.79	0.4383
		s.d.	= (0.702)	(0.0088)	(0.0260)				(0.2295)	(0.3618)	(0.0516)		(0.00030)	(0.0946)	(0.0146)	(1.877)	(6.90)	(17.84)	
2B	(2)	STMA (even)	= −3.458	+0.0666	+0.0642				+0.6038	+0.3980	−0.0947		+0.00190	−0.3057	−0.0666	−2.872	−10.89	+27.63	0.3879
		s.d.	= (0.536)	(0.0101)	(0.0181)				(0.1953)	(0.2752)	(0.0497)		(0.00027)	(0.1242)	(0.0300)	(1.696)	(7.49)	(18.08)	
3	(1)	STMA	= −2.030	+0.0751	+0.0236				+0.4920	+0.5214	−0.0389	+0.00084		−0.6535	−0.1117	−2.800	−11.42	+25.25	0.4321
		s.d.	= (0.389)	(0.0067)	(0.0143)				(0.1498)	(0.2170)	(0.0354)	(0.00010)		(0.0749)	(0.0248)	(1.218)	(4.88)	(12.20)	
4	(1)	STMA	= −23.49			+0.4979	−0.3522	−0.1095	+0.4497	+0.7401	+0.1726		+0.00180	−0.1839	−0.0780				0.4270
		s.d.	= (4.66)			(0.0500)	(0.0801)	(0.0876)	(0.1531)	(0.2142)	(0.0518)		(0.00019)	(0.0849)	(0.0218)				
5	(1)	STMA	= −13.77			+0.4048	−0.458	−0.2353	+0.4063	+0.7591			+0.00178	−0.2974	−0.0814	−3.304	−14.29	+30.56	0.4133
		s.d.	= (2.97)			(0.0348)	(0.0675)	(0.0770)	(0.1500)	(0.2243)			(0.00019)	(0.0748)	(0.0238)	(1.157)	(4.48)	(11.66)	
5A	(2)	STMA (odd)	= −14.73			+0.4280	−0.4449	−0.2423	+0.2833	+0.9807			+0.00159	−0.2824	−0.1303	−2.958	−15.72	+27.68	0.4377
		s.d.	= (4.63)			(0.0508)	(0.0968)	(0.1216)	(0.2369)	(0.3781)			(0.00030)	(0.1113)	(0.0406)	(1.892)	(6.62)	(17.92)	
5B	(2)	STMA (even)	= −11.26			+0.3483	−0.4485	−0.1809	+0.4887	+0.4642			+0.00199	−0.3031	−0.0444	−3.173	−17.37	+31.70	0.3888
		s.d.	= (4.17)			(0.0554)	(0.1001)	(0.1074)	(0.2122)	(0.2915)			(0.00027)	(0.1187)	(0.0301)	(1.678)	(7.39)	(17.96)	
	(1)	STMA	= −18.66			+0.4665	−0.3875	−0.2547	+0.4455	+0.6692	+0.1093	+0.00085		−0.4957	−0.1092	−2.875	−11.11	+26.54	0.4281
		s.d.	= (4.93)			(0.0539)	(0.0813)	(0.0868)	(0.1623)	(0.2305)	(0.0558)	(0.00010)		(0.0873)	(0.0248)	(1.214)	(4.95)	(12.10)	

(1) 138 cements; Avg=4.133×10^3 psi; S.D.=0.909×10^3 psi. (2) 69 cements.

TABLE 8–19. *Calculated contributions of independent variables to the compressive strength of mortar cubes, steam-cured after 24 hrs and tested when in a moist condition, (STMA) and the calculated ranges of such contributions*

Independent variable	Range of variable (percent)	Coefficient from eq (2) table 8–18	Calculated contribution to STMA ($\times 10^{-3}$)	Calculated range of contribution to STMA ($\times 10^{-3}$)
			Const. = −3.092	
C_3S	20 to 65	+0.0749	+1.498 to +4.868	3.370
C_3A	1 to 15	+0.0512	+0.051 to +0.768	0.717
SO_3	1.2 to 3.0	+0.5280	+0.634 to +1.584	0.950
K_2O	0 to 1.1	+0.6548	0 to +0.720	0.720
MgO**	0 to 5.0	−0.0524	0 to −0.262	0.262
WAGN	*1200 to 3000	+0.00175	+2.100 to +5.250	3.150
Loss	0.3 to 3.3	−0.3954	−0.119 to −1.305	1.186
Air, 1:4 mortar.	1 to 21	−0.0951	−0.095 to −1.997	1.902
Ba	0 to 0.2	−3.021	0 to −0.604	0.604
Cu	0 to 0.05	−10.31	0 to −0.516	0.516
Li	0 to 0.02	+26.97	0 to +0.539	0.539

*cm^2/g.
**Coefficient of doubtful significance as coef./s.d. ratio was less than 2.

TABLE 8–20. *Frequency distribution of cements with respect to compressive strength of mortars, autoclaved after 5 hr, and tested after drying (AUGR)*

Type cement	Compressive strength, psi$\times 10^{-3}$									Total
	9.0 to 10.0	10.0 to 11.0	11.0 to 12.0	12.0 to 13.0	13.0 to 14.0	14.0 to 15.0	15.0 to 16.0	16.0 to 17.0	17.0 to 18.0	
	Number of cements									
I	----	1	4	18	28	11	----	----	----	
IA	1	----	1	4	----	----	----	----	----	6
II	1	----	7	14	22	11	4	----	----	59
IIA	----	----	----	1	1	----	----	----	----	2
III	----	----	----	----	2	3	6	4	3	18
IIIA	----	----	----	----	1	----	----	----	----	1
IV, V	----	----	3	1	3	4	----	----	----	11
Total	2	1	15	38	57	29	10	4	3	159

eqs 2 and 5 resulted in significantly lower S.D. values. In the equations for the "odds" and "evens' there were instances where Ba, SiO_2, and V had coef./s.d. ratios less than 1. The coefficients for SiO_2 and V were probably not significant with the larger group of cements in eqs 2 and 5.

The estimated contributions of the various independent variables to the compressive strength of the autoclaved mortars were calculated from the variables and their coefficients in eq 2 of table 8–22 and are presented in table 8–23 together with the calculated ranges of these contributions. It appears that increases in C_3A, C_3S, C_2S, SO_3, fineness, Li, and Cr are associated with higher compressive strength values. It also appears that increases in (air, 1:4 mortar), Na_2O, Ba, Cu, and possibly V, are associated with lower compressive strength values. Of these variables, variations in C_3S, C_2S, fineness, and the air content of the 1:4 mortar appear to have the greatest effect.

TABLE 8–21. *Coefficients for equations relating the compressive strength of mortars of AE+NAE cements, cured with high-pressure steam after 5 hrs, to various independent variables (AUGR)*

Equation	Note	psi $\times 10^{-3}$	Const	C_3A	C_3S	C_2S	CaO	SiO_2	SO_3	Na_2O	APF	WAGN	Air 1:4 mortar	Ba	Cu	Li	Cr	V	S.D.
1	(1)	AUGR =	−3.677	+0.0914	+0.1457	+0.1308	--------	--------	+0.8424	−2.072	--------	+0.00300	−0.1050	--------	--------	--------	--------	--------	0.7486
		s.d. =	(2.499)	(0.0309	(0.0289)	(0.0303)	--------	--------	(0.2478)	(0.379)	--------	(0.00031)	(0.0179)	--------	--------	--------	--------	--------	--------
2	(1)	AUGR =	−4.599	+0.0995	+0.1550	+0.1446	--------	--------	+0.9264	−2.830	--------	+0.00304	−0.1094	−4.663	−24.86	+92.37	+37.45	−6.52	0.6732
		s.d. =	(2.334)	(0.0291)	(0.0273)	(0.0288)	--------	--------	(0.2343)	(0.376)	--------	(0.00029)	(0.0162)	(2.033)	(7.28)	(18.72)	(14.26)	(3.80)	--------
2A	(2)	AUGR (odd) =	−0.462	+0.0830	+0.0893	+0.0990	--------	--------	*+0.3097	−2.920	--------	+0.00343	−0.1168	*−2.790	−37.31	+123.54	+43.19	−8.33	0.6181
		s.d. =	(3.384)	(0.0400)	(0.0398)	(0.0416)	--------	--------	(0.3369)	(0.495)	--------	(0.00040)	(0.0192)	(3.314)	(12.87)	(31.76)	(18.62)	(7.04)	--------
2B	(3)	AUGR (even) =	−8.866	+0.1369	+0.2084	+0.1808	--------	--------	+1.3440	−2.662	--------	+0.00281	−0.1052	−6.390	−22.24	+84.02	+33.14	*−3.28	0.7146
		s.d. =	(3.420)	(0.0433)	(0.0393)	(0.0426)	--------	--------	(0.3332)	(0.584)	--------	(0.00044)	(0.0299)	(3.066)	(10.50)	(26.92)	(22.13)	(4.99)	--------
3	(1)	AUGR =	−5.321	+0.0630	+0.1820	+0.1773	--------	--------	+0.8773	−2.533	+0.00132	--------	−0.1152	−5.886	−24.83	+72.84	+41.93	−4.51	0.7518
		s.d. =	(2.608)	(0.0318)	(0.0301)	(0.0319)	--------	--------	(0.2725)	(0.419)	(0.00017)	--------	(0.0180)	(2.258)	(8.14)	(20.81)	(15.96)	(4.26)	--------
4	(1)	AUGR =	−9.591	--------	--------	--------	+0.2456	+0.0699	+0.8304	−2.095	--------	+0.00296	−0.0943	--------	--------	--------	--------	--------	0.7625
		s.d. =	(3.872)	--------	--------	--------	(0.0575)	(0.0630)	(0.2525)	(0.379)	--------	(0.00029)	(0.0983)	--------	--------	--------	--------	--------	--------
5	(1)	AUGR =	−13.785	--------	--------	--------	+0.2987	+0.1122	+0.9476	−2.858	--------	+0.00292	−0.0982	−5.124	−31.63	+102.12	+35.54	−8.11	0.6655
		s.d. =	(3.549)	--------	--------	--------	(0.0519)	(0.0614)	(0.2316)	(0.361)	--------	(0.00026)	(0.0160)	(1.996)	(7.08)	(18.53)	(14.08)	(3.76)	--------
5A	(2)	AUGR (odd) =	−4.576	--------	--------	--------	+0.1636	+0.1175	+0.4032	−2.790	--------	+0.00312	−0.1081	−3.431	−41.64	+121.19	+41.45	−9.53	0.6156
		s.d. =	(5.342)	--------	--------	--------	(0.0741)	(0.0860)	(0.3355)	(0.474)	--------	(0.00035)	(0.0189)	(3.277)	(12.50)	(31.06)	(18.49)	(7.14)	--------
5B	(3)	AUGR (even) =	−21.394	--------	--------	--------	+0.4266	*+0.0614	+1.3077	−2.733	--------	+0.00282	−0.0844	−6.747	−30.78	+102.39	+29.15	−5.43	0.7069
		s.d. =	(5.010)	--------	--------	--------	(0.0774)	(0.0958)	(0.3284)	(0.569)	--------	(0.00040)	(0.0292)	(3.000)	(10.21)	(27.20)	(21.91)	(4.90)	--------
--------	(1)	AUGR =	−15.701	--------	--------	--------	+0.2929	+0.2577	+0.8852	−2.649	+0.00134	--------	−0.1056	−6.054	−30.85	+86.13	+41.02	−6.23	0.7355
		s.d. =	(3.903)	--------	--------	--------	(0.0580)	(0.0660)	(0.2658)	(0.402)	(0.00015)	--------	(0.0176)	(2.199)	(7.82)	(20.54)	(15.57)	(4.17)	--------

[1] 147 cements; avg=13.414×10^3 psi; S.D.=1.332×10^3 psi. [2] 74 cements. [3] 73 cements. *Coef./s.d. ratio less than 1.

TABLE 8-22. *Coefficients for equations relating the compressive strength of mortars of NAE cements, cured with high-pressure steam after 5 hrs, to various independent variables (AUGR)*

Equation	Note	psi ×10⁻³	Const	C_3A	C_3S	C_2S	CaO	SiO_2	SO_3	Na_2O	APF	WAGN	Air 1:4 mortar	Ba	Cu	Li	Cr	V	S.D.
1	(1)	AUGR =	−4.314	+0.0984	+0.1524	+0.1391			+0.9417	−1.944		+0.00299	−0.1278						0.7565
		s.d. =	(2.563)	(0.0318)	(0.0297)	(0.0313)			(0.2602)	(0.414)		(0.00033)	(0.0411)						
2	(1)	AUGR =	−5.291	+0.1095	+0.1640	+0.1540			+1.0753	−2.676		+0.00300	−0.1581	−5.169	−22.02	+97.92	+38.84	−5.71	0.6708
		s.d. =	(2.362)	(0.0294)	(0.0278)	(0.0293)			(0.2425)	(0.391)		(0.00030)	(0.0387)	(2.045)	(7.35)	(19.39)	(14.48)	(3.80)	
2A	(2)	AUGR(odd) =	−7.224	+0.1749	+0.1901	+0.1804			+0.9469	−2.128		+0.00293	−0.2316	*−2.495	−18.48	+104.66	+41.35	−11.12	0.6238
		s.d. =	(3.208)	(0.0417)	(0.0368)	(0.0388)			(0.3508)	(0.510)		(0.00042)	(0.0619)	(3.052)	(9.67)	(26.35)	(21.65)	(5.04)	
2B	(2)	AUGR (even) =	−1.716	+0.0529	+0.1125	+0.1062			+1.0277	−2.923		+0.00339	−0.1438	−4.888	−22.86	+79.13	+44.68	*+4.43	0.6584
		s.d. =	(3.420)	(0.0421)	(0.0414)	(0.0434)			(0.3285)	(0.612)		(0.00042)	(0.0499)	(2.980)	(12.74)	(31.04)	(19.15)	(5.69)	
3	(1)	AUGR =	−5.963	+0.0764	+0.1926	+0.1886			+1.0483	−2.310	+0.00130		−0.2023	−6.083	−21.77	+84.77	+41.35	*−3.76	0.7422
		s.d. =	(2.614)	(0.0302)	(0.0302)	(0.0321)			(0.2777)	(0.431)	(0.00017)		(0.0422)	(2.254)	(8.14)	(21.43)	(16.04)	(4.22)	
4	(1)	AUGR =	−10.43				+0.2547	+0.0791	+0.9301	−1.963		+0.00294	−0.1104						0.771
		s.d. =	(3.96)				(0.0587)	(0.0651)	(0.2652)	(0.410)		(0.00031)	(0.0414)						
5	(1)	AUGR =	−14.79				+0.3130	+0.1181	+1.0935	−2.703		+.00287	−0.1365	−5.764	−29.98	+105.92	+37.51	−7.35	0.6641
		s.d. =	(3.59)				(0.0525)	(0.0625)	(0.2398)	(0.374)		(0.00027)	(0.0378)	(2.017)	(7.14)	(19.29)	(14.31)	(3.76)	
5A	(2)	AUGR(odd) =	−16.23				+0.3559	+0.1031	+1.0491	−2.294		+0.00248	−0.1974	+4.630	−27.58	+117.92	+43.27	−13.36	0.641
		s.d. =	(4.82)				(0.0677)	(0.0919)	(0.3547)	(0.521)		(0.00038)	(0.0634)	(3.056)	(9.83)	(27.59)	(22.11)	(5.20)	
5B	(2)	AUGR (even) =	−8.94				+0.2064	+0.1218	+1.0606	−2.947		+0.00337	−0.1271	−5.225	−27.59	+83.98	+43.26	*+3.00	0.6481
		s.d. =	(5.52)				(0.0846)	(0.0845)	(0.3243)	(0.560)		(0.00040)	(0.0477)	(2.945)	(12.16)	(30.61)	(18.85)	(5.58)	
6	(1)	AUGR =	−16.36				+0.3049	+0.2638	+1.0527	−2.428	+0.00130		−0.1802	−6.426	−28.66	+95.67	+40.88	−5.49	0.7274
		s.d. =	(3.91)				(0.0581)	(0.0665)	(0.2712)	(0.412)	(0.00015)		(0.0410)	(2.204)	(7.81)	(21.19)	(15.68)	(4.15)	

[1] 138 cements; avg=13.493×10³ psi; S.D.=1.3012×10³ psi. [2] 69 cements. *Coef./s.d. ratio less than 1.

TABLE 8-23. *Calculated contributions of independent variables to the compressive strength of mortar cubes, cured with high-pressure steam after 5 hrs and tested dry (AUGR), and the calculated ranges of such contributions*

Independent variable	Range of variable (percent)	Coefficient from eq (2) table 8-22	Calculated contribution to AUGR (×10⁻³)	Calculated range of contribution to AUGR (×10⁻³)
			Const.=−5.291	
C_3A	1 to 15	+0.1095	+0.110 to +1.642	1.532
C_3S	20 to 65	+0.1640	+3.280 to +10.660	7.380
C_2S	5 to 50	+0.1540	+0.770 to +7.700	6.930
SO_3	1.2 to 3.0	+1.0753	+1.290 to +3.226	1.936
Na_2O	0 to 0.7	−2.676	0 to −1.873	1.873
WAGN	*1200 to 3000	+0.0030	+3.600 to +9.000	5.400
Air, 1:4 mortar.	1 to 21	−0.1581	−0.158 to −3.162	3.004
Ba	0 to 0.2	−5.169	0 to −1.034	1.034
Cu	0 to 0.05	−22.02	0 to −1.101	1.101
Li	0 to 0.02	+97.92	0 to +1.958	1.958
Cr	0 to 0.02	+38.84	0 to +0.777	0.777
V**	0 to 0.1	−5.71	0 to −0.571	0.571

*cm²/g.
**Coefficient of doubtful significance as coef./s.d. ratio was less than 2.

5.6. Compressive Strength of Mortars, High-Pressure-Steam-Cured after 24 Hr, and Tested after Drying (AUMA)

The frequency distributions of the various types of cements with respect to the compressive strength of AUMA mortars are presented in table 8-24. As indicated in a previous subsection, these mortars were autoclaved after 24 hr in the moist closet and for a shorter period of time than the AUGR specimens, the results of which were presented in the previous subsection. The cements within each of the types as classified had a broad range of compressive-strength values and there was an overlapping of the strength values of the cements of the different types. (See also fig. 8-1.)

Selected equations relating the AUMA compressive-strength values to various independent variables are presented in table 8-25 for the AE+NAE cements, and in table 8-26 for the NAE cements.

Commonly determined variables having a coef./s.d. ratio greater than one, as presented in eqs 1 and 4, resulted in a significantly lower S.D. value.

TABLE 8-24. *Frequency distribution of cements with respect to compressive strength of mortars, autoclaved after 24 hr and tested after drying (AUMA)*

Type cement	Compressive strength, psi×10⁻³: 9.5 to 10.0	10.0 to 10.5	10.5 to 11.0	11.0 to 11.5	11.5 to 12.0	12.0 to 12.5	12.5 to 13.0	13.0 to 13.5	13.5 to 14.0	14.0 to 14.5	14.5 to 15.0	15.0 to 15.5	15.5 to 16.0	Total
	Number of cements													
I	1	3	2	10	5	12	14	13	1	1	1			63
IA	1	1			3		1	1						7
II			1	5	4	7	13	12	13	5	1			61
IIA								1					1	2
III								4	1	6	5	1		17
IIIA							1							1
IV, V					2			5	4		1	1	1	14
Total	2	4	3	15	14	19	29	36	19	12	8	2	2	165

TABLE 8–25. *Coefficients for equations relating the compressive strength of mortars of AE+NAE cements, cured with high-pressure steam after 24 hrs, to various independent variables (AUMA)*

Equation	Note	psi×10⁻³	Const.	C_3A	C_2S	SiO_2	Fe_2O_3	SO_3	Na_2O	K_2O	APF	WAGN	Air 1:4 mortar	Insol	MgO	SrO	Rb	Ba	V	S.D.
1	(1)	AUMA	= +9.784	−0.0710	+0.0410	--------	--------	+0.946	−2.092	−1.420	+0.000692	--------	−0.0449	−0.8493	--------	--------	--------	--------	--------	0.7495
		s.d.	= (0.776)	(0.0271)	(0.0117)	--------	--------	(0.237)	(0.384)	(0.332)	(0.000159)		(0.0188)	(0.4702)	--------	--------	--------	--------	--------	------
2	(1)	AUMA	= +9.960	−0.0595	+0.0457	--------	--------	+1.186	−1.878	−1.143	+0.000554	--------	−0.0560	−0.9550	--------	−1.434	−99.24	−3.03	−4.56	0.7128
		s.d.	= (0.765)	(0.0283)	(0.0112)	--------	--------	(0.233)	(0.387)	(0.347)	(0.000157)	--------	(0.0182)	(0.4531)	--------	(0.768)	(36.13)	(2.12)	(3.90)	------
2A	(2)	AUMA (odd)	= +9.935	−0.0772	+0.0499	--------	--------	+1.337	−1.856	−1.207	+0.000531	--------	−0.0925	−1.4255	--------	*−0.139	−107.31	−6.00	*−0.01	0.7312
		s.d.	= (1.144)	(0.0430)	(0.0159)	--------	--------	(0.370)	(0.519)	(0.546)	(0.000212)	--------	(0.0286)	(0.6185)	--------	(1.257)	(50.87)	(3.29)	(5.21)	------
2B	(3)	AUMA (even)	= +10.146	−0.0484	+0.0446	--------	--------	+1.070	−1.909	−1.378	+0.000550	--------	−0.0311	*−0.4852	--------	−2.343	−76.58	*−1.16	−9.71	0.7022
		s.d.	= (1.155)	(0.0414)	(0.0174)	--------	--------	(0.328)	(0.627)	(0.503)	(0.000254)	--------	(0.0245)	(0.7237)	--------	(1.022)	(53.96)	(3.03)	(6.40)	------
3	(1)	AUMA	= +9.698	−0.0477	+0.0410	--------	--------	+1.360	−1.850	−1.212	--------	+0.00103	−0.0536	−0.8011	--------	−1.861	−88.24	−2.70	−6.17	0.7144
		s.d.	= (0.830)	(0.0295)	(0.0109)	--------	--------	(0.211)	(0.388)	(0.342)	--------	(0.00030)	(0.0183)	(0.4502)	--------	(0.770)	(36.42)	(2.15)	(3.87)	------
4	(1)	AUMA	= +1.252	--------	--------	+0.3488	+0.2460	+1.137	−1.943	−1.463	+0.000658	--------	−0.0488	−0.7297	+0.1499	--------	--------	--------	--------	0.7528
		s.d.	= (1.895)	--------	--------	(0.0678)	(0.0846)	(0.250)	(0.381)	(0.356)	(0.000149)	--------	(0.0194)	(0.4635)	(0.0558)	--------	--------	--------	--------	------
5	(1)	AUMA	= +1.452	--------	--------	+0.3619	+0.2360	+1.384	−1.716	−1.146	+0.000496	--------	−0.0578	−0.7600	+0.1198	−1.302	−90.85	−2.87	−5.20	0.7212
		s.d.	= (1.950)	--------	--------	(0.0712)	(0.0821)	(0.250)	(0.389)	(0.370)	(0.000150)	--------	(0.0189)	(0.4503)	(0.0544)	(0.762)	(36.30)	(2.17)	(3.99)	------
6	(1)	AUMA	= +2.614	--------	--------	+0.3118	+0.2051	+1.526	−1.716	−1.228	--------	+0.00086	−0.0551	−0.6406	+0.0968	−1.705	−82.74	− .72	−6.52	0.7266
		s.d.	= (1.909)	--------	--------	(0.0726)	(0.0827)	(0.235)	(0.393)	(0.368)	--------	(0.00029)	(0.0192)	(0.4528)	(0.0546)	(0.759)	(36.92)	(2.20)	(3.99)	------
6A	(2)	AUMA (od d	= +1.972	--------	--------	+0.4048	+0.2196	+1.700	−1.675	−1.364	--------	+0.00090	−0.0904	−0.9408	+0.1229	*−0.155	−111.82	−5.98	*−2.91	0.7472
		s.d.	= (3.009)	--------	--------	(0.1145)	(0.1212)	(0.404)	(0.535)	(0.597)	--------	(0.00034)	(0.0304)	(0.6434)	(0.0794)	(1.259)	(52.11)	(3.37)	(5.28)	------
6B	(3)	AUMA (even)	= +4.166	--------	--------	+0.2649	+0.1891	+1.445	−1.789	−1.600	--------	+0.00071	−0.0361	*−0.2067	+0.1303	−2.772	*−36.64	*−0.37	−10.06	0.7197
		s.d.	= (2.759)	--------	--------	(0.1016)	(0.1242)	(0.301)	(0.656)	(0.526)	--------	(0.00042)	(0.0257)	(0.6999)	(0.0869)	(1.050)	(55.16)	(3.29)	(6.58)	------

[1] 147 cements; Avg=12.804×10³ psi; S.D.=1.150×10³ psi. [2] 74 cements. [3] 73 cements. *Coef./s.d. ratio less than 1.

Table 8–26. *Coefficients for equations relating the compressive strength of mortars of NAE cements, cured with high pressure steam after 24 hrs, to various independent variables (AUMA)*

Equation	Note	psi×10⁻³	Const.	C_3A	C_2S	SiO_2	Fe_2O_3	SO_3	Na_2O	K_2O	APF	WAGN	Air 1:4 mortar	Insol	MgO	SrO	Rb	Ba	V	S.D.
1	(1)	AUMA	= +9.859	−0.0669	+0.0438	------	------	+0.967	−2.030	−1.334	+0.000699	------	−0.0765	−1.248	------	------	------	------	------	0.7429
		s.d.	= (0.797)	(0.0276)	(0.0119)	------	------	(0.240)	(0.411)	(0.340)	(0.000159)	------	(0.0400)	(0.509)	------	------	------	------	------	------
2	(1)	AUMA	= +9.935	−0.0486	+0.0493	------	------	+1.196	−1.788	−1.004	+0.000562	------	−0.0803	−1.366	------	−1.844	−100.57	−3.26	*−3.08	0.6993
		s.d.	= (0.772)	(0.0284)	(0.0113)	------	------	(0.233)	(0.415)	(0.353)	(0.000156)	------	(0.0382)	(0.484)	------	(0.789)	(35.77)	(2.11)	(3.87)	------
2A	(2)	AUMA (odd)	= +9.705	−0.0653	+0.0466	------	------	+1.350	−1.578	−0.813	+0.000667	------	−0.1378	−1.715	------	*−1.116	−120.55	−5.64	−2.75	0.7414
		s.d.	= (1.093)	(0.0443)	(0.0159)	------	------	(0.382)	(0.613)	(0.574)	(0.000240)	------	(0.0676)	(0.661)	------	(1.382)	(51.70)	(3.57)	(6.39)	------
2B	(3)	AUMA (even)	= +10.128	*−0.0331	+0.0548	------	------	+1.281	−2.207	−1.584	+0.000384	------	*−0.0246	−1.060	------	−2.491	*−51.90	*−1.63	−8.81	0.6874
		s.d.	= (1.232)	(0.0474)	(0.0194)	------	------	(0.342)	(0.688)	(0.542)	(0.000225)	------	(0.0492)	(0.864)	------	(1.038)	(55.35)	(2.98)	(5.17)	------
3	(1)	AUMA	= +9.648	−0.0386	+0.0442	------	------	+1.370	−1.815	−1.112	------	+0.00102	−0.0618	−1.135	------	−2.194	−90.87	−3.04	−4.83	0.7030
		s.d.	= (0.855)	(0.0295)	(0.0110)	------	------	(0.213)	(0.417)	(0.348)	------	(0.00030)	(0.0386)	(0.483)	------	(0.794)	(36.16)	(2.13)	(3.84)	------
4	(1)	AUMA	= +1.066	------	------	+0.3686	+0.2187	+1.193	−1.832	−1.352	+0.000653	------	−0.0871	−1.104	+0.1566	------	------	------	------	0.7449
		s.d.	= (1.903)	------	------	(0.0683)	(0.0849)	(0.252)	(0.403)	(0.365)	(0.000149)	------	(0.0408)	(0.500)	(0.0558)	------	------	------	------	------
5	(1)	AUMA	= +1.525	------	------	+0.3711	+0.2048	+1.429	−1.565	−1.002	+0.000485	------	−0.0904	−1.113	+0.1261	−1.666	−89.38	−3.09	*−3.90	0.7083
		s.d.	= (1.939)	------	------	(0.0707)	(0.0820)	(0.249)	(0.416)	(0.376)	(0.000148)	------	(0.0395)	(0.479)	(0.0540)	(0.786)	(35.95)	(2.17)	(3.96)	------
6	(1)	AUMA	= +2.585	------	------	+0.3232	+0.1819	+1.569	−1.618	−1.116	------	+0.00081	−0.0734	−0.939	+0.1020	−1.992	−83.35	−3.06	−5.30	0.7159
		s.d.	= (1.910)	------	------	(0.0724)	(0.0828)	(0.237)	(0.420)	(0.374)	------	(0.00029)	(0.0400)	(0.485)	(0.5455)	(0.787)	(36.65)	(2.20)	(3.97)	------
6A	(2)	AUMA (odd)	= +0.932	------	------	+0.3650	+0.1813	+1.825	−1.431	−0.823	------	+0.00107	−0.1296	−1.364	+0.1010	−1.368	−118.92	−6.17	*+0.74	0.7562
		s.d.	= (3.112)	------	------	(0.1204)	(0.1347)	(0.387)	(0.633)	(0.619)	------	(0.00045)	(0.0731)	(0.681)	(0.0803)	(1.336)	(52.95)	(3.61)	(6.47)	------
6B	(3)	AUMA (even)	= +3.075	------	------	+0.3158	+0.1815	+1.519	−1.768	−1.800	------	+0.00058	*−0.0285	*−0.240	+0.1661	−2.789	*−12.79	*+0.26	−9.72	0.6974
		s.d.	= (2.644)	------	------	(0.0965)	(0.1152)	(0.334)	(0.669)	(0.539)	------	(0.00042)	(0.0496)	(0.763)	(0.0852)	(1.073)	(56.51)	(3.29)	(5.35)	------

[1] 139 cements; Avg=12.847×10³ psi; S.D.=1.1386×10³ psi. [2] 70 cements. [3] 69 cements. *Coef./s.d. ratio less than 1.

With the addition of the 4 trace elements, SrO, Rb, Ba, and V in eqs 2 and 6, further significant reductions in the S.D. values were attained although the coefficients for neither SrO, Ba, nor V were highly significant. In this case, unlike those presented above, the use of air-permeability rather than Wagner fineness (eq 3) did not result in an increased S.D.

In eqs 2A and 2B calculated for the "odds" and "evens" in the array of cements, SrO, Ba, and V, as well as Insol, had coef./s.d. ratios less than one in one or the other of the equations. In eqs 6A, and 6B, Rb also had a coef./s.d. ratio less than 1.

The equations calculated for the NAE cements alone, presented in table 8–26, are in close agreement with those calculated for both AE and NAE cements. It may be noted, however, that the coefficient for C_3A which was of questionable significance in eq 2 and 3 had a coef./s.d. ratio less than 1 in eq 2B. The variable (air, 1:4 mortar) also had coef./s.d. ratios less than one in eqs 2B and 6B in table 8–26 for the NAE cements.

The estimated contributions of the different variables to the compressive strength were calculated from their coefficients as obtained in eq 3 of table 8–26 and are presented in table 8–27 together with the calculated ranges of contributions to the compressive strength. Increases in C_2S, SO_3, and fineness were associated with higher compressive strength values. Increases in Na_2O, K_2O, SrO, Rb, and possibly Insol, were associated with lower strength values. Increases in C_3A, air content, Ba, and V, though of doubtful significance, may possibly be associated with lower compressive strength.

TABLE 8–27. *Calculated contributions of independent variables to the compressive strength of mortar cubes, cured with high-pressure steam after 24 hrs, and tested dry, (AUMA) and the calculated ranges of such contributions*

Independent variable	Range of variable (percent)	Coefficient from eq (3) table 8–26	Calculated contribution to AUMA (×10⁻³)	Calculated range of contribution to AUMA (×10⁻³)
			Const. = +9.648	
C_3A**	1 to 15	−0.0386	−0.039 to −0.579	0.540
C_2S	5 to 50	+0.0442	+0.221 to +2.210	1.989
SO_3	1.2 to 3.0	+1.370	+1.644 to +4.110	2.466
Na_2O	0 to 0.7	−1.815	0 to −1.271	1.271
K_2O	0 to 1.1	−1.112	0 to −1.223	1.223
WAGN	*1200 to 3000	+0.00102	+1.224 to +3.060	1.836
Air, 1:4 mortar**	1 to 21	−0.0618	−0.062 to −1.298	1.236
Insol	0 to 1.0	−1.135	0 to −1.135	1.135
SrO	0 to 0.4	−2.194	0 to −0.878	0.878
Rb	0 to 0.01	−90.87	0 to −0.909	0.909
Ba**	0 to 0.2	−3.04	0 to −0.608	0.608
V**	0 to 0.1	−4.83	0 to −0.483	0.483

*cm^2/g.
**Coefficient of dubtful significance as coef./s.d. ratio was less than 2.

TABLE 8–28. *"F" ratios for significance of reduction of variance due to added variables*

Table	Equations	"F" ratio	D.F.	Critical "F" ratio $\alpha=0.01$	Critical "F" ratio $\alpha=0.05$
8–5	1, 2	8.16	3:139	3.92	2.68
8–5	4, 5	13.65	2:137	4.75	3.07
8–6	1, 2	7.20	3:131	3.93	2.68
8–6	4, 5	10.99	2:129	4.76	3.07
8–9	1, 2	3.43	5:133	3.16	2.28
8–9	4, 5	5.50	3:135	3.92	2.68
8–10	1, 2	3.97	5:124	3.16	2.28
8–10	4, 5	5.02	3:126	3.94	2.68
8–13	1, 2	10.16	3:135	3.92	2.68
8–13	4, 5	10.11	3:135	3.92	2.68
8–14	1, 2	9.05	3:126	3.94	2.68
8–14	4, 5	9.42	3:126	3.94	2.68
8–17	1, 2	3.38	4:135	3.46	2.45
8–18	1, 2	3.58	4:126	3.47	2.45
8–21	1, 2	7.58	5:134	3.16	2.28
8–21	4, 5	7.43	5:135	3.16	2.28
8–22	1, 2	8.07	5:125	3.16	2.28
8–22	4, 5	10.14	5:126	3.16	2.28
8–25	1, 2	4.64	4:134	3.46	2.45
8–25	4, 5	4.07	4:133	3.46	2.45
8–26	1, 2	5.18	4:126	3.47	2.45
8–26	4, 5	4.42	4:125	3.47	2.45

6. Discussion

6.1. Variables Associated With Strength After Different Curing Conditions

In order to compare more easily the variables associated with the compressive strength after the different curing conditions, a single equation was selected from each of the previously presented tables for the NAE cements. These are presented in table 8–29. As in table 7–77 of the previous section of this series of articles, the equations are here presented vertically instead of horizontally. Also presented are the coef./s.d. ratios and the calculated ranges of the contributions of the different variables. A coef./s.d. ratio of 3 or greater is considered significant although there is a probability of one percent of this ratio occurring by chance alone. Coef./s.d. ratios between 2 and 3 may indicate a significant relationship, whereas if the value is below 2 it is questionable whether the variable is truly significant and further information relative to its role in affecting compressive strength would be desirable.

In comparing the variables associated with the compressive strength of moist-air-cured specimens, WAGR, with those of the STGR and STMA specimens, it may be noted that the variables C_3A, SO_3, and K_2O may be associated with the STGR values and are probably associated with the STMA values. They did not appear in the equation for the normal-23 °C-cure, WAGR values, because the coef./s.d. ratios were less than 1. It would appear then, that possible consideration should be given to variations of these variables and to P and Li in addition, in any accel-

TABLE 8–29. *Coeffcients, coef./s.d. ratios, and calculated ranges of contributions of independent variables associated with compressive strength values after the different curing conditions* [1]

Equation No.	2	2	2	2	2	3
Table No.	8–6	8–10	8–14	8–18	8–22	8–26
Dependent variable	WAGR =	WAMA =	STGR =	STMA =	AUGR =	AUMA =
Constant, coef	+3.609	+2.691	−2.094	−3.092	−5.291	+9.648
C_3A, coef		+0.0823	+0.0475	+0.0512	+0.1095	**−0.0386
coef./s.d.		2.8	2.4	3.5	3.7	1.3
calculated range*		1.152	0.665	0.717	1.533	0.540
C_3S coef	+0.0413	+0.0569	+0.0853	+0.0749	+0.1640	
coef./s.d.	5.5	5.6	10.4	11.7	5.9	
calculated range	1.858	2.560	3.838	3.370	7.380	
C_2S, coef					+0.1540	+0.0442
coef./s.d.					5.3	4.0
calculated range					6.930	1.989
C_4AF, coef		**+0.0509				
coef./s.d.		1.6				
calculated range		0.763				
SO_3, coef		**+0.4166	+0.4949	+0.5280	+1.0753	+1.370
coef./s.d.		1.99	2.9	3.8	4.4	6.4
calculated range		0.750	0.891	0.950	1.936	2.466
Loss, coef	−0.2000	−0.3200	−0.3111	−0.3954		
coef./s.d.	2.3	2.7	3.2	5.6		
calculated range	0.600	0.960	0.933	1.186		
Insol, coef	−0.7850	−0.8495				−1.135
coef./s.d.	2.3	1.9				2.3
calculated range	0.785	0.850				1.135
MgO, coef				**−0.0525		
coef,/s.d.				1.5		
calculated range				0.262		
Na_2O, coef		**−0.3843			−2.676	−1.815
coef,/s.d.		1.01			6.8	4.4
calculated range		0.269			1.873	1.270
K_2O, coef			+0.5892	+0.6548		−1.112
coef./s.d.			2.3	3.1		3.2
calculated range			0.648	0.720		1.223
WAGN, coef	+0.00180	+0.00174	+0.00223	+0.00175	+0.00300	+0.00102
coef./s.d.	9.5	6.2	9.3	9.2	10.0	3.4
calculated range	3.240	3.132	4.014	3.150	5.400	1.836
Air 1:4 mortar, coef	−0.1420	−0.1407	−0.0967	−0.0951	−0.1581	**−0.0618
coef./s.d.	5.6	3.8	3.4	4.0	4.1	1.6
calculated range	2.840	2.814	1.934	1.902	3.162	1.236
Ba, coef	−3.71	−4.772	−5.64	−3.021	−5.169	**−3.04
coef./s.d.	2.7	2.7	3.8	2.6	2.5	1.4
calculated range	0.742	0.954	1.128	0.604	1.034	0.608
Cr, coef					+38.84	
coef./s.d.					2.7	
calculated range					0.777	
Cu, coef	−17.81	**−9.37	**−6.98	−10.31	−22.02	
coef./s.d.	3.3	1.3	1.2	2.2	3.0	
calculated range	0.890	0.468	0.349	0.515	1.101	
Li, coef				+26.97	+97.92	
coef./s.d.				2.3	5.0	
calculated range				0.539	1.958	
P, coef			−1.46			
coef./s.d.			3.4			
calculated range			0.730			
Rb, coef						−90.87
coef./s.d.						2.5
calculated range						0.909
SrO, coef		**−1.325				−2.194
coef,/s.d.		1.8				2.8
calculated range		0.530				0.878
V, coef					**−5.71	**−4.83
coef./s.d.					1.5	1.3
calculated range					0.571	0.483

[1] The coefficients and calculated ranges of their contributions must be multiplied by 1000 to obtain the respective values in psi.
*The calculated range was computed from the range of values for the cements times the coefficient for each of the independent variables.
**The independent variable is probably not significant as the coef./s.d. ratio is less than 2.

erated strength test of mortars if cements of different composition are involved. This could apply to cement from a single source as well as cements from different sources.

The variables C_3A, C_3S, and C_2S were all associated with the compressive strength of AUGR specimens, autoclaved after 5 hr of moist curing but, of these, only C_2S was associated with the compressive strength of the AUMA specimens, autoclaved after 24 hr. The coefficient for SO_3 was significant in both the AUGR and AUMA equations as well as in the STMA equations but of borderline significance in the STGR equation. (In table 7–77 of the previous section, the coefficient for SO_3 was probably significant at 1, 3 and 7 days but not at 28 days for the water-stored 1:2.75 mortars.) The coef./s.d. for SO_3 was less than 1 in the equation WAGR for 28-day moist-air-cured specimens in this series of tests. The SO_3 contents of the cements were probably lower than the optimum values, or than those permitted in present specifications. To extrapolate the effects of SO_3 to the higher values now permitted may be of questionable value.

The coefficients for Wagner fineness of the cements were highly significant and related to the compressive strength with each of the curing conditions used. Although the equations in this table were for NAE cements, the coefficient for (air, 1:4 mortar) were significant at the one-percent level for all but the AUMA specimens. (Where the AE cements were included in table 8–25, the coefficient for air entrainment was also significant in this case.)

The coefficients for Loss-on-ignition were significant in equations for the low-pressure-steam-cured specimens, were possibly significant in equations for specimens cured at normal temperatures, but had coef./s.d. values less than 1 in the equations for the autoclaved specimens.

The coefficient for Na_2O was significant with both autoclave treatments and the coefficients had negative signs. (Referring back to table 7–77 of the previous section, the coefficients for Na_2O were also significant and with a negative sign for the 1, 5, and 10-year tests of the 1:2.75 mortar but were not significant at the early ages.) The coefficients for K_2O were probably significant, and were positive in equations for the low-pressure-steam-cured specimens. This variable had a coef./s.d. ratio less than 1 in the equations for AUGR but appeared significant, having a negative sign in the AUMA equation. (The coefficient for K_2O was significant and positive at 1 day, and probably significant at 3 and 7 day tests but not at later ages as reported in table 7–77 of the previous section.)

Of the other alkalies, the coefficient for Li was significant in the equation for the AUGR specimens, and possibly so for the equation for STMA specimens. The coefficient for Rb was significant at the 5-percent level in the equations for AUMA specimens. The coefficients for Li were positive, whereas that for Rb was negative.

The coefficients for the other trace elements were, in general, not highly significant, and except for Ba and Cu, not found consistently in equations for compressive strength after the different curing treatments. The coefficient for Ba was significant in the STGR equation and possibly significant in the others except the AUMA equation. Cu had a coef./s.d. ratio greater than 3 for the 28 day moist-air-stored, and the AUGR specimens but the coefficient was probably not significant under the other curing conditions.

Reference was previously made to differences in the variables associated with the low-pressure-steam-cured compressive strength and the strength obtained after curing at normal temperatures. The last 2 equations in table 8–29 indicate that the variables can also differ, depending on either the age at which the specimens are autoclaved, (5 or 24 hr) or the period of autoclaving (11 hr or 4 hr) for the AUGR and AUMA specimens respectively. The curing cycle used for the AUMA specimens would be preferable for use as a laboratory test method because of the difficulty of removing specimens from their molds at 5 hr or earlier as used in commercial practice.

6.2. Relationship of Compressive Strength Values of 1:3.525 (Cement to Silica) Mortars When Cured Under Different Conditions

A series of linear equations are presented in table 8–30 to indicate the relationships between compressive strengths of the mortars of this series achieved by different curing methods. Presented also are values for reduction in variance, "F" values, resulting from the use of these equations. "F" values, greater than 4.75 (for 2:150 degrees of freedom) or 5.03 (for 2:55 degrees of freedom) are significant at the 1 percent level. Each of the equations indicated that there was a statistically significant relationship. It may be noted, however, that the "F" values ranged from a low of 6.8 to a high of 656.

Plots were made of the relationships of the compressive-strength values obtained when using the different curing conditions. Six of these plots were selected to illustrate the spread of test values corresponding to a range of S.D. and "F" values obtained in some of the equations of table 8–30, namely the first 5 equations and eq (18) which had the highest "F" values in this series. These plots were all made using the same scale ranges, but it was necessary to shift the origin of the scale to accommodate the different values. These plots do not fully indicate the concentration of points where one dot on the grid may represent more than one value when plotted by means of the computer.

TABLE 8–30. *Relationships of compressive strengths of mortar cubes, cured and tested under various conditions as indicated in the text* (*see p. 69*)

Equation	Dependent variable	Const.	Independent variable	S.D.	"F."	D.F.
1	WAGR= s.d. =	+0.348 (0.245)	+0.805 WAMA (0.028)	0.360	410	2:149
2	WAGR s.d. =	+2.937 (0.234)	+0.675 STGR (0.036)	0.497	180	2:149
3	WAGR= s.d.	+3.960 (0.207)	+0.811 STMA (0.049)	0.544	138	2:149
4	WAGR= s.d. =	+0.743 (0.521)	+0.488 AUGR (0.039)	0.637	80	2:149
5	WAGR= s.d. =	+2.964 (0.753)	+0.339 AUMA (0.059)	0.830	17	2:149
6	WAMA= s.d. =	+0.964 (0.271)	+1.052 WAGR (.037)	0.411	410	2:149
7	WAMA= s.d. =	+3.487 (0.245)	+0.797 STGR (0.037)	0.520	229	2:149
8	WAMA= s.d. =	+4.469 (0.190)	+1.012 STMA (0.045)	0.500	254	2:149
9	WAMA= s.d. =	+1.405 (0.617)	+0.539 AUGR (0.046)	0.754	70	2:149
10	STGR = s.d. =	+1.678 (0.164)	+1.163 STMA (0.039)	0.431	451	2:149
11	STGR = s.d. =	−1.244 (0.687)	+0.574 AUGR (0.051)	0.840	64	2:149
12	STRG = s.d. =	+2.229 (0.979)	+0.332 AUMA (0.076)	1.078	10	2:149
13	STMA = s.d. =	−1.434 (0.588)	+0.414 AUGR (0.044)	0.720	45	2:149
14	STMA = s.d. =	+1.226 (0.793)	+0.227 AUMA (0.062)	0.873	6.8	2:149
15	AUGR= s.d. =	+8.239 (0.468)	+0.805 STGR (0.071)	0.994	64	2:149
16	AUGR= s.d. =	+9.682 (0.406)	+0.913 STMA (0.096)	1.069	45	2:149
17	AUGR= s.d. =	+3.437 (0.913)	+0.782 AUMA (0.071)	1.006	61	2:149
18	DRYS = s.d. =	+1.636 (0.166)	+1.165 WETS (0.032)	0.244	656	2:55
19	WAGR= s.d. =	+3.234 (0.282)	+0.877 WETS (0.055)	0.415	129	2:55
20	WAMA= s.d. =	+3.597 (0.269)	+1.087 WETS (0.052)	0.396	217	2:55
21	STGR = s.d. =	+0.953 (0.338)	+1.178 WETS (0.065)	0.496	162	2:55
22	STMA = s.d. =	−0.820 (0.220)	+1.043 WETS (0.043)	0.323	300	2:55
23	AUGR= s.d. =	+8.868 (0.628)	+0.993 WETS (0.122)	0.924	33	2:55
24	AUMA= s.d. =	+10.81 (0.56)	+0.475 WETS (0.109)	0.828	9	2:55

It may be noted in figure 8–2, a plot of the relationship presented in eqs 5 of table 8–30 that there is a considerable scatter of results. The "F" value was 17. There appears to be somewhat less scatter in figure 8–3 (eq 4 table 8–30, "F" value 80). In figures 8–4 and 8–5 and 8–6 with "F" values of 138, 180, and 410 respectively, (eqs 3, 2, and 1 of table 8–30) there was less scatter as the "F" values increased. The values for the WETS and DRYS (both steam cured for 24 hr), when plotted in figure 8–7, do not indicate as broad a band as was indicated in the previous figures. There were fewer values plotted and used in the equation (eq 18 table 8–30, "F" value of 656).

It may be noted in table 8–30 that the numerical values for "F" in eqs 7 and 8 are slightly higher than those of eqs 2 and 3. This may then indicate that the compressive strength of steam-cured specimens, STGR and STMA, are more reliable in predicting the compressive strength of the 28-day specimens, air-dried for 2 weeks before testing, WAMA, than those cured continuously in moist air for the 28 days, WAGR. The numerical value for "F" in eq 10 relating the compressive strength

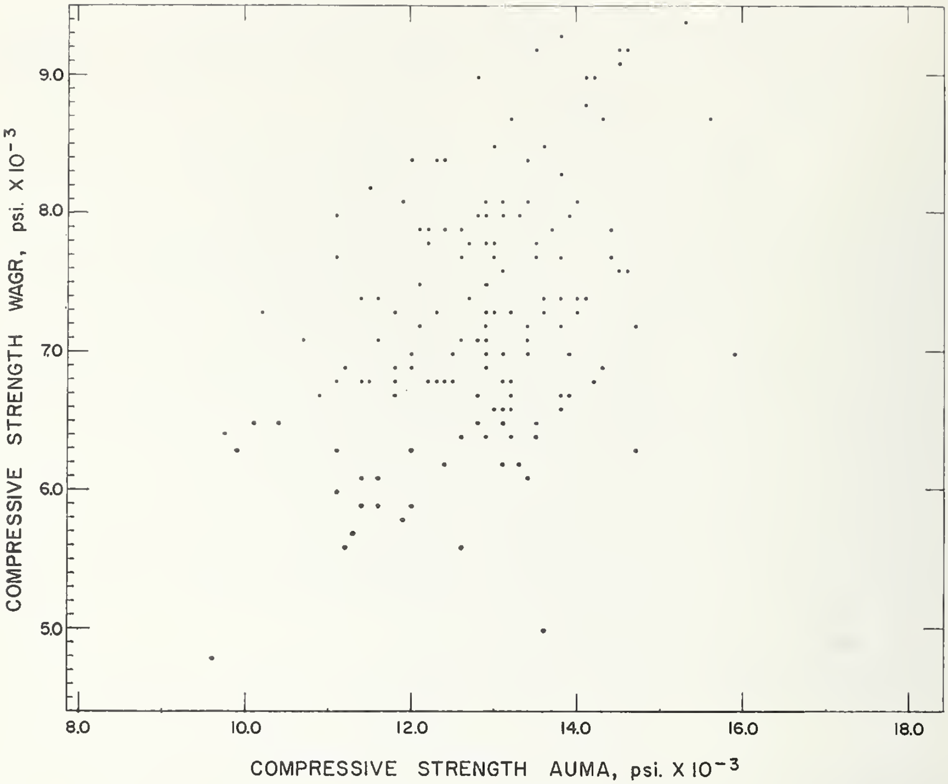

FIGURE 8–2. *Results of plotting the 28 day compressive strength of moist-air-stored mortar cubes versus the compressive strength of cubes of identical mortars, moist cured for 24 hr, then autoclaved at 10 atm for 4 hr, then oven dried.*

(See eq 5, table 8–30.)

of STGR and STMA, (the one steam cured after 5 hr, the other after 24 hr) was 451 which would indicate a rather small scatter of points. The "F" of eq 17 relating the compressive strength of AUMA and AUGR (the one autoclaved after 24 hr and the other after 5 hr) was 61, and, judging by figure 8–3, this would indicate a fairly broad scatter of points. This then indicates that a laboratory evaluation test of the suitability of a cement or other ingredients used in autoclaved-cured products must simulate as closely as possible the curing cycle or cycles employed in the commercial production. It is also indicated that, with some cements, higher strength values can be obtained by autoclaving after a 24-hr presteaming period but with other cements a shorter period may be advantageous.

Reference has been made in previous subsections and tables 8–4, 8–8, 8–12, 8–16, 8–20 and 8–24 to the frequency distributions of the strength values of the different types of cement after the different curing conditions. In most of these tables, the values for the Type III cements were generally among the upper values in the frequency-distribution curves for all the cements. The cements classified as Types IV, V had 28-day compressive strength values about the same as for all cements for the moist-air-stored specimens, WAGR, (table 8–4) and when moist-air-cured for only 14 days and then air-dried, WAMA, (table 8–8) but their strength values were relatively low when cured by low-pressure steam, STGR, STMA (tables 8–12 and 8–16). When autoclaved after 5 hr, AUGR, the average compressive strength values were about the same as the average of all cements (table 8–20), but if autoclaved after 24 hr, AUMA, the the strengths were generally above the average of all combined (table 8–24). The broad overlapping and range of the compressive strength vlaues of the Types I and II cements make it impossible to attribute any advantage to either of these types in so far as compressive strength is concerned.

The frequency-distribution curves for all the cements indicated considerable overlapping of the compressive-strength values when the cements were cured under the different conditions. This has been indicated in figure 8–1. In comparing these distribution curves, consideration must also be given to the time of curing as well as to whether the specimens were tested in a wet or dry condition.

The high-pressure-steam-cured specimens AUMA and AUGR had higher compressive strengths than either those cured in moist air or those cured in steam at atmospheric pressure

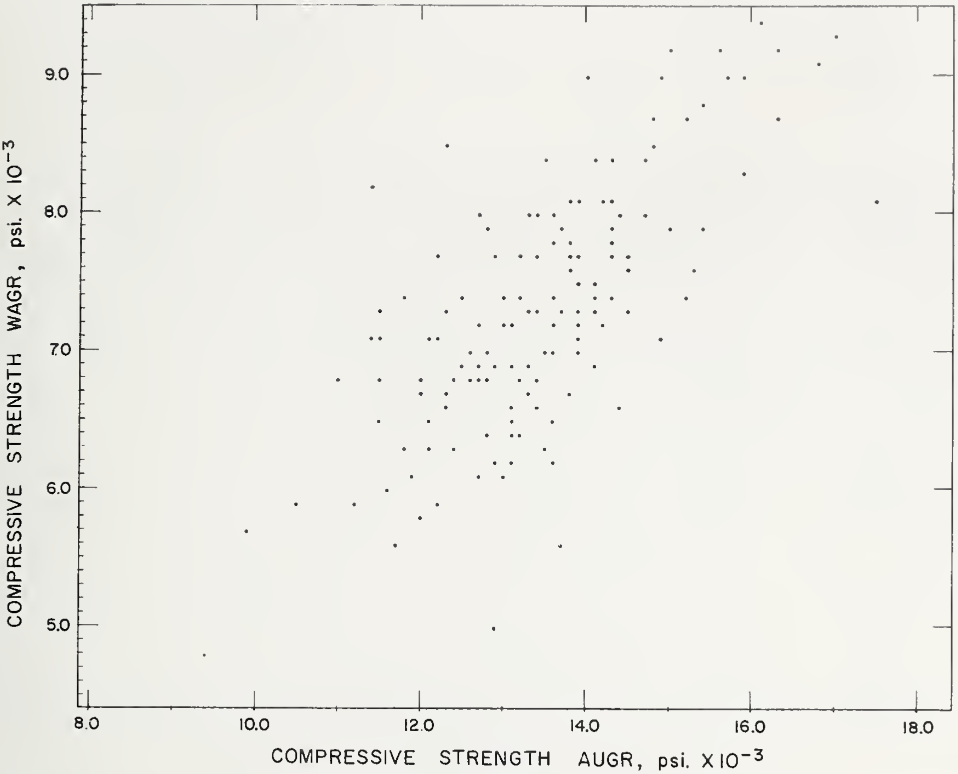

FIGURE 8–3. *Results of plotting the 28 day compressive strength of moist-air-stored mortar cubes versus the compressive strength of cubes of identical mortars, moist cured for 5 hr, then autoclaved at 10 atm for 11 hr, then oven dried.*

(See eq 4, table 8–30.)

STGR and STMA. The distribution curves for the low-pressure-steam-cured specimens STMA and STGR indicated lower compressive strengths than the 28-day moist-air-cured WAGR, or the WAMA specimens which had 14 days of moist curing and then 14 days of air drying. For both steam-cured and autoclaved specimens, those which started steam curing green achieved significantly higher average strength than those whose curing started at 24 hr.

TABLE 8–31. *Comparison of average compressive strengths and S.D. values obtained for the cements when cured and tested under the different conditions as explained in the text*

Identification	AE+NAE cements			NAE cements		
	Comp. strength p.s.i.	S.D. p.s.i.	Coef. of variation %	Comp. strength p.s.i.	S.D. p.s.i.	Coef. of variation %
WAGR	7323	907	12.4	7377	879	11.9
WAMA	8653	1037	12.0	8699	1028	11.8
STGR	6491	1141	17.6	6535	1140	17.4
STMA	4119	903	21.9	4133	908	22.0
AUGR	13414	1332	9.9	13493	1301	9.6
AUMA	12804	1150	9.0	12847	1139	8.9
WETS	5063	1014	20.0	----------	------	----------
DRYS	7535	1206	16.0	----------	------	----------

The average compressive-strength values previously presented in individual tables are summarized in table 8–31 together with calculated coefficient-of-variation values. The averages coincide fairly closely with the maxima of the frequency distribution curves.

The curves presented in figure 8–8 are regression lines drawn from equations relating the 28-day moist-air-cured compressive strength values WAGR to those obtained after the other curing conditions. A limited number of cements (65) were available for the WETS and DRYS (curves 2 and 4), and because of this, only the same cements were used in computing the other relationships. The cements used in the equations for figure 8–8 had STGR and STMA compressive-strength values about 400 psi higher than the averages for all the cements for the same curing conditions. The calculated S.D. values were also slightly greater than when all cements were included. Included also is the line denoting equality (dashed line labeled 5). The longer steaming period for the WETS, 24 hr at 66° C (curve 2) against 7½ hr at 71° C for STMA (curve 1) increased the strength values to some extent. Both groups of cement mortars were tested when wet, but were also both below those of

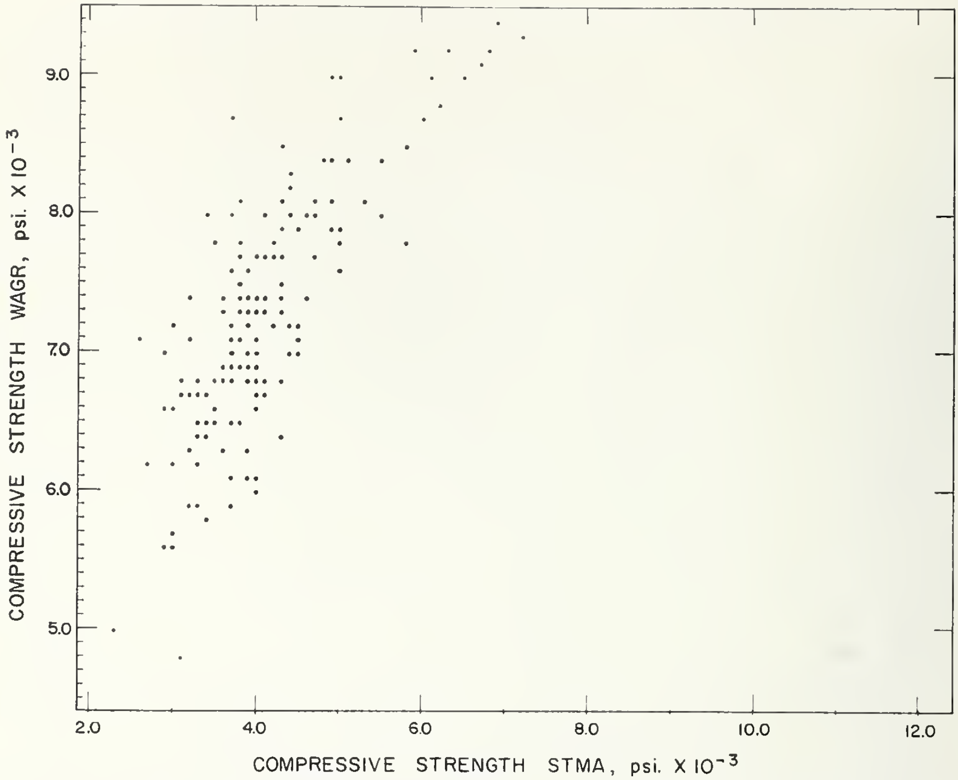

FIGURE 8–4. *Results of plotting the 28 day compressive strength of moist-air-stored mortar cubes versus the compressive strength of cubes of identical mortars, moist cured for 24 hr, then steam cured at 71 °C for 7.5 hr and tested wet.*

(See eq 3, table 8–30.)

curve 5. Similarly, the DRYS, steam cured 24 hr and air dried, (curve 4) indicated somewhat higher strength values than the STGR specimens (curve 3) steam cured about 12 hr then air-dried. The DRYS (curve 4) also had higher strength values than the WETS (curve 2). The curves 3 and 4 (STGR and DRYS) may be compared to curve 6 for specimens cured at normal temperatures 14 days and then air-dried WAMA. Although it appears that the slopes of many of the curves in this figure, especially 7 and 8, are much lower than that of line 5, this is probably not significant. Reference should again be made to figures 8–2 and 8–3 to appreciate the scatter that the computed curves in figure 8–8 do not indicate. The curves presented in figure 8–8 indicate only the general trends of the results obtained with the particular mortar used and the relative positions on the strength scale of the values obtained after the various curing conditions.

6.3. Estimated Standard Deviation of Duplicate Tests

The estimated standard deviations of duplicate determinations of the compressive strength values are presented in table 8–32. Also presented in this table are the S.D. values of calculated equations relating the various independent variables to the dependent variable. The equations selected for this purpose were the same as those used in table 8–29. The S.D. values of the duplicates were smaller than those of the equations in every instance. The S.D. values of the autoclaved specimens, AUGR and AUMA most nearly approached the S.D. values of the duplicates as indicated by the ratios in the last column.

6.4. Relationship of Compressive-Strength of Mortars in This Series to Those of 1:2.75 (Cement to Sand) Mortars Presented in the Previous Section

Another series of equations are presented in table 8–33 to indicate the relationship of the compressive-strength values of the 1:3.525 (cement to silica) mortars of this section, cured under different conditions to some of the strength values of 28 days to 5 years of the 1:2.75 (cement to graded Ottawa sand) mortars as reported in section 7 of this series. Presented also are the S.D. values, and the reduction in variance ("F" values) resulting from the fitting of the equations. With the number of degrees of freedom involved,

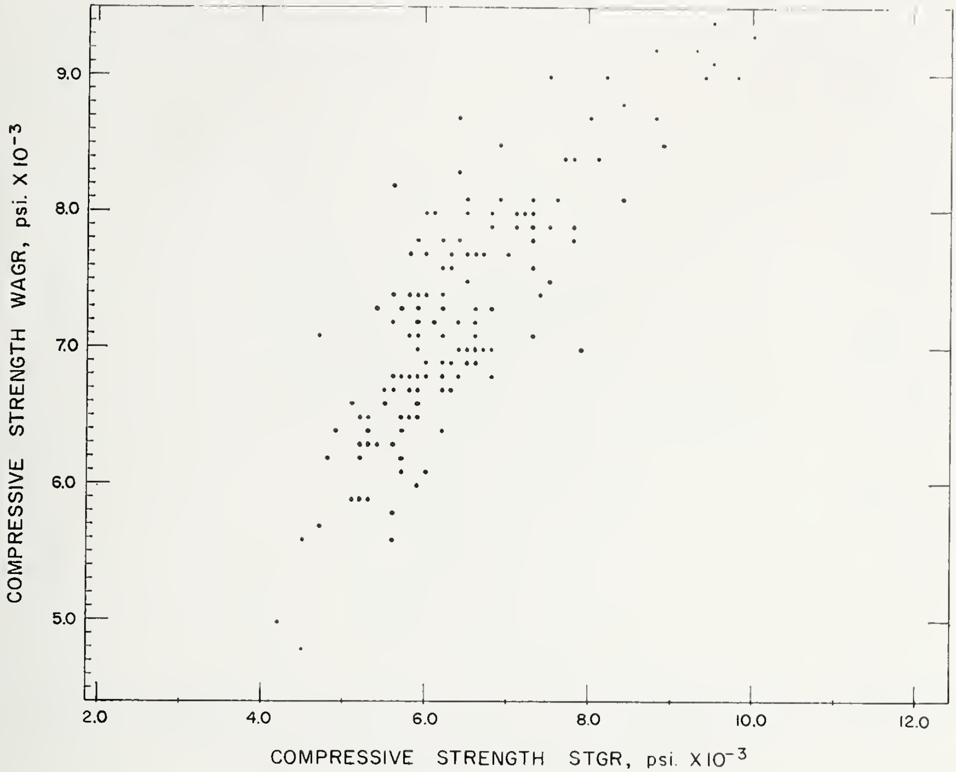

FIGURE 8–5. *Results of plotting the 28 day compressive strength of moist-air-cured mortar cubes versus the compressive strength of cubes of identical mortars, moist cured for 5 hr then steam cured at 66 °C for 12 hr, then air-dried at 23 °C, 50 percent R.H.*

(See eq 2, table 8-30.)

TABLE 8–32. *Comparison of S.D. values of pairs of duplicate determinations with those obtained in the fitted equations*

Identification	No. of duplicates	S.D. of duplicates	S.D. of equations	Ratio of S.D. values
WAGR	21	248	524	2.11
WAMA	21	391	643	1.64
STGR	21	350	544	1.55
STMA	20	163	414	2.54
AUGR	21	586	671	1.15
AUMA	21	511	699	1.37
WETS	10	184	------------	------------
DRYS	10	376	------------	------------

there was evidence of a relationship at the 1 percent probability level in all but eqs 28, 39, and 40. Other equations where the 5 year compressive strength values were used as the dependent variable (eqs 25, 26, 27, 29 and 30) also had relatively low numerical values for the reduction in variance when compared to eqs 1 and 2 where the age and curing conditions were more nearly the same. The relationship of the compressive strength of low-pressure-steam-cured specimens, to the 28-day compressive strength of the 1:2.75 mortars (eqs 3, 4, 31, and 32) had intermediate "F" values ranging from 78 to 132. The reduction in variance in eqs 5 and 6, relating the compressive strength of the autoclaved specimens to the 28 day strengths of the 1:2.75 mortars gave "F" values of 13 and 45. The reduction in variance values in eqs 9, 10, 11, 12, 15, 16, 17, 18, 21, 22, 23, 24, and 33 through 38, relating the compressive strengths of steam cured and autoclaved specimens to the 1-year compressive strengths of the 1:2.75 mortars were generally fairly low.

It was indicated in both figure 8–1 and in eqs 1 and 7 of table 8–33 that the compressive strengths of the 28-day moist-air-cured specimens, WAGR, were generally higher than those of the 1:2.75 (cement to sand) standard test mortars after both 28-day and 1-year water storage. A number of factors may be involved, including the pozzolanic action of the hydration products with the fine silica, the gradation of the sand, ratio of fines to coarse material, or possibly a lower air content.

6.5. Mix Proportions

The mix proportion used in the present series of tests was designed primarily with high-pressure-steam curing requirements in mind, where the use of finely ground silica or other pozzolanic material is highly desirable. The distributions of

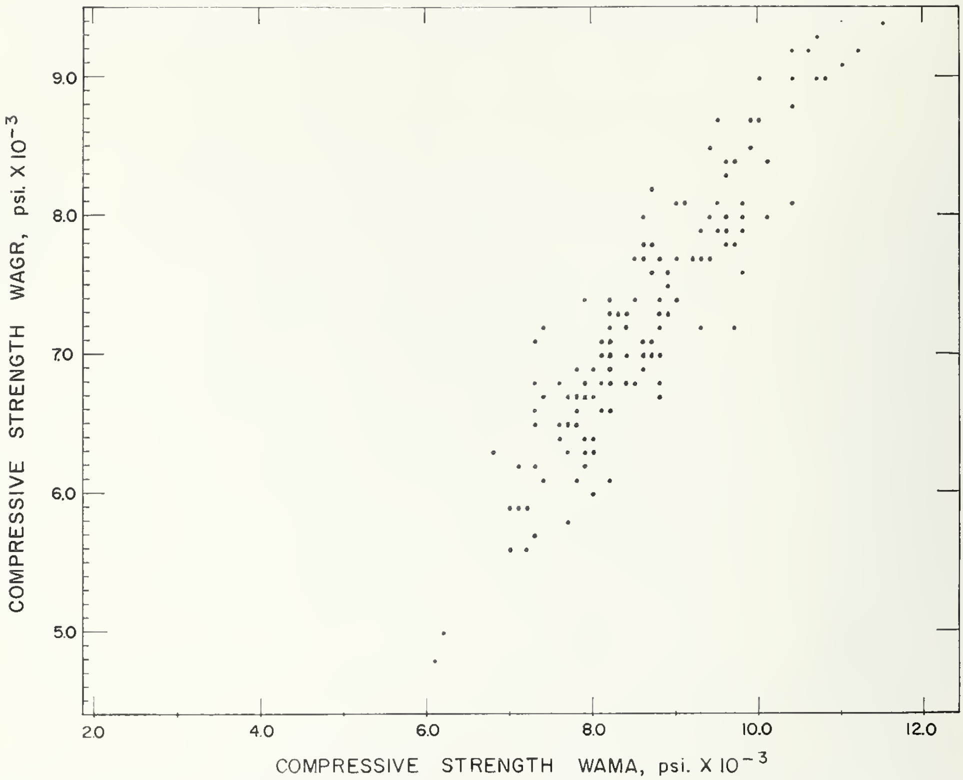

FIGURE 8–6. *Results of plotting the 28 day compressive strength of moist-air-cured mortar cubes versus the compressive strength of cubes of identical mortars, moist-air-cured for 14 days, then dried at 23 °C, 50 percent R.H. for 14 days and tested dry.*

(See eq 1, table 8–30.)

fines to coarse materials were computed three ways as follows:

A. (1 cement +0.19 sand pass #200 sieve) to 2.81 sand retained #200 sieve
B. (1 cement +0.24 sand pass #140 sieve) to 2.52 sand retained #140 sieve
C. (1 cement +0.43 sand pass #100 sieve) to 2.16 sand retained #100 sieve

In A, 16 percent of the cement may be considered replaced with finer silica, in B, 19 percent, and in C, 30 percent depending on whether the percentage passing the No. 200, the No. 140 or the No. 100 sieve is taken as the dividing line between reactive and nonreactive silica. Because of the fineness of the silica flour used in this series of tests, some pozzolanic activity may be expected at temperatures used for the low-pressure-steam curing and possibly also at laboratory temperatures. The quantity of silica fines used was lower than that found by Menzel [7] to give the optimum strength but it was considered that the fineness of the silica flour must also be taken into consideration.

6.6. Compressive Strength Versus Time of Set

A particular penetration resistance as determined by the time-of-setting test has been proposed as a criterion for the time at which steam curing of concrete specimens for purpose of accelerated testing should be started [19]. It was not possible in the present study to make time-of-set tests on the mortars and to use different times for starting the heating or steaming cycle. However, calculations were made of the relationships of the compressive strength values with the times of initial and final set of the neat portland cements. The results of these calculations are presented in table 8–34. The "F" ratio for reduction in variance must exceed 3.05 or 7.4 to indicate a significant relationship at the 5- or 1-percent probability levels, respectively.

A longer time of initial set of the neat cement may be associated (see eq 1) with a lower compressive strength when the low-pressure steam curing of the mortars was started at about 5 hr (STGR) and with a higher compressive strength (see eq 6) when the low-pressure steam curing was started after 24 hr. (STMA). There was no

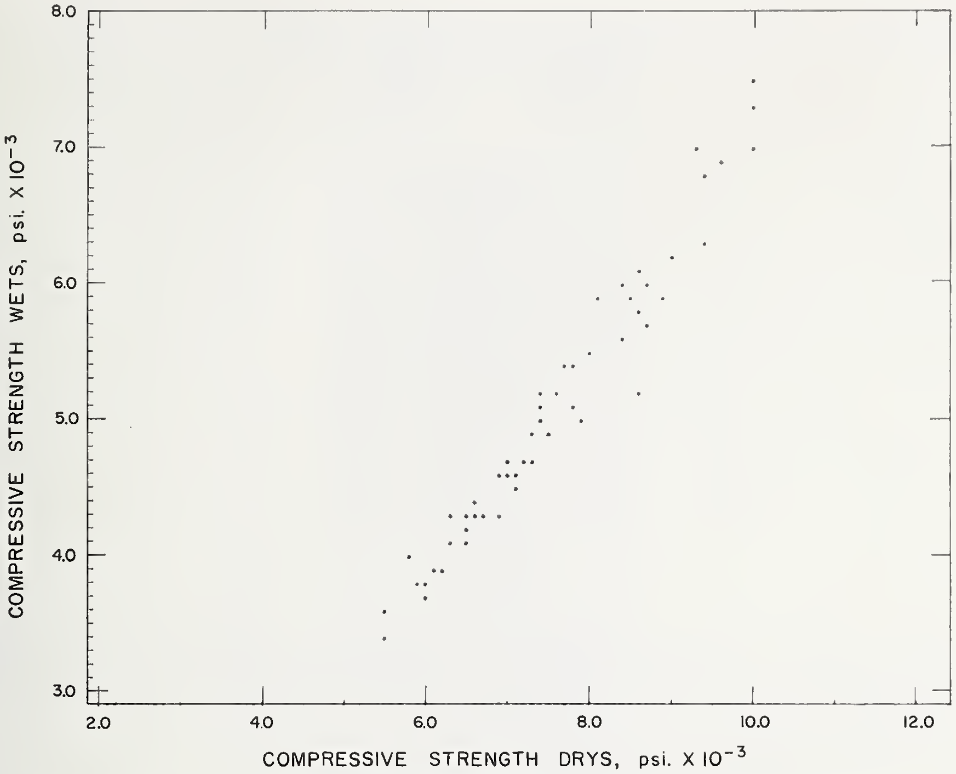

FIGURE 8–7. *Results of plotting the compressive strength of mortar cubes, moist-air-cured for 24 hours then steam cured for 24 hr and tested, versus the compressive strength of cubes of identical mortars which had an additional 14 days of air-drying at 23 °C 50 percent R.H.*

(See eq 15, table 8-30.)

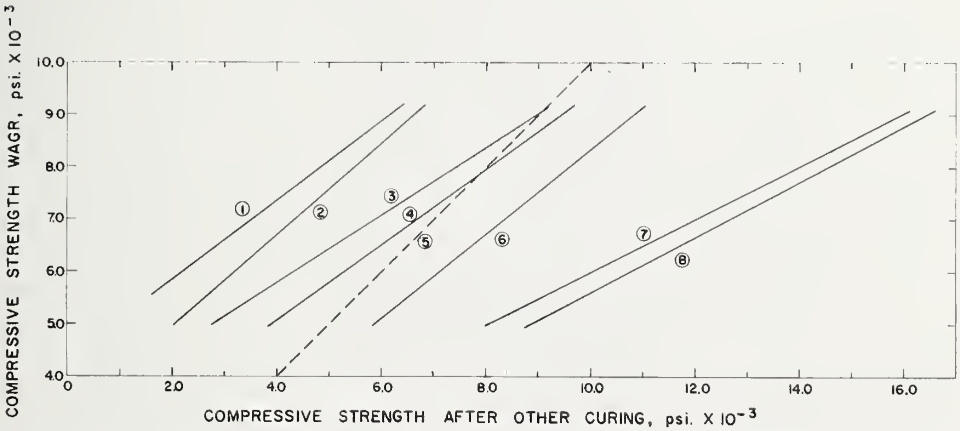

FIGURE 8–8. *Curves drawn from regression equations calculated for the 65 cements used for the "WETS" and "DRYS" and moist-air cured for 28 days versus the compressive strength of the same cements cured and tested under the various conditions.*

(1=WAGR versus STMA, 2=WAGR versus WETS, 3=WAGR versus STGR, 4=WAGR versus DRYS, 5=45° equality line, 6=WAGR versus WAMA, 7=WAGR versus AUMA, 8=WAGR versus AUGR. See text and table 8-3 for notations and details of curing and testing conditions.)

TABLE 8–33. *Relationships of compressive strengths of the mortars of this series to those of the standard 1:2.75 (cement to Ottawa sand) mortars of section 7*

Equation	Dependent variable	Const.	Independent variable	S.D.	"F"	D.F.
1	ST28 = s.d. =	−1.108 (0.291)	+0.846 WAGR (0.040)	0.439	229	2:146
2	ST28 = s.d. =	−1.296 (0.306)	+0.738 WAMA (0.035)	0.446	220	2:146
3	ST28 = s.d. =	+1.121 (0.264)	+0.611 STGR (0.040)	0.555	117	2:146
4	ST28 = s.d. =	+1.835 (0.205)	+0.787 STMA (0.048)	0.534	132	2:146
5	ST28 = s.d. =	−0.336 (0.578)	+0.403 AUGR (0.043)	0.705	45	2:146
6	ST28 = s.d. =	+1.233 (0.746)	+0.301 AUMA (0.058)	0.821	13	2:146
7	ST1Y= s.d. =	+2.192 (0.441)	+0.560 WAGR (0.060)	0.665	44	2:146
8	ST1Y= s.d. =	+2.855 (0.502)	+0.397 WAMA (0.058)	0.730	24	2:146
9	ST1Y= s.d. =	+4.814 (0.380)	+0.227 STGR (0.058)	0.800	7.8	2:146
10	ST1Y= s.d. =	+5.345 (0.313)	+0.229 STMA (0.074)	0.815	4.8	2:146
11	ST1Y= s.d. =	+1.235 (0.546)	+0.376 AUGR (0.040)	0.666	43	2 :146
12	ST1Y= s.d. =	+0.854 (0.616)	+0.424 AUMA (0.048)	0.678	39	2:146
13	ST1A= s.d. =	+0.929 (0.320)	+0.596 WAGR (0.043)	0.482	94	2:146
14	ST1A= s.d. =	+0.943 (0.346)	+0.502 WAMA (0.040)	0.504	80	2:146
15	ST1A= s.d. =	+2.242 (0.234)	+0.469 STGR (0.035)	0.492	87	2:146
16	ST1A= s.d. =	+2.831 (0.188)	+0.595 STMA (0.044)	0.488	90	2:146
17	ST1A= s.d. =	+0.820 (0.469)	+0.469 AUGR (0.035)	0.571	46	2:146
18	ST1A= s.d. =	+2.112 (0.608)	+0.248 AUMA (0.047)	0.669	14	2:146
19	ST1M= s.d. =	+1.398 (0.441)	+0.722 WAGR (0.060)	0.605	73	2:146
20	ST1M= s.d. =	+1.968 (0.511)	+0.545 WAMA (0.059)	0.745	43	2:146
21	ST1M= s.d. =	+4.197 (0.395)	+0.383 STGR (0.060)	0.831	20	2:146
22	ST1M= s.d. =	+4.868 (0.327)	+0.439 STMA (0.077)	0.850	16	2:146
23	ST1M= s.d. =	+0.580 (0.579)	+0.453 AUGR (0.043)	0.707	56	2:146
24	ST1M= s.d. =	+0.555 (0.685)	+0.478 AUMA (0.053)	0.754	40	2:146
25	ST5Y= s.d. =	+1.915 (0.586)	+0.577 WAGR (0.070)	0.783	34	2:146
26	ST5Y= s.d. =	+2.781 (0.586)	+0.388 WAMA (0.067)	0.854	17	2:146
27	ST5Y= s.d. =	+4.721 (0.434)	+0.219 STGR (0.066)	0.912	5.5	2:146
28	ST5Y= s.d. =	+5.392 (0.358)	+0.181 STMA (0.085)	0.932	2.3	2:146
29	ST5Y= s.d. =	+1.010 (0.648)	+0.381 AUGR (0.048)	0.790	32	2:146
30	ST5Y= s.d. =	+0.727 (0.732)	+0.422 AUMA (0.057)	0.806	28	2:146
31	ST28 = s.d. =	+0.992 (0.322)	+0.883 WETS (0.063)	0.470	99	2:54
32	ST28 = s.d. =	+0.012 (0.440)	+0.723 DRYS (0.058)	0.515	78	2:54

TABLE 8–33. *Relationships of compressive strengths of the mortars of this series to those of the standard 1:2.75 (cement to Ottawa sand) mortars of section 7*—Continued

Equation	Dependent variable	Const.	Independent variable	S.D.	"F"	D.F.
33	ST1Y= s.d. =	+4.959 (0.463)	+0.318 WETS (0.090)	0.676	6.2	2:54
34	ST1Y= s.d. =	+4.421 (0.568)	+0.285 DRYS (0.075)	0.666	7.3	2:54
35	ST1A= s.d. =	+1.984 (0.319)	+0.687 WETS (0.062)	0.466	61	2:54
36	ST1A= s.d. =	+1.132 (0.404)	+0.575 DRYS (0.053)	0.473	59	2:54
37	ST1M= s.d. =	+4.725 (0.474)	+0.495 WETS (0.092)	0.692	14	2:54
38	ST1M= s.d. =	+3.992 (0.580)	+0.430 DRYS (0.076)	0.680	16	2:54
39	ST5Y= s.d. =	+5.160 (0.486)	+0.242 WETS (0.094)	0.710	3.3	2:54
40	ST5Y= s.d. =	+4.794 (0.603)	+0.211 DRYS (0.079)	0.706	3.6	2:54

TABLE 8–34. *Relationships of compressive strengths of the mortars of this series to the time of set of neat cements of normal consistency and the early compressive strengths of the standard 1:2.75 (cement to Ottawa sand) mortars of section 7*

Eq. No.	Equation	S.D.	"F"	D.F.
1	STGR= +7.941 −0.4037 ISET s.d.= (0.513) (0.1402)	1.114	4.15	2:149
2	STGR= +6.920 −0.0658* FSET s.d.= (0.689) (0.1039)	1.143	0.20	2:149
3	STRG= +4.443 +2.087 ST01 s.d.= (0.146) (0.137)	0.715	116	2:149
4	STGR= +3.760 +1.261 ST03 s.d.= (0.169) (0.074)	0.668	145	2:149
5	STGR= +3.239 +0.990 ST07 s.d.= (0.190) (0.055)	0.647	159	2:149
6	STMA= +5.262 +0.3125 ISET s.d.= (0.409) (0.1119)	0.889	3.90	2:149
7	STMA= +4.394 −0.0391* FSET s.d.= (0.550) (0.0828)	0.912	0.11	2:149
8	STMA= +2.414 +1.760 ST01 s.d.= (0.105) (0.098)	0.514	160	2:149
9	STMA= +1.739 +1.109 ST03 s.d.= (0.103) (0.045)	0.405	304	2:149
10	STMA= +1.284 +0.869 ST07 s.d.= (0.111) (0.333)	0.379	357	2:149
11	AUGR=+14.18 −0.201 ISET s.d.= (0.62) (0.170)	1.349	0.70	2:149
12	AUGR=+13.21 +0.038* FSET s.d.= (0.82) (0.123)	1.355	0.05	2:149
13	AUGR=+11.57 +1.930 ST01 s.d.= (0.22) (0.205)	1.074	44.1	2:149
14	AUGR=+10.91 +1.180 ST03 s.d.= (0.26) (0.115)	1.039	52.2	2:149
15	AUGR=+10.69 +0.842 ST07 s.d.= (0.31) (0.094)	1.091	40.5	2:149
16	AUMA=+11.94 +0.243 ISET s.d.= (0.53) (0.145)	1.150	1.41	2:149
17	AUMA=+11.31 +0.229 FSET s.d.= (0.69) (0.104)	1.143	2.43	2:149
18	AUMA=+11.89 +0.954 ST01 s.d.= (0.22) (0.208)	1.087	10.5	2:149
19	AUMA=+11.71 +0.514 ST03 s.d.= (0.28) (0.122)	1.098	8.9	2:149
20	AUMA=+11.67 +0.349 ST07 s.d.= (0.33) (0.095)	1.112	6.7	2:149

*Coef./s.d. ratio less than 1.

apparent relationship (eqs 11 and 16) between the initial time-of-set values and the compressive strength values of the autoclaved specimens (AUGR, AUMA). There appeared to be no significant relationship between the time-of-final-set values of the neat cements and the compressive strength values obtained with any of the steam curing procedures used.

6.7. Compressive Strength of Steam-Cured Mortars Versus Early Strength of 1:2.75 (Cement to Sand) Water-Cured Mortars

The compressive strength values of the steam-cured concretes are sometimes expressed as a percentage of the 28-day moist air-cured compressive strength and not in terms of the earlier strength values. Because of the limited quantities of the cements available, it was not possible to make these tests on the mortars used in this series. Calculations were therefore made of the relationship to the compressive strength values of the 1:2.75 (cement to sand) mortars of the previous section of this series of papers (see previous section).

The reduction in variance in equations calculated for the relationships of STGR or STMA to the compressive strengths of the 1:2.75 mortars at one, three and seven days, eqs 3, 4, 5, 8, 9 and 10 (table 8–34), was highly significant. With high-pressure-steam-cured specimens, AUGR and AUMA, the reduction in variance resulting in the equations with 1, 3, and 7 day strengths was, in all instances but one, eq 20, highly significant. The numerical values were, however, much smaller than those obtained in equations with the low-pressure-steam-cured specimens.

6.8. Linearity of Relationships

An hyperbolic relationship has been reported for the relationship of the compressive strength of accelerated cured concrete to that cured for 28 days under standard conditions [18]. The shapes of the curves as well as the numerical values of the coefficients and constants represented by the curves obtained by different investigators differ to some extent. Other investigators have expressed their results as a linear relationship.

The calculations in this section of this series of articles have been based on a linear relationship, although it may be noted in figures 8–4 and 8–5 that there is appearance of nonlinearity. The use of the hyperbolic relationship as in table 8–35 resulted in a lower S.D. value (numerically) for the STGR–WAGR relationship than was obtained in eq 2 of table 8–30, and for the STMA–WAGR relationship in eq 3 of table 8–30. The results for the high pressure-steamed cured compressive strength values, AUGR and AUMA showed greater S.D. values than when a linear relationship was assumed as in eqs 4 and 5 of table 8–30.

7. Summary and Conclusions

TABLE 8–35. *Relationships of compressive strengths of mortar cubes cured and tested under the conditions explained in the text, and which were compared using an hyperbolic relationship*

Values for compressive strengths are in 1000 psi units. (See p. 72).

Eq. No.	Equation	S.D.
1	STGR=+0.536 WAGR+0.0525 (WAGR×STGR) s.d.= (0.026) (0.0038)	0.424
2	STMA=+0.273 WAGR+0.0684 (WAGR×STMA) s.d.= (0.015) (0.0033)	0.295
3	AUGR=+1.638 WAGR+0.0139 (WAGR×AUGR) s.d.= (0.128) (0.0093)	1.168
4	AUMA=+1.049 WAGR+0.0529 (WAGR×AUMA) s.d.= (0.183) (0.0141)	1.455

Determinations were made of the compressive strengths of mortar cubes after steam-curing both at atmospheric pressure and in an autoclave at 10 atm gage pressure. The steam curing was started either 5 or 24 hr after molding. The 1:3.525 (cement to silica (including silica flour)) mortar cubes with a water cement ratio of 0.5 were made with 161 portland cements. Companion specimens were cured in moist air for 28 days, and some for only 14 days with a 14-day drying period. In another series of tests on 65 portland cements, the specimens were steam-cured for 24 hr after 24 hr in moist storage. Half of these were tested when still moist and the remainder dried in laboratory air for 2 weeks prior to making the compressive strength tests.

The compressive strength values obtained after the different curing conditions were compared both by statistical and graphic means. Equations were computed by least-squares methods to resolve which of the commonly determined variables as well as the trace elements were associated with the compressive-strength values of the different cements after the different curing and test conditions.

These tests on mortars, made using a constant proportion of cement, sand, and silica flour with a constant water-cement ratio, indicated that:

(1) A considerable range of compressive strength values were obtained for the different cements after each of the curing conditions employed.

(2) There was an overlapping of the compressive strength values obtained with the different types of cement (as classified) with each of the curing conditions.

(2.1) The type III cements were, in general, in the upper area of the frequency distribution curves for compressive strength.

(2.2) The cement classified as Types IV, V, had low compressive strength values after the low-pressure-steam curing (STGR and STMA), but had fairly high values with autoclave curing after 24 hr at normal temperature (AUMA).

(2.3) The individual characteristics of the various Types I and II cements were such that no general statement can be made relative to the advantage of either type as classified.

(3) The frequency distribution curves (see fig 8–1) indicated a considerable overlapping of compressive strength values of the low-pressure-steam-cured (STGR and STMA), and the moist-air-cured mortars of different cements (WAGR).

(3.1) The low-pressure-steam-cured specimens (STGR and STMA) had lower average compressive strength values than the 28 day moist-air stored specimens (WAGR).

(3.2) The specimens which were air-dried after steam curing or moist curing had higher average compressive strengths than when tested moist.

(3.3) The mortar used in the present series of tests resulted in higher 28 day compressive strength values (WAGR) than were obtained at 28 days (ST28) or 1 year (ST1Y) for the standard 1:2.75 (cement to graded Ottawa sand) mortar.

(3.4) The cements cured in high-pressure steam, and then oven dried (AUGR and AUMA) had the highest average compressive strength values.

(4) The relationship between strength, and the chemical composition and the properties of the cements, was affected by the different curing conditions.

(4.1) For specimens cured with low-pressure steam at 66 °C for 12 hr after a 5 hr presteaming period, and then air-dried (STGR) an increase in C_3S content and fineness and probably also the C_3A, SO_3, and K_2O contents of the cements were associated with higher compressive strengths. Increased values for loss on ignition, air content 1:4 mortar, (the air content of the mortar of the present series used not being determined), Ba and

P in the cements were associated with lower compressive strength values. The variations of C_3S, fineness, and (air, 1:4 mortar) appeared to be most significant.

(4.2) For the specimens cured with low pressure steam at 71 °C for 7.5 hr after a 24 hr presteaming period and tested when still moist (STMA), increases in C_3A, C_3S, SO_3, K_2O, fineness, and possibly Li were associated with higher compressive strength values. Of these, the differences of C_3S and fineness appear to be the most significant. Increases in loss on ignition (air, 1:4 mortar), and possibly Ba and Cu appear to be associated with lower compressive strength values.

(4.3) For specimens cured with high pressure steam for 11 hr after a 5 hr presteaming period and tested after oven drying (AUGR), increases in C_3A, C_3S, C_2S, SO_3, fineness, and possibly Cr, and Li were associated with higher compressive strength values. Of these, differences in C_3S, C_2S and fineness appear to be most significant. Increases in Na_2O, (air, 1:4 mortar), and possibly Ba and Cu were associated with lower compressive strength values.

(4.4) Specimens autoclaved for 4 hr after they were 24 hr old (AUMA) had increased strength with an increase in the C_2S, SO_3 and fineness of the cements used. An increase in Na_2O, K_2O, and possibly insoluble residue, Rb and SrO were associated with lower compressive strength values. The (air, 1:4 mortar) was probably not significant in equations for the NAE cements but the variable was probably significant when the air-entraining cements were included.

(4.5) The compressive strengths of the mortars made of the different cements, and cured after 5 and 24 hr with low-pressure steam, (STGR and STMA) have a more highly significant relationship to strengths obtained under normal curing conditions than do those cured in an autoclave after 5 and 24 hr at normal temperatures (AUGR and AUMA). A laboratory test based on autoclave treatment after 24 hr appears to be a poor indicator of strengths which may be obtained with normal curing conditions.

(5) The equations calculated for the air-entraining plus non-air-entraining cements were fairly consistent with those for only the non-air-entraining cements.

(6) The use of the oxide composition instead of the calculated compound composition resulted in approximately the same estimated standard deviations for the equations.

(7) The use of trace elements found to have coef./s.d. ratios greater than one in the equations in addition to regularly determined variables usually resulted in a highly significant reduction in variance. In general, none of the trace elements were highly significant, and, except for Ba and Cu, did not appear consistently in the equations calculated for the compressive strength after the various curing conditions.

(8) The estimated standard deviations computed from the residuals in equations relating compressive strength to the independent variables were larger than the estimated S.D. values for duplicate tests on different days. This appears to indicate that other variables, not considered in the present study, may also have an effect on the compressive strength values obtained with the different cements after the different curing conditions.

(9) The effect on shrinkage or shrinkage-reduction, or on other important properties of steam-cured or autoclave-cured cement mortars were not determined, but these must be considered in commercial practice in addition to the compressive strength as evaluated in this study.

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