Factors Affecting Strength and Durability of Concrete Made with Various Cements

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This investigation examined variables influencing the 28-day compressive strength and 50-cycle salt scaling loss of concretes made with 18 Type 10 cements. Statistical analysis was performed on test data consisting of chemical and physical properties of cements; properties of fresh concretes; compressive strength, salt scaling loss, and air void parameters of mature concretes. For a similar water-cement ratio and cement content, results from the correlation analysis indicated that the 28-day concrete strength and 50-cycle salt scaling loss were influenced significantly by the chemical and physical properties of the cement used in the mix. Compressive strength has a strong negative correlation with alkali content, indicating that cements with a high alkali content produced concretes with lower compressive strength. Fineness (percent of particles in the 4 to 20-μm range) is related to low salt scaling loss. Equations predicting strength and salt scaling loss of concrete were developed by using multiple linear regression.

It has been observed for some time that the quality of the concrete used in Ontario has shown considerable variation, even though all the cements used in the manufacture of concrete met the Ontario Provincial Standard Specifications Form 1301 (CSA standard CAN 3-A5-M83) requirements for Type 10 cements. As a result of the observed variation in concrete quality in Ontario, a program of testing (*1*) was undertaken by the Concrete Section in the Engineering Materials Office of the Ontario Ministry of Transportation (MTO). First, physical and chemical properties of 18 samples of cement from 14 different cement plants were measured. These cements were then used to produce samples of concrete with nominal compressive strengths of 20 and 30 MPa, respectively. Within each of these strength categories two types of coarse aggregate were used in the mix, a good-quality crushed dolomitic limestone called A and a poorer-quality partially crushed natural gravel called B. Various properties of these four resulting concrete types (20A, 20B, 30A and 30B) were also measured.

The experimental investigation was designed to examine the influence of various cements on the strength and durability of concrete. Traditional factors such as cement content and water-cement ratio were not intended to be variables. These two factors have a profound influence on the strength and durability of concretes made from a single cement. Within each of the four concrete types examined in this experiment, all used the same aggregate, had the same cement content, and had virtually the same water-cement ratio. For example, the 30A concretes had the following batch quantities:

Fine aggregate, 37.3 kg; coarse aggregate, 53.7 kg; cement, 17.75 kg; and WRDA, 78.3 ml. DAREX AEA was adjusted to give an air content of 6.0 percent and total water was adjusted to give a slump of 80 mm.

The four concrete types had the same components so that the effect of the cements alone could be studied. This paper is based on a statistical analysis of the test data and was undertaken to address three objectives:

1. Verify that there was a significant difference between the quality of the concretes produced by the various cements.
2. Identify the cement properties responsible for the observed variations in the quality of the concrete specimens.
3. Develop a methodology to help predict the quality of a concrete produced by a cement.

It was decided that the quality of the concrete should be assessed in terms of the compressive strength of the concrete (CSA standard A23.2-3C, 9C) and also the cumulative mass loss (mass of material lost from surface) in a salt scaling test (ASTM C672-84, using 3 percent sodium chloride solution as the de-icer), since these properties most closely reflect the concerns expressed about the durability of concrete. Strength was measured at 3, 7, 28, and 91 days, and salt scaling loss was measured at 5, 10, 15, 25, and 50 cycles. It was decided that the 28-day compressive strength and the 50-cycle salt scaling loss would be the most appropriate variables to use. Therefore, for the purposes of this analysis, these two variables (for each of the four types of concrete) were considered to be the dependent variables. A more detailed description of the analyses reported in this paper is available (*2*).

DATA FILES

The MTO data have been reported (*1*) in the form of 12 tables labeled *A* through *L*. These tables included measurements of chemical and physical properties of the cements, measurements made on the fresh concrete, and measurements made on the mature concretes. These variables are defined in Table 1.

Table *C* of the MTO data contained the grading curves for the cements. The original 13 variables showed the percent passing specified sieve sizes. It was decided to augment these data by calculating the percentage of cement between two sieve sizes that was passing the larger sieve but retained by the smaller. This step resulted in 42 additional variables. Because the data are highly correlated, only one or two were

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TABLE 1 VARIABLES AND DEFINITIONS AND TEST METHODS

VARIABLE	DEFINITION/TEST METHOD
Air content	Measured at time of casting (%)
Air void content (total)	Measured on hardened concrete (%)
Alkali content	$Na_2O + 0.658(K_2O)$ (%)
Aluminum oxide	Al_2O_3 content of cement (%)
Carbonate addition	[L.O.I.(at 1050 °C) - L.O.I. (at 550 °C)] limestone (L.O.I.)] (%)
Cement content	Cement content per m^3 concrete (kg/m^3)
Chord length (total)	Determined by ASTM C457-82a (mm)
Density, Concrete	CSA Standard CAN 3-A23.2-M77 (kg/m^3)
Effective water-cement ratio	Mass of water/mass of cement
Effective water-cement ratio*	Mass of water/mass of cement finer than 45 μm
False set	CSA Standard CAN 3-A5-M83 (%)
Ferric oxide	Fe_2O_3 content of cement (%)
Fineness (% passing xx μm)	Cement finer than xx μm
Fineness (% between x-yy μm)	Cement between x and yy sizes (%)
Free calcium oxide	ASTM C114-83a (%)
Insoluble residue	CSA Standard CAN 3-A5-M83 (%)
Loss on ignition	CSA Standard CAN 3-A5-M83 (at 1050 °C)(%)
Paste-air ratio (total)	Measured on hardened concrete
Potassium oxide	K_2O content of cement (%)
Relative density, cement	CSA Standard CAN 3-A5-M83
Spacing factor (total)	Measured on hardened concrete (mm)
Specific surface area	Calculated from cement grading (mm^{-2})
Set time	CSA Standard CAN 3-A5-M83 (min)
Silicon dioxide	SiO_2 content of cement (%)
Slump	CSA Standard CAN 3-A23.3-M77 (mm)
Soundness	Le Chatelier Test (% expansion)
Strength x-day, cement	CSA Standard CAN 3-A5-M83 at x days (MPa)
Strength x-day, concrete	CSA Standard CAN 3-A23.2-M77 at x days (MPa)
Sulphur trioxide	SO_3 content of cement
Tetracalcium aluminoferrite	C_4AF content of cement (%)
Tricalcium aluminate	Calculated C_3A content of cement
Tricalcium silicate	Calculated C_3S content of cement
Voids per 25 mm (total)	Measured on hardened concrete
Void specific surface (total)	Measured on hardened concrete (mm^{-1})

used in any models that were developed. Finally, it was decided to include the calculated total specific area of the cements as a variable. This variable was included because its calculation made use of all the data in the grading curve.

Table *D* contained the results of 19 chemical tests performed on the cements. In addition, the data were used to calculate three more variables (the percentage of C_3S, C_2S, and C_4AF) thought to be of possible relevance.

PRELIMINARY ANALYSIS

The first stage in the analysis was to verify that the observed variation in the measured strength and salt scaling loss for the various concretes was not due to chance alone. The 28-day compressive strength of each concrete sample was measured for four cylinders, and the 50-cycle salt scaling loss for each concrete sample was measured on two cylinders. From these data an analysis of variance was undertaken to test if the variation in results was caused by the various cements. The results of this analysis are summarized in Table 2.

These results show that in all cases there is better than a 99.5 percent confidence (i.e., the probability that the *F* values could occur by chance is less than 0.005) that the cements differ in their effects on the observed compressive strength and salt scaling loss in the concretes. We therefore concluded that the observed differences in quality are real.

CORRELATION ANALYSIS

The basic step in developing models that can be used to predict concrete quality is to identify the degree of association between a dependent variable and the independent variables. The SYSTAT (*3*) package of statistical programs was used to analyze the data. The Pearson correlation coefficient provides a measure of the interrelationships between pairs of variables. A correlation coefficient close to +1 (or −1) indicates a strong association with a positive (or negative) relationship. A coefficient close to zero indicates little or no association between the pair of variables. The calculated correlation coefficient between the dependent variables and each of the independent variables was classified as

- potentially important (correlation coefficient between −1.0 and −0.4 or +0.4 and +1.0);
- possibly important (correlation coefficient between −0.4 and −0.2 or +0.2 and +0.4); and
- not important (correlation coefficient between −0.2 and +0.2).

The first breakpoint (of ±0.4) for making a decision is based on the fact that the 95 percent confidence level for the correlation coefficient of 18 pairs of observations is ±0.44.

Initially the correlation between the 28-day strength and the 50-cycle salt scaling loss for each type of concrete was calculated. Using the above criteria, there was no relationship between these properties for 30A, 30B, and 20B concretes. In the case of the 20A concrete, the correlation coefficient was −0.51. In all cases the calculated correlation coefficient was negative, indicating that the samples with higher strength had lower durability. Tables 3 and 4 show which of the measured variables were found to be potentially important for the 28-day strength and the 50-cycle salt scaling loss, respectively, for each of the four concrete types. The number associated with each variable is the calculated correlation coefficient.

The independent variables that were found to be potentially important were further analyzed to detect any cross-correlation between them. This analysis was necessary because a good predictive model should not contain closely related variables.

One other test was made on the potentially important variables. Influence plots were made for each variable. In this way it was possible to verify that the high correlation coefficient was not caused by an unusual outlying point. In no case was it necessary to reject a variable because of outlying points, suggesting that the experimental data were representative.

Of equal interest are the variables that were found to be unimportant in their association with concrete strength and durability. These variables are listed in Tables 5 and 6.

TABLE 2 VARIANCE ANALYSIS FOR TEST DATA

CONCRETE TYPE		F RATIO FOR CEMENT SOURCE	PROBABILITY THAT F VALUE COULD OCCUR BY CHANCE
30A	STRENGTH	76.31	< 0.001
	SALT SCALING	4.57	0.003
30B	STRENGTH	116.12	< 0.001
	SALT SCALING	3.89	0.005
20A	STRENGTH	60.09	< 0.001
	SALT SCALING	24.75	< 0.001
20B	STRENGTH	52.07	< 0.001
	SALT SCALING	16.92	< 0.001

TABLE 3 VARIABLES POTENTIALLY IMPORTANT TO 28-DAY STRENGTH OF CONCRETE SPECIMENS IN ORDER OF DECREASING IMPORTANCE

INDEPENDENT VARIABLE	COEFFICIENT	INDEPENDENT VARIABLE	COEFFICIENT
20A CONCRETE		30A CONCRETE	
Soundness	-0.66	Alkali content	-0.75
Alkali content	-0.57	Ferric oxide	0.68
Silicon dioxide	0.53	Tetracalcium aluminoferrite	0.68
Spacing factor (total)	-0.52	Potassium oxide	-0.60
Free calcium oxide	-0.48	Strength 28-day, cement	0.60
Chord length (total)	-0.47	Relative density, cement	0.57
Potassium oxide	-0.47	Set time	0.55
Set time	0.46	Fineness (% passing 50μm)	0.55
Relative density, cement	0.46	Carbonate addition	-0.54
Voids per 25mm (total)	0.45	Soundness	-0.48
Void specific surface (total)	0.44	Density, concrete	0.46
Sulphur trioxide	-0.43	Tricalcium aluminate	-0.46
Fineness (% passing 40 μm)	0.40	Cement content	0.45
Carbonate addition	-0.40	False set	0.45
		Loss on ignition	-0.41
20B CONCRETE		30B CONCRETE	
Alkali content	-0.85	Alkali content	-0.79
Cement content	0.77	Silicon dioxide	0.62
Potassium oxide	-0.71	Potassium oxide	-0.62
Free calcium oxide	-0.68	Cement content	0.62
Density, concrete	0.64	Sulphur trioxide	-0.62
Silicon dioxide	0.60	Soundness	-0.58
Relative density, cement	0.59	Density, concrete	0.56
Soundness	-0.59	Air void content (total)	-0.53
Ferric oxide	0.58	Air content	-0.53
Slump	-0.55	Free calcium oxide	-0.51
Set time	0.55	Tricalcium aluminate	-0.49
Sulphur trioxide	-0.53	Paste-air ratio (total)	0.48
Strength 3-day, cement	-0.49	Aluminum oxide	-0.46
Effective water-cement ratio*	-0.46	Relative density, cement	0.44
Tricalcium aluminate	-0.45	Ferric oxide	0.44
Effective water-cement ratio	-0.43	Tetracalcium aluminoferrite	0.44
		Strength 3-day, cement	-0.43
		Set time	0.43
		Carbonate addition	-0.43
		Effective water-cement ratio*	-0.41

* Mass of water/mass of cement finer than 45 μm

TABLE 4 VARIABLES POTENTIALLY IMPORTANT TO 50-CYCLE SALT SCALING LOSS OF CONCRETE SPECIMENS IN ORDER OF DECREASING IMPORTANCE

INDEPENDENT VARIABLE	COEFFICIENT	INDEPENDENT VARIABLE	COEFFICIENT
20A CONCRETE		30A CONCRETE	
Fineness (% between 2-20 μm)	-0.79	Fineness (% between 2-20 μm)	-0.75
Effective water-cement ratio*	0.68	Effective water-cement ratio*	0.67
Aluminum oxide	0.68	Aluminum oxide	0.66
Tricalcium aluminate	0.67	Tricalcium aluminate	0.65
Fineness (% passing 45 μm)	-0.66	Strength 91-day, concrete	-0.63
Paste-air ratio (total)	0.61	Fineness (% passing 45 μm)	-0.61
Air void content (total)	-0.59	Strength 7-day, concrete	-0.60
Strength 28-day, concrete	-0.52	Insoluble residue	0.58
Ferric oxide	-0.49	Potassium oxide	0.48
Tetracalcium aluminoferrite	-0.49	Tricalcium silicate	-0.46
Voids per 25 mm (total)	-0.49	Ferric oxide	-0.44
Insoluble residue	0.49	Tetracalcium aluminoferrite	-0.44
Strength 91-day, concrete	-0.48	Strength 28-day, concrete	-0.44
Set time	-0.42	Specific surface areas	0.43
Tricalcium silicate	-0.41	Chord length (total)	0.43
		Effective water-cement ratio	0.43
		Cement content	-0.40
		Spacing factor (total)	0.40
20B CONCRETE		30B CONCRETE	
Fineness (% between 4-20 μm)	-0.53	Effective water-cement ratio*	0.73
Air content	-0.46	Fineness (% between 2-20 μm)	-0.72
Set time	-0.45	Fineness (% passing 45 μm)	-0.62
Strength 3-day, concrete	-0.43	Tricalcium aluminate	0.61
		Aluminum oxide	0.57
		Ferric oxide	-0.57
		Tetracalcium aluminoferrite	-0.57
		Potassium oxide	0.50
		Alkali content	0.48
		Insoluble residue	0.46
		Set time	-0.46
		Air content	-0.46

* Mass of water/mass of cement finer than 45 μm

TABLE 5 VARIABLES NOT RELATED TO 28-DAY STRENGTH OF CONCRETE SPECIMENS

20A Concrete	20B Concrete
Fineness (air permeability), cement	Fineness (air permeability)
7 day strength, cement	Air content, cement
Insoluble residue, cement	7 day strength, cement
Magnesium oxide, cement	Magnesium oxide, cement
Sodium oxide, cement	Sodium oxide, cement
Tricalcium silicate, cement	Tricalcium silicate, cement
Water (total), concrete	Dicalcium silicate, cement
Slump, concrete	Air void content, concrete
Air content, concrete	Voids per 25mm (total), concrete
Relative density, concrete	Average chord length (total), concrete
Yield, concrete	Paste-air ratio (total), concrete
Cement content, concrete	Void specific surface (total), concrete
Effective water-cement ratio, concrete	Spacing factor (total), concrete
Effective water-cement ratio*, concrete	Specific surface area, cement
Air void content (total), concrete	
Paste-air ratio (total), concrete	

*Based on cement passing 45 micron sieve

30A Concrete	30B Concrete
Fineness (air permeability), cement	Fineness (air permeability), cement
Air content, cement	Air content, cement
Sodium oxide, cement	7 day strength, cement
Tricalcium silicate, cement	Sodium oxide, cement
Dicalcium, silicate, cement	Tricalcium silicate, cement
Water (total), concrete	Average chord length (total), concrete
DAREX AEA dosage	Void specific surface (total), concrete
Slump, concrete	Spacing factor (total), concrete
Effective water-cement ratio, concrete	
Average chord length (total), concrete	
Void specific surface (total), concrete	

TABLE 6 VARIABLES NOT IMPORTANT TO 50-CYCLE SALT SCALING LOSS IN CONCRETE SPECIMENS

20A Concrete	20B Concrete
False set, cement	Relative density, cement
Air content, cement	Soundness, cement
3 day strength, cement	False set, cement
7 day strength, cement	Air content, cement
Loss on ignition, cement	3 day strength, cement
Sulphur trioxide, cement	7 day strength, cement
Free calcium oxide, cement	Loss on ignition, cement
DAREX AEA dosage	Insoluble residue, cement
Air content, concrete	Tricalcium aluminate, cement
Relative density, concrete	Magnesium oxide, cement
3 day strength, concrete	Alkali content, cement
Average chord length (total), concrete	Aluminium oxide, cement
Void specific surface (total), concrete	Ferric oxide, cement
	Calcium oxide, cement
	Free calcium oxide, cement
	Tricalcium silicate, cement
	Tetracalcium aluminoferrite, cement
	Water (total), concrete
	Slump, concrete
	Yield, concrete
	Cement content, concrete
	Effective water-cement ratio, concrete
	Effective water-cement ratio*, concrete
	28 day strength, concrete

*Based on cement passing 45 μm sieve

TABLE 6 (*continued on next page*)

GRADING CURVE DATA

The 56 variables derived from the cement grading curve data were treated separately because of their strong interrelationships. For each dependent variable, plots were made showing the range of particle size under consideration, labeled with the corresponding correlation coefficient. From an inspection of these plots a representative variable was selected for inclusion in the modeling process.

A consistent pattern emerged from these plots. The 28-day strength had few or no strong correlations with grading. The salt scaling results on the other hand exhibited two common features. First, the percentage of very fine particles (<2 μm) had a strong positive correlation. Second, the percentage of particles in the variables around the range of 4–20 μm had very strong negative correlations (the strongest of any of all the variables measured), much stronger than the commonly used percentage passing 45 μm.

Table 7 lists the variables from the grading curve data, (and their correlation coefficients), that were retained for the model building phase of the analysis.

REGRESSION ANALYSIS

For this stage of the analysis, it was decided to use regression analysis to develop an equation to predict the 28-day strength and 50-cycle salt scaling loss of the concretes.

Three criteria were used to select the equations:

1. The equation should preferably contain variables that can easily be measured before the concrete has set.
2. The equation should contain only three or four variables. That is, a simple equation that requires the measurement of a few variables is preferable to an equation requiring many measurements, even if some precision is lost.

TABLE 6 (*continued*)

	91 day strength, concrete
	Voids per 25 mm (total), concrete
	Average chord length (total), concrete
	Void specific surface (total), concrete
	Spacing factor (total), concrete
30A Concrete	30B Concrete
Fineness (air permeability), cement	Fineness (air permeability), cement
Set time, cement	False set, cement
Air content, cement	3 day strength, cement
3 day strength, cement	7 day strength, cement
7 day strength, cement	Loss on ignition, cement
Loss on ignition, cement	Sulphur trioxide, cement
Sulphur trioxide, cement	Sodium oxide, cement
Free calcium oxide, cement	Silicon dioxide, cement
Carbonate addition, cement	Calcium oxide, cement
DAREX AEA dosage	Free calcium oxide, cement
Air content, concrete	Carbonate addition, cement
3 day strength, concrete	Dicalcium silicate, cement
Voids per 25mm (total), concrete	Relative density, concrete
Average chord length (total, concrete	Yield, concrete
Void specific surface (total), concrete	Cement content, concrete
Spacing factor (total), concrete	3 day strength, concrete
	Air void content (total), concrete
	Paste-air ratio (total), concrete

3. The equation should be logical, i.e., the signs of the coefficients should make sense.
4. The equations must be statistically significant.

The SYSTAT program contains a set of routines called Multiple General Linear Hypothesis that can calculate several types of regression equations and apply many tests to check their statistical significance. One particular option in the SYSTAT package is stepwise regression. With this method the program reviews the selected independent variables and introduces them into the equation one at a time in an attempt to maximize the coefficient of multiple regression. This technique is useful in reviewing candidate variables, but the resulting equations must be examined with care. In this analysis over 30 equations were evaluated before final selection. This approach was applied to the 28-day compressive strength and the 50-cycle salt scaling loss for each type of concrete. Tables 8 and 9 show the final equations derived for the strength and the salt scaling loss of each type of concrete (along with the most relevant statistics), respectively. An explanation of the output is as follows: "Variable" lists the variables in the estimated regression equation; and "Coefficient" is the calculated value of the coefficient for each variable in the equation.

TABLE 7 POTENTIALLY IMPORTANT VARIABLES FROM THE GRADING CURVE

Case	Variable	Coefficient
28-Day strength		
20A concrete	% Passing 40 μm	0.40
20B concrete	None	—
30A concrete	% Passing 50 μm	0.55
30B concrete	None	—
50-Cycle salt scaling		
20A concrete	% Between 2 and 20 μm	−0.79
20B concrete	% Between 4 and 20 μm	−0.53
30A concrete	% Between 2 and 20 μm	−0.75
30B concrete	% Between 2 and 20 μm	−0.72

TABLE 8 REGRESSION ANALYSIS FOR 28-DAY STRENGTH OF CONCRETE SPECIMENS

TYPE	VARIABLE	COEFFICIENT	t	R^2	E	F
20A	Constant	-128.49	-3.26	0.86	1.09	17.07
	Soundness	-18.23	-3.84			
	Chord length (total)	-43.91	-4.13			
	Relative density, cement	52.69	4.19			
	Fineness (% passing 40 μm)	0.18	2.29			
20B	Constant	45.28	20.45	0.89	1.13	34.97
	Alkali content	-15.21	-6.55			
	Free calcium oxide	-1.76	-2.45			
	Set time	0.03	3.20			
30A	Constant	-163.23	-1.91	0.78	2.09	13.87
	Alkali content	-14.86	-3.31			
	Fineness (% passing 50 μm)	0.55	2.85			
	Relative density, cement	55.05	2.13			
30B	Constant	71.23	15.99	0.88	1.22	30.81
	Alkali content	-16.12	-6.84			
	Air content	-3.04	-4.33			
	Carbonate addition	-0.55	-2.66			

TABLE 9 REGRESSION ANALYSIS FOR 50-CYCLE SALT SCALING LOSS OF CONCRETE SPECIMENS

TYPE	VARIABLE	COEFFICIENT	t	R^2	E	F
20A	Constant	1858.58	1.39	0.74	215	11.23
	Fineness (% between 2-20 μm)	-26.59	-1.21			
	Aluminum oxide	238.08	2.39			
	Air void content	-195.34	-1.74			
20B	Constant	10673.21	2.83	0.28	1160	5.78
	Fineness (% between 4-20 μm)	-203.88	-2.40			
30A	Constant	3705.41	3.99	0.68	245	13.71
	Fineness (% between 2-20 μm)	-66.95	-4.25			
	Potassium oxide	577.65	2.14			
30B	Constant	-748.56	-0.61	0.80	237	17.08
	Effective water-cement ratio	8674.63	4.65			
	Air content	-492.64	-3.64			
	Insoluble residue	622.65	2.00			

For example, for the 28-day strength of type 30A concrete:

$$\begin{aligned}\text{28-day strength} = & -163.23 - 14.86\ (\text{alkali content}) \\ & + 0.55\ (\text{fineness, \% passing } 50\ \mu\text{m}) \\ & + 55.05\ (\text{relative density, cement})\end{aligned}$$

t is the Student's t statistic for each coefficient. It is a test to see whether the value of the coefficient is different from zero. A value of t larger than ± 2 for a sample size of 18 indicates a 95 percent confidence that the calculated coefficient is significant.

R^2 is a measure of the success of the regression equation in the variation in the data. The value is between 0 and +1—the larger the value the better the equation. Care must be taken not to overload the equation with variables just to improve the value of this statistic.

E is the standard error of the estimate. This an estimate of the variation about the regression. The smaller the value, the more precise will be the predictions. Analysis of Variance is a test of the overall significance of the regression. The higher the value of the F-ratio, the better.

Reviewing these equations reveals the following observations:

1. Strength: Good equations were obtained for 20A, 20B, 30A, and 30B concretes. The R^2 values were large and all of the coefficients were significant.
2. Salt scaling.
   - 20A concrete: The overall quality of the equation was getting worse. In particular, the t value of the coefficients was approaching ± 2, indicating lower confidence in the calculated values of the coefficients.
   - 20B concrete: The equation had a very low value for R^2 and would be of little practical use.
   - 30A concrete: The R^2 value in the equation was reasonably large. This, combined with the fact that all the coefficients were significant, means that the equation has some potential.
   - 30B concrete: The R^2 value in the equation was large, but the t value of the constant term was very small. This difference is probably because of the inclusion of a variable in the equation that has a large mean value but a small standard deviation. To the regression equation this variable looks like a constant term even though the variable is highly correlated to the dependent variable.

To give an overall impression of the effectiveness of the equations, Figure 1 shows a typical plot of the predicted values along with the corresponding measured values of 28-day strength for 30B concrete. Since it contains several variables, the regression equation cannot be plotted. The graph shows a line at 45 degrees to the axes, indicating perfect agreement between the predicted and measured 28-day strengths. The points show the results from the equation.

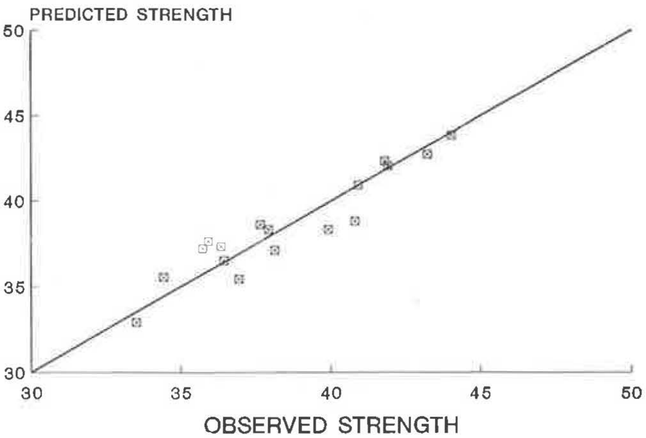

FIGURE 1 Predicted versus observed strength of 30B concrete.

CONCLUSION

The results of this analysis indicate that, for the cements used in this experiment (with similar water-cement ratio and cement content), the concrete strength and salt scaling loss are highly dependent on the chemical and physical properties of the cement used in the mix. The cement variables found to be correlated to the concrete strength and salt scaling loss are shown in Tables 6 and 7, respectively.

A review of these tables indicates that consistent patterns emerge for both compressive strength and salt scaling and that several variables were found to be significant for all of the concretes tested. The 28-day compressive strength had a strong negative correlation with alkali content (in particular K_2O content), indicating that cements with a higher alkali content were associated with lower strength concretes. Soundness (as measured by a Le Chatellier expansion) also had a significant negative correlation in all cases. On the other hand, relative density and set time had positive correlations.

In the case of the 50-cycle salt scaling loss, fineness (percentage of particles in the range of 4–20 μm) has a strong negative correlation. Since we are interested in low scaling losses, this is a desirable attribute in a cement. To a lesser extent the iron content and aluminum content are also associated with salt scaling loss. The iron content has a negative (desirable) correlation, and the aluminum content has a positive (undesirable) correlation.

Because this study investigated a limited number of cements it is premature to draw general conclusions. However, cement manufacture has changed significantly in the past two decades, mainly as a result of environmental and energy concerns (*4*). Environmental concerns have resulted in the use of fuels with reduced SO_3; in addition, kiln dust, which is rich in alkalis, is routinely collected and returned to the kiln, resulting in cements with a higher alkali content. Energy concerns have probably led to a gradual reduction in kiln firing temperatures and also, perhaps, the length of time the clinker is retained in the kiln.

Certainly it is now being reported worldwide that modern cements do not produce concretes as durable as those made with older cements. Concrete placed since about 1970 is much more vulnerable to carbonation (*5*), and older parking structures appear to suffer less deterioration than newer ones (*6*).

It has been suggested that excessive expansion of concrete subjected to wetting and drying cycles is related to incomplete kiln reactions and that deleterious reactions occur in the larger cement particles (*7*).

The experimental results clearly show that different cements produce concretes with widely differing strengths and durabilities at the same cement content, air content, slump, aggregate type, and content (the basic concrete properties held constant within each class of concrete). Equally clearly, the different cement properties are a function of the raw material properties and cement manufacturing processes.

Unfortunately, we have no knowledge of the manufacturing process or the raw materials used for the cements studied. Some of these data were requested, but no information was made available to us by the various cement companies. Although we do not know the sources of the various cements, we are aware that some were manufactured in Canada and some were manufactured in the United States.

The concrete samples and measurements were made under carefully controlled laboratory conditions, and the statistical analysis has shown that the differences in strengths and durabilities are a function of the cement and are not a random effect of experimental error. We therefore concluded that the finding of this analysis should prove useful in identifying methods to improve the strength and durability of concrete.

To refine these results, we would suggest that researchers consider undertaking similar measurements using other cements so that the data base used to estimate these relationships can be broadened.

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