

PAPER SP 16-1 Computer analysis of compression tests of concrete provides a rapid evaluation of quality, uniformity, and testing discrepancies. The computer can be programmed to determine compliance with project specifications and to develop the information recommended by ACI 214-65. Reports serve as a record of concrete in place and as a means of establishing the adequacy of the concrete mix for continued or future use.

Application of Computers in the Evaluation of Quality Control of Concrete

By G. B. SOUTHWORTH and NEIL M. MOSS

COMPUTERS HAVE BECOME such an important part of today's science that the use of a computer to control the quality of concrete would seem to be a possibility. However, those who have used computers are well aware that the computer can only do what it is programmed to do and that the program is limited to the ability and knowledge of the programmer.

Once a proper program is established, the real advantage of the computer is apparent in the vast amount of data which can be processed and analyzed in a very short time. Work that would take days or even weeks if done manually can be done in seconds, or at the most, in minutes. The prime requisite in establishing the program is the ability to do the work manually by the correct method.

It is apparent, then, that computers cannot control the quality of concrete since no one has yet discovered the means by which the variables in concrete quality can be eliminated. What computers can do, and are doing very successfully, is to rapidly analyze test data and supply key information from which the range of quality of concrete in place can be determined. This same information can also be used to predict, with reasonable accuracy, the acceptability of a concrete mix for future work.

The kind of information desired may vary from one job to another but, in general, the minimum information needed is the number of tests involved, the average strength, and the standard deviation or coefficient of variation. About two-thirds of the test

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values fall within one standard deviation (plus and minus) of average. When the average and standard deviation are known, the full range of test values can be predicted. Should the probability of low test values represent an intolerable condition, the concrete mix would not be satisfactory. Reference to Figure 3 of "Recommended Practice for Evaluation of Compression Test Results of Field Concrete (ACI 214-65)" will indicate the probability of values exceeding stated percentages of average strength. It also indicates the probability of values falling below a given percentage of average strength.

Because the computer can process the data so rapidly and economically, there is little reason to settle for the minimum information required when recent test reports are being analyzed. The program can be arranged to check compliance with any concrete specification and to further measure performance of concrete and adequacy of testing procedures as recommended in ACI 214-65. Using ASTM C 94 (Standard Specifications for Ready-Mixed Concrete) as an example, compliance should be checked with the following requirements.

1. Average of all tests shall be equal to or greater than specified strength.
2. Average of any five consecutive tests shall be equal to or greater than specified strength.
3. Not more than one test in ten shall have an average value less than 90 percent of the specified strength.

To provide this information, the computer should be programmed to print test numbers in numerical sequence, print the individual test values (usually two or three cylinders), average

the values and print the test average, average all previous test averages and print the cumulative average strength, average five consecutive test averages, and print the moving-five average strength.

To determine the quality of the control, the coefficient of variation should also be determined on a cumulative basis. For computer purposes this is done by the average square versus square of average method. As each test value is found, the computer squares the test values and stores the cumulative average square. At each test value, the square of the cumulative average strength is subtracted from the cumulative average square, the square root of the difference is found and is printed "Cumulative C. of V." (Figure 1-1). It is thus possible to determine the progress of job control.

The cumulative coefficient of variation determined in this way is not statistically accurate since it employs n instead of $(n-1)$ in computing the standard deviation. The error is insignificant when more than 30 test averages are involved. When fewer than 30 tests are used to establish the probable quality of concrete in place or to predict future variations, the cumulative coefficient of variation must be weighted.

To pinpoint methods of excessive variation, a control index can be computed on a moving-five basis in the same manner as the coefficient of variation. For this purpose, the computer is programmed to add the new test strength and the new strength squared and eliminate the sixth previous value of both. The five consecutive tests and squares are averaged; the average test is squared and subtracted from the average square; the square root of the difference is extracted and is printed as a percentage of the moving-five average strength under the heading of "Moving 5 Index."

As previously stated, this Moving 5 Index or Moving 5 C. of V. uses n instead of $(n-1)$ in securing the standard deviation. Since many texts on statistics indicate that $(n-1)$ gives a more reliable estimate of the standard deviation of an infinite number of tests when only a limited number are being analyzed, it is recommended that the computer be programmed to multiply the standard deviation in both the Cumulative C. of V. and the Moving 5 columns by the square root of $n/(n-1)$. This has the effect of increasing the value in the Moving 5 column by approximately 12 percent (the square root of $5/4$ is 1.118). In the Cumulative C. of V. column this correction varies from a maximum of 41.4 percent for only two tests (the square root of $2/1$ is 1.414) to a negligible increase when a large number of tests are analyzed.

Because testing discrepancies can sometimes influence the apparent variation of concrete quality, it is recommended that the

TEST NUMBER	TEST VALUES		TEST AVERAGE	CUMULATIVE AVERAGE	MOVING 5 AVERAGE	CUMULATIVE C. OF V.	MOVING 5 C. OF V.	TEST RANGE	AVERAGE	MOVING 10 AVG. RANGE	WITHIN-TEST C. OF V.
1	4245	4386	4315	4315.0000	.0000	.0000	.0000	141	141	0	2.8967
2	3926	4457	4191	4253.0000	.0000	2.0616	.0000	531	336	0	7.0036
3	3926	4068	3997	4167.6666	.0000	3.8457	.0000	142	271	0	5.7715
4	5023	5271	5147	4412.5000	.0000	11.4867	.0000	246	266	0	5.3340
5	5342	5450	5396	4609.1999	4609.1999	13.4815	13.4815	108	234	0	4.5005
6	4740	5164	4952	4666.3333	4736.5999	12.2824	12.9040	424	266	0	5.0470
7	4669	4846	4757	4679.2857	4849.7999	11.2052	10.9738	177	253	0	4.7931
8	5058	5200	5129	4735.5000	5076.1999	10.7867	4.6969	142	239	0	4.4764
9	4528	4528	4528	4712.4443	4952.3999	10.2450	6.7445	0	213	0	3.9985
10	5235	5306	5270	4768.1999	4927.1999	10.2373	5.9792	71	198	198	3.6886
11	4846	5005	4925	4782.4545	4921.7999	9.7333	5.9792	159	195	200	3.6112
12	5023	5164	5093	4808.3333	4989.0000	9.4168	5.7221	141	190	161	3.5091
13	4988	5164	5076	4828.9230	4978.3999	9.1082	5.6225	176	189	165	3.4739
14	5200	5271	5235	4857.9285	5119.7999	8.9809	2.6996	71	181	147	3.2990
15	5306	5306	5306	4887.7999	5127.0000	8.9210	2.8973	0	169	136	3.0603
16	4881	5058	4969	4892.8750	5135.7999	8.6196	2.6130	177	169	111	3.0665
17	5200	5522	5361	4920.4117	5189.3999	8.6140	3.1452	322	178	122	3.2112
18	4935	5094	5014	4925.6110	5177.0000	8.3600	3.3967	159	177	128	3.1880
19	5129	5414	5271	4943.7894	5184.1999	8.2517	3.4628	285	183	156	3.2780
20	5023	5342	5182	4955.6999	5159.3999	8.0841	3.2287	319	190	181	3.3925
21	4988	5306	5147	4964.8095	5195.0000	7.9097	2.5202	318	196	197	3.4954
22	4811	4917	4864	4960.2272	5095.5999	7.7384	3.1210	106	192	193	3.4257
23	4422	4687	4554	4942.5651	5003.5999	7.7786	5.8738	265	195	202	3.4951
24	3537	3803	3670	4889.5416	4683.3999	9.3467	13.2480	266	198	222	3.5866
25	4422	4457	4439	4871.5199	4534.7999	9.3682	12.2807	35	191	225	3.4815
26	4386	4457	4421	4854.1922	4389.5999	9.3894	10.0168	71	187	215	3.4094
27	4740	4952	4846	4853.8888	4386.0000	9.2081	9.9154	212	188	204	3.4268
28	4705	4740	4722	4849.1785	4419.5999	9.0593	10.3412	35	182	191	3.3304
29	4492	4634	4563	4839.3103	4598.1999	8.9816	3.9911	142	181	177	3.5118
30	4722	4775	4748	4836.2666	4660.0000	8.8377	3.6022	53	177	150	3.2359
31	4775	4775	4775	4834.2902	4730.7999	8.6957	2.2109	0	171	119	3.1327
32	5023	5129	5076	4841.8437	4776.7999	8.5864	3.9034	106	169	119	3.0906
33	4333	4422	4377	4827.7575	4707.7999	8.6400	5.5400	89	166	101	3.0554
34	4245	4422	4333	4813.2058	4661.7999	8.7139	6.6205	177	167	92	3.0704
35	4068	4316	4192	4795.4570	4550.5999	8.8905	8.0177	248	169	113	3.1247
36	4510	4599	4554	4788.7500	4506.3999	8.8150	7.6257	89	167	115	3.0879
37	4245	4422	4333	4776.4323	4357.7999	8.8541	2.9828	177	167	112	3.1010
38	4599	5023	4811	4777.3421	4444.5999	8.7328	5.4527	424	174	151	3.2258
39	4510	4599	4554	4771.6153	4488.7999	8.6600	5.2798	89	172	145	3.1893
40	3714	3803	3758	4746.2749	4402.0000	9.2334	9.0368	89	170	149	3.1677
41	4952	4988	4970	4751.7316	4485.1999	9.1364	10.5633	36	166	152	3.1033
42	4599	4952	4775	4752.2857	4573.5999	9.0236	10.4838	353	171	177	3.1858
43	4510	4687	4598	4748.6976	4531.0000	8.9360	10.2025	177	171	166	3.1909
44	4245	4775	4510	4743.2727	4522.1999	8.8741	10.2195	530	179	221	3.3471
45	4156	5129	4642	4741.0222	4699.0000	8.7826	3.8126	973	197	294	3.6780
46	4775	4864	4819	4742.7173	4668.7999	8.6847	2.7259	89	194	294	3.6335
47	4775	4864	4819	4744.3403	4677.5999	8.5901	2.9400	89	192	285	3.5903
48	5041	5218	5129	4752.3541	4783.7999	8.5639	4.8850	177	192	200	3.5784
49	4033	4068	4050	4738.0203	4691.7999	8.7597	8.5114	35	189	255	3.5293

FIGURE 1-1 TYPICAL COMPUTER PRINTOUT OF TEST VALUES AND DERIVED INFORMATION



computer program also include a measure of the consistency of testing procedures. ACI 214 suggests that this be done by studying the range of tests (difference between the high and low values of two or three cylinders of the same load of concrete broken at the same age). The computer finds and prints the difference under the heading, "Test Range." The test range values are averaged

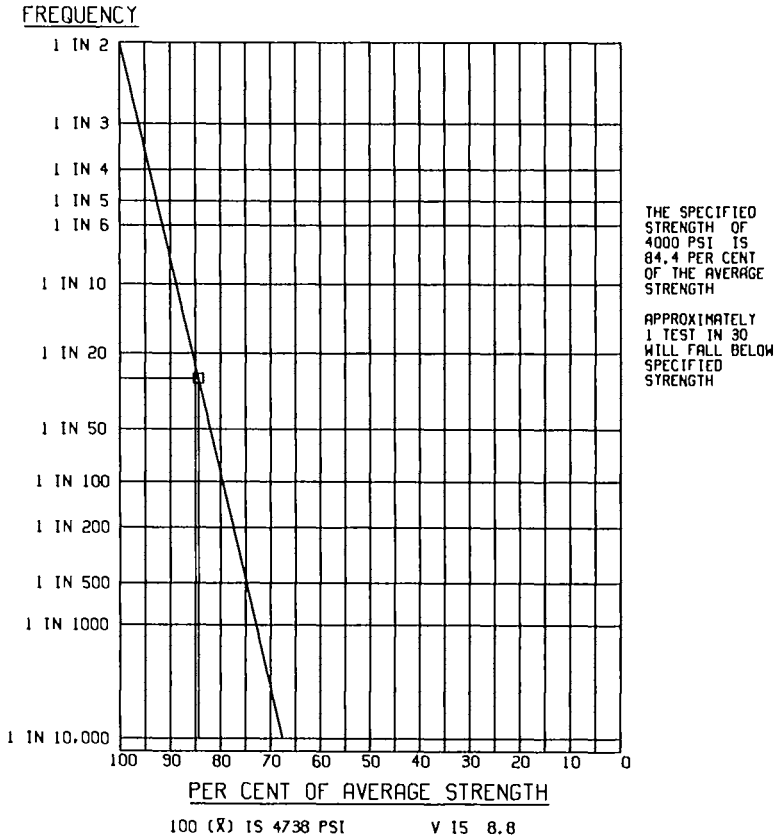


FIGURE 1-2

cumulatively and printed under "Average Range" and are also computed on a moving-ten average (ACI 214 recommendation) and printed under "Moving 10 Average Range."

Finally, the within-test coefficient of variation is determined by dividing the average range by a constant (1.128 for two cylinder tests and 1.693 for three cylinder tests) which result, expressed as a percentage of the cumulative average strength, is printed under "Within-Test C. of V." Figure 1-1 shows the entire printout of all data.

The analysis provided by the computer is useful both to the engineer of the project represented by the test reports and to the engineer who may study them to determine whether a proposed concrete mix is satisfactory for use on a new project. For example, the over-all quality control shown in Figure 1-1 can be interpreted in accordance with ACI 214 to indicate that approximately 97 percent of test values will exceed 4000 psi. Thus, when adequate test data are available from previous work, the computer report provides a sound approach to selection of concrete mixes.

The probable frequency of tests falling below certain values can be more clearly illustrated when a plotter is available for use with the computer. In Figure 1-2, the cumulative average strength and the cumulative coefficient of variation are used by the plotter to establish a normal distribution line on a graph with a probability scale as the ordinate and a uniform arithmetic scale as the abscissa. Percentages of average strength are shown on the abscissa and the frequency with which values will fall below percentages of average strength are given on the ordinate. (The coefficient of variation line drawn by the plotter may be more easily recognized as the below average half of a normal distribution curve.)

In Figure 1-2, it is predicted that 1 test in 2 will fall below 100 percent of average which is obvious; 1 in 3 will fall below 96 percent of average; 1 in 6 will be lower than 91.5 percent of average; 1 in 20 can be expected to be below 85.5 percent of average; 1 in 1000 may be under 73 percent of average and 1 in 10,000 (negligible) may be less than 68 percent of average.

TABLE 1-1 NUMBER OF TESTS FALLING BELOW
STATED VALUES

Strength	Predicted	Actual
Lower than 4550 psi	127 (1 in 3)	116 (1 in 3.3)
Lower than 4335 psi	63 (1 in 6)	44 (1 in 8.6)
Lower than 4050 psi	19 (1 in 20)	17 (1 in 22.4)
Lower than 3460 psi	- (1 in 1000)	1 (1 in 380)
Lower than 3220 psi	- (1 in 10,000)	0

The 49 tests shown in Figure 1-1 are part of a series of 429 tests from one job. It is interesting to compare the frequency forecast with actual performance of the last 380 tests.

The fact that actual performance was better than the predicted performance is due to an improvement in uniformity as

the job progressed (8.76V to 8.04V). This condition is usually a byproduct of statistical evaluations since the fact that test results are being studied and analyzed invariably results in more attention and care in the production of concrete. In this sense, it may be said that computers are instrumental in controlling the quality of concrete.

The data shown in Figure 1-1 were processed by the Univac 1107 computer, and an ALGOL subroutine, using plotter routines in the EXEC library, operates and controls a CalComp plotter to produce the graph shown in Figure 1-2. Equipment used in this program is installed at Case Institute of Technology in Cleveland, and is available for industrial use when not required for instructional purposes. Similar units are available at other engineering institutions in the United States and Canada.

PAPER SP 16-2 Digital computers are used for control of concrete quality during its manufacture and for analysis and interpretation of concrete test results. Statistical parameters normally used for quality control are defined and their use is explained with the help of job control charts. The three case histories presented show: (1) the use of computers in establishing the degree of reliance of the strength of accelerated-cured test cylinders; (2) the multiple correlation analyses of 1176 compressive strength test results and several independent variables; and (3) a computer method for the trial and error fitting of a hyperbolic curve to compressive strength test results.

Applications of Digital Computers in the Quality Control of Concrete

By V. M. MALHOTRA

THE ADVANTAGES OF USING statistical methods both in the presentation of field test data and the interpretation of test results are now widely recognized by concrete technologists. Concrete control engineers are well aware that their test results are always subject to certain errors due to the inherent variability of the concrete-making materials. It is most essential that sufficient allowance be made for these variables during the manufacture of concrete and the analysis of the test results. The statistical methods are the only means of doing so since otherwise it is difficult to distinguish between chance causes and real effects of any particular factor, unless the latter are obviously very large when compared with the former causes.

Repetition is a key word in the statistical analysis of test data. When data are limited and a problem has no repetitive aspects, one can carry out the calculations much more quickly by manual methods than one can program it for a computer. However, when data run into hundreds of test results, as is often the case on big hydroelectric projects and paving jobs and in the operation of large ready-mixed concrete plants, manual statistical computations become very tedious and time-consuming and a resort to electronic computing facilities has to be made. This paper presents the applications of digital computers to the quality control of concrete both during its manufacture and during the analysis and interpretation of test results.

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QUALITY CONTROL DURING MANUFACTURE OF CONCRETE

The uniformity of concrete production at a batch plant is measured by the testing of 6x12-in. concrete cylinders. The strength of standard test cylinders not only shows the potential compressive strength of concrete in a structure but is also used to estimate other structural properties of concrete such as flexural strength and modulus of elasticity.

The degree of production control is measured by the uniformity achieved in the testing of cylinders, uniform strength indicating uniform control. Large variations in the 28-day compressive strength of test cylinders invariably require increased average strength, (resulting in increased cost) to meet the minimum design strength. If large variations are allowed in the control strength of concrete, the danger of low strength concrete being placed in the critical sections of a structure is increased.

The variations in compressive strength of concrete are measured by statistical parameters known as "standard deviation" and "coefficient of variation."

Standard deviation is a measure of the spread of observations about the central value. The standard deviation σ of the population is found by extracting the square root of the average of the squares of deviations of individual test values from their average, i.e.:

$$\sigma = \sqrt{\frac{(X_1 - \bar{X})^2 + (X_2 - \bar{X})^2 + \dots + (X_n - \bar{X})^2}{n}}$$

The calculation of σ by this formula is laborious when the number of test results exceeds 30, which is often the case on large construction jobs. Under such circumstances the calculations can easily be handled by a computer using the following form of the formula:

$$\sigma = \sqrt{\frac{\sum X^2 - \frac{(\sum X)^2}{n}}{n}}$$

The standard deviation is expressed in the same units as the compressive strength. When the number of observations is less than 30, a minor correction called Bessel's correction has to be applied to the above formula.

PROBLEM IDENT	NO. OF OBSERVATIONS	AVERAGE VALUE	STANDARD DEVIATION	COEFFICIENT OF VARIATION
10000	241	.90904564E+03	.18401188E+03	20.24
20000	35	.11935714E+04	.25041083E+03	21.03
30000	49	.15291836E+04	.23064131E+03	15.08
40000	102	.95274509E+03	.24044992E+03	25.24
50000	119	.10810924E+04	.21627372E+03	20.01
60000	171	.13292397E+04	.32025007E+03	24.09
10000	241	.23007468E+04	.42092754E+03	18.30
20000	35	.31820000E+04	.62913011E+03	19.77
30000	49	.39526530E+04	.40822710E+03	10.33
40000	102	.27748039E+04	.57461790E+03	20.71
50000	119	.29768067E+04	.50922007E+03	17.11
60000	171	.36229239E+04	.61295139E+03	16.92

FIGURE 2-1 COMPUTER PRINTOUT FOR AVERAGE, STANDARD DEVIATION, AND COEFFICIENT OF VARIATION

The coefficient of variation (CV) is simply the standard deviation expressed as a percentage of the arithmetic mean, i.e.:

$$CV = \frac{\text{standard deviation}}{\text{arithmetic mean}} \times 100$$

It is a dimensionless quantity.

Some authorities use standard deviation, whereas others, like the U. S. Bureau of Reclamation, prefer the use of coefficient of variation as the statistical tool to indicate the amount of variation. Calculations for both these parameters together with arithmetic mean can be carried out by a computer in one operation. A sample printout from a computer is shown in Figure 2-1.

Test data can be fed into a computer daily, weekly, and monthly as the job demands. The results obtained bring the

quality control engineer up to date about the quality of concrete being placed and enable him to effect changes in the mix proportions, if necessary. The accompanying control charts illustrate the use of standard deviation and coefficient of variation in the quality control of concrete.

The control chart in Figure 2-2 shows the results for structural concrete for which the 28-day minimum specified strength was 3000 psi and the number of failures was not to exceed 10 percent. This control chart based upon the results of the first 25 tests indicates that the job was under excellent control with a CV of only 9.4 percent and that there were no test results falling below the minimum specified strength. (It is, of course, assumed that all samples were taken at random.) Using the information from the control chart, the quality control engineer would be justified in effecting changes in the mix proportions in order to reduce the 28-day average compressive strength from 3970 psi to 3440 psi.¹ This means reduction in the cement content per cu yd of concrete, with resulting savings in cost.

The control chart in Figure 2-3 gives the results for a structural mass concrete for which the 28-day minimum specified strength was 2500 psi. The number of failures allowed was 20 percent. The control chart based upon the first 26 test results indicates that the job was under poor control, with a CV of 20.1 percent and 31 percent of the test results falling below the minimum specified strength. Under such conditions the quality control engineer must insist upon much tighter production controls. However, if the circumstances on the job are such that the tighter control cannot be achieved, then the engineer has no alternative but to reportion the concrete mix. The reportioned concrete mix must give 28-day average compressive strength of at least 3040 psi as compared to 2825 psi, so that the number of test results falling below the minimum specified strength does not exceed 20 percent.² It is stressed that apart from the increased cost, the latter alternative is a poor solution to the problem and always should be discouraged.

ANALYSIS AND INTERPRETATION OF TEST RESULTS

Engineering problems often require the presentation of data showing the observed relationship between two variables. Before the analysis can be carried out the pairs of data are plotted. If the relationship between the observations is nearly exact, a straight line or curve drawn by eye may be sufficient. Unfortunately in concrete technology the exact relationships are indeed elusive. More often than not, the relationship between two variables is less certain and drawing by eye results in graphs which depend too much upon the judgment of the research worker

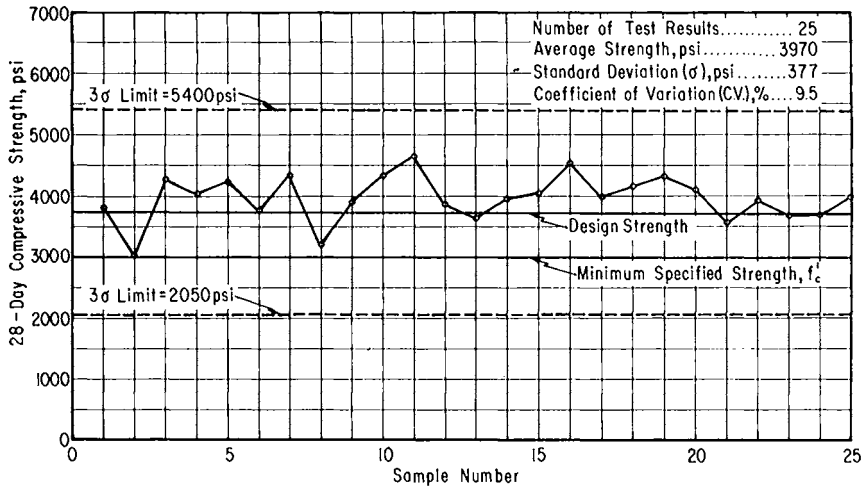


FIGURE 2-2 CONTROL CHART FOR INDIVIDUAL STRENGTH TESTS--STRUCTURAL CONCRETE:
CV OF 9.5 PERCENT INDICATES EXCELLENT JOB CONTROL

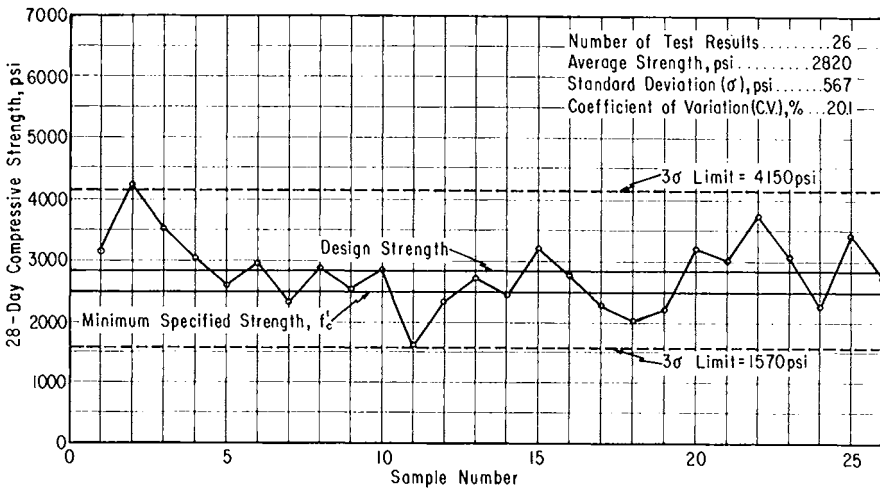


FIGURE 2-3 CONTROL CHART FOR INDIVIDUAL STRENGTH TESTS--STRUCTURAL MASS CONCRETE:
CV OF 20.1 PERCENT INDICATES POOR JOB CONTROL

involved. Different investigators observing the same data may produce significantly different graphs. In such cases, fitting a straight line or a curve by eye is not justified and a more precise method of determining the relationship between two variables is needed. In many other types of problems the differences in one variable may be due to several other variables all acting at the same time. The techniques for solving such problems are based upon statistical methods and are known as "linear, multiple linear regression and correlation analyses." Using these techniques one can obtain a mathematical description of the relationship between independent and dependent variables. Such techniques have been used in biological sciences for a long time but their use in concrete technology is of relatively recent origin. The following three case histories illustrate the use of statistical techniques in the analysis of concrete test data. All the necessary computations were carried out using a digital computer.

Case History 1 -- Regression Analysis and Prediction Limits

This case involves the analyses of the results of accelerated 24-hr concrete strengths obtained during the construction of a huge hydroelectric project.³ The accelerated curing method used consisted of placing the standard 6x12-in. concrete cylinders, 1/2 hr after molding, in a water tank thermostatically controlled at $165 \pm 5^\circ\text{F}$. The cylinders were removed from the tank 21-1/2 hr later and tested at the age of 24 hr. A total of 737 pairs of test results was available. It was necessary to establish the relationship between the accelerated and the 28-day strengths and also to determine the degree of confidence that could be placed in the 24-hr accelerated strengths.

The test results were analyzed using an IBM 1620 computer. Both 90 and 95 percent prediction limits were determined using the following expression:⁴

$$a + bx^0 \pm t_{\alpha/2; n-2} \times S_{y/x} \sqrt{1 + \frac{1}{n} + \frac{(x^0 - \bar{x})^2}{\sum_{i=1}^n (x_i - \bar{x})^2}}$$

where

a = an estimate of the intercept

b = an estimate of the slope

n = number of observations

$t_{\alpha/2; n-2}$ = 100 $\alpha/2$ percentage point of "Student's t " distribution with $(n-2)$ degrees of freedom; values to be obtained from standard statistical tables

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7          1 717  0 450.      10.      3500.      1.645
7 83  0 1 0 11.00153417E+02 31.47821875E+01      MEAN AND STD ERR
7 83  0 2  0 29.51631799E+02 77.05992288E+01      MEAN AND STD ERR
7 84  0 1 2      .83450      CORRELATION CARD
7 85  1 1 1 20.42893417E-01 50.44534364E-03 40.497 .6963 REG COEFF
7 86  1 1 1 29.60906807E+07 29.60906807E+07 1640.020 AN. OF VAR (REG)
7 86  1 2 715 12.90867699E+07 18.05408531E+04 AN. OF VAR (ERR)
7 86  1 3 716 42.51773907E+07 AN. OF VAR (TOT)
7 87  1 0 0 7.41356256E+01 42.49009921E+01 0.000 .6963 MISC.
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FIGURE 2-4 COMPUTER PRINTOUT FOR THE REGRESSION ANALYSIS

X0	LOWER LIMIT	UPPER LIMIT	Y0
450.00	921.9107	2324.9645	1623.4376
460.00	942.4029	2345.3301	1643.8665
470.00	962.8943	2365.6967	1664.2955
480.00	983.3845	2386.0643	1684.7244
490.00	1003.8738	2406.4328	1705.1533
500.00	1024.3622	2426.8024	1725.5823
510.00	1044.8496	2447.1728	1746.0112
520.00	1065.3360	2467.5442	1766.4401
530.00	1085.8215	2487.9167	1786.8691
540.00	1106.3059	2508.2901	1807.2980

FIGURE 2-5 COMPUTER PRINTOUT FOR THE 90 PERCENT PREDICTION LIMITS

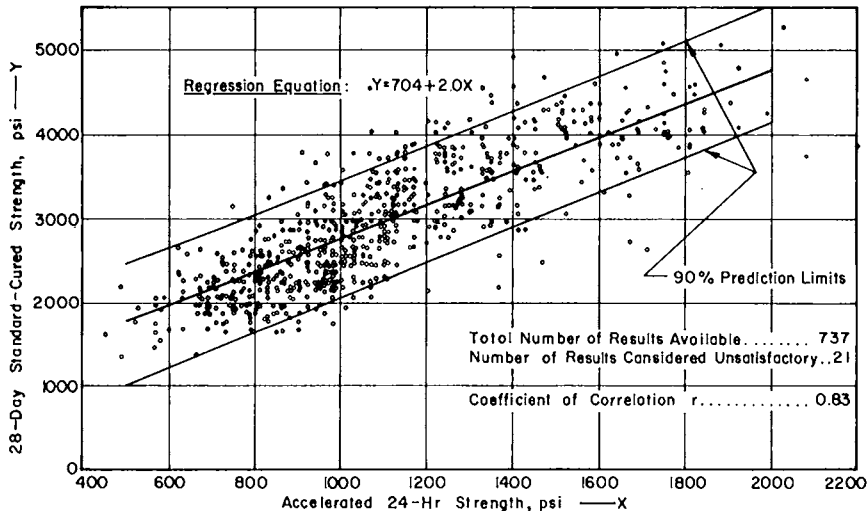


FIGURE 2-6 RELATIONSHIP OF 24-HR ACCELERATED TO 28-DAY STRENGTH; COMBINED DATA FOR ALL TYPES OF CONCRETE

x_i = accelerated 24-hr strength

$\bar{x}$ = mean of accelerated 24-hr strength

x^0 = some future observation of accelerated 24-hr strength

$S_{y/x}$ = an estimate of the variability about the line; to be calculated using standard statistical methods

A sample of computer printout in its original form is shown in Figures 2-4 and 2-5. A plot of the test results is shown in Figure 2-6, together with "the line of best fit" and the regression equation. Also shown in this figure are the 90 percent prediction limits. Figure 2-7 compares the above relationship for the same type of concrete but having different water-cement ratios (by weight). The general conclusions drawn from these analyses are:

The 28-day standard-cured strength can be predicted from the accelerated 24-hr strength with a reasonable degree of accuracy.

At low strengths the relationship between the accelerated 24-hr strength and the 28-day standard-cured strength is dependent upon the water-cement ratio of the concrete mix. This conclusion is rather significant since it is not generally practical to carry out this large number of computations manually.

Case History 2 -- Multiple Correlation Analysis

In concrete quality control it is very desirable to predict the strength development trends of concrete on the basis of the available field and laboratory test data. This invariably involves the selection of a minimum number of test results, which at the same time is large enough to encompass all the possible variables so that the compressive strength at the selected age will be predicted with reasonable accuracy. This case history is one in which statistical studies using a digital computer were performed to correlate the different variables and the 28-day compressive strength, and to select the minimum number of test results required for the analysis of the entire test data.

A total of 1176 compressive strength test results on 6x12-in. concrete cylinders was available from the construction of a concrete-arch dam.⁵ Since the compressive strength of concrete at any age is known to be dependent not only upon the water-cement ratio but also upon such factors as percentage of entrained air and aggregate-cement ratio, it was important to establish the relationship between the 28-day compressive strength and the following variables:

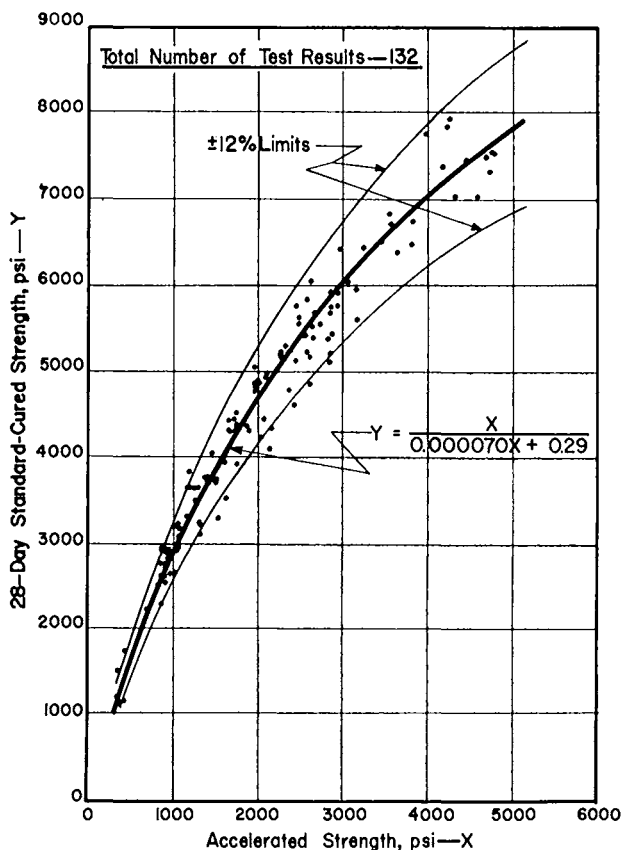
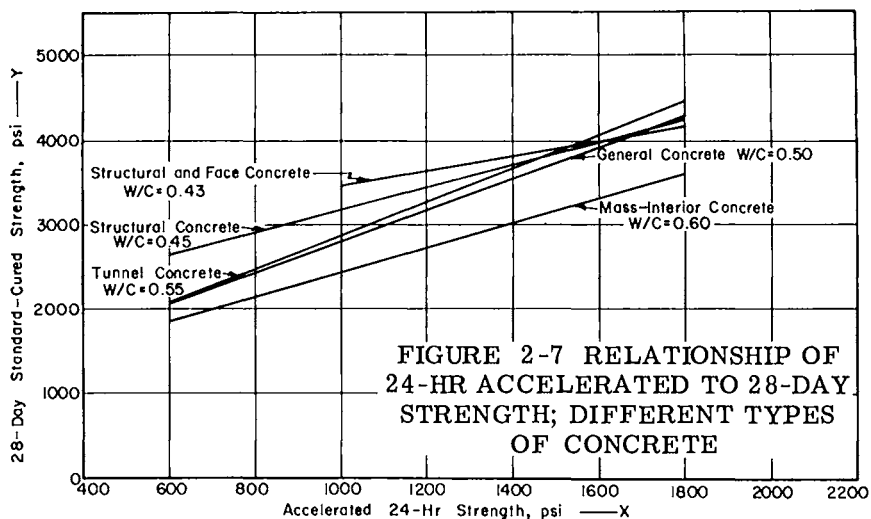


FIGURE 2-8 28-1/2-HR ACCELERATED VERSUS 28-DAY STRENGTH

- 1. Log water-cement ratio
- 2. Air content, percent
- 3. Density of 6x12-in. concrete cylinders 24-hr after casting, lb per cu ft
- 4. Slump, in.

It should be emphasized that the effects of variables other than the water-cement ratio on the compressive strength of concrete are relatively small, but to be able to determine their effect quantitatively a large quantity of test data is needed. An electronic computer to process these data is necessary to avoid the tedious and time-consuming manual computation.

Correlation coefficient for the entire test data and for 50 and 200 test results selected at random from the test data were computed. This was followed by the formation of the three multiple linear regression equations, one for each of the three sets under analysis.⁶ The regression equations so formed are given in Table 2-1.

TABLE 2-1 SUMMARY OF MULTIPLE LINEAR REGRESSION EQUATIONS

Number	Number of Test Results Under Analysis	Equations*
1	50	$Y = (10,805)X_1 - (111.8)X_2 + (13.9)X_3 - (179.1)X_4 - 1,175$
2	200	$Y = (11,636)X_1 - (38.1)X_2 + (79.7)X_3 - (37.4)X_4 - 12,026$
3	1176	$Y = (11,584)X_1 - (128.3)X_2 + (37.3)X_3 - (71.4)X_4 - 5,122$

*Where: Y = compressive strength at 28 days, psi; X₁ = log (to the base 10) of water-cement ratio, by weight; X₂ = air content, percent; X₃ = density of 6x12-in. concrete cylinders at 24 hr after casting, lb per cu ft; and X₄ = slump, in.

The multiple correlation analysis indicated that the independent variables selected predict the 28-day compressive strength within acceptable limits of accuracy, with the added advantage that these predicted values are available within 24 hr of placing the concrete. Furthermore, the analysis showed that the degree of accuracy in forecasting 28-day compressive strengths based upon 50 test results selected at random from the data is of the same order as that based upon 200 results (selected at random) or 1176 test results.

In order to be able to appreciate the complex nature of the analyses of the above type a similar problem has been worked out manually and is shown in Tables 2-2 and 2-3. In this problem a set of 31 compressive strength test results at 7, 28, 90, and 365 days was available. The data were analyzed so that, in

TABLE 2-2 COMPUTATION OF SUMS OF SQUARES AND PRODUCTS

No.	Compressive Strength at Various Ages, psi				$\sum X_i + Y$			X_1	X_2	X_3	Y
	7-Day	28-Day	90-Day	365-Day							
	X_1	X_2	X_3	Y							
1	450	960	1,830	2,220	5,460	$SP_{X_1 X_1}$			79,302,200	123,854,700	144,771,500
2	630	1,420	2,280	3,250	7,580	$S_{X_1} \cdot S_{X_2}/n$			67,159,890	107,750,367	128,439,003
3	570	1,260	2,380	3,120	7,330	$SPD_{X_1 X_2}$			12,142,310	16,104,333	16,332,497
4	1,480	3,580	5,180	5,680	15,920						
5	840	2,000	3,560	4,080	10,480						
6	1,790	3,910	5,870	6,300	17,870						
7	1,530	3,490	5,650	5,740	16,410	$SP_{X_2 X_2}$			264,443,800	308,435,400	
8	1,060	2,390	4,050	5,270	12,770	$S_{X_2} \cdot S_{X_3}/n$			229,421,793	273,471,980	
9	1,260	2,880	4,560	5,080	13,780	$SPD_{X_2 X_3}$			35,022,007	34,963,420	
10	2,270	4,650	6,940	7,560	21,420						
11	1,560	2,670	4,800	5,500	14,530						
12	680	1,780	3,700	4,000	10,140						
13	950	2,230	3,750	4,800	11,730	$SP_{X_3 X_3}$					488,332,800
14	960	2,240	3,650	4,700	11,150	$S_{X_3} \cdot S_{X_1}/n$					438,754,535
15	830	1,930	3,270	3,880	9,910	$SPD_{X_3 X_1}$					49,578,265
16	710	1,690	2,870	3,820	9,090						
17	1,040	1,900	3,190	3,850	9,980						
18	1,760	3,360	4,580	5,880	15,580						
19	500	1,040	1,860	2,680	6,080						
20	820	1,450	2,570	3,220	8,060						
21	930	1,660	2,630	3,400	8,620						
22	730	1,390	2,630	3,060	7,810						
23	840	1,610	1,910	2,600	6,960						
24	1,510	3,000	4,140	4,980	13,630						
25	1,260	2,820	3,590	4,360	12,030						
26	1,030	2,320	3,230	3,900	10,480						
27	800	1,520	2,460	3,160	7,940						
28	550	1,130	1,820	2,630	6,130						
29	400	950	1,770	2,180	5,300						
30	720	1,530	3,080	3,580	8,910						
31	830	1,820	3,020	3,250	8,920						
S	31,270	66,580	106,820	127,330	332,000						
SS	37,559,100	169,149,400	418,764,800	573,616,500	4,017,370,600						
S^2/n	31,342,351	142,996,658	368,081,045	522,997,706	3,555,612,903						
SSD	6,016,749	26,152,742	50,683,755	50,618,794	461,757,697						
S/n	1006.7	2147.7	3445.8	4107.4							
									CHECK		
									SSD_{X_1+Y}		133,472,040
									$SPD_{X_1 X_2 X_2}$		89,158,280
									$SPD_{X_2 X_1 X_2}$		139,970,854
									$SPD_{X_3 X_1 X_2}$		99,156,530
											461,757,704



TABLE 2-3 LINEAR REGRESSION ANALYSIS WITH THREE INDEPENDENT VARIABLES : SOLUTION OF NORMAL EQUATIONS

Explanation of Computations	b_1	b_2	b_3	SPR_{xy}	
(1)	$a_{11} = 6,016,749$	$a_{12} = 12,142,310$	$a_{13} = 16,104,333$	$a_{10} = 16,332,497$	
(2)		$a_{22} = 26,152,742$	$a_{23} = 35,022,007$	$a_{20} = 34,963,420$	
(3)			$a_{33} = 50,683,755$	$a_{30} = 49,578,265$	
(4) = (1) $\times \left(-\frac{a_{12}}{a_{11}} \right)$		$-\frac{(a_{12})^2}{a_{11}} = -24,504,152$	$\frac{-a_{12} \times a_{13}}{a_{11}} = -32,499,832$	$\frac{-a_{12} \times a_{10}}{a_{11}} = -32,960,285$	
(5) = (2) - (4)		$a_{22,1} = + 1,648,590$	$a_{23,1} = + 2,522,175$	$a_{20,1} = + 2,003,135$	
(6) = (1) $\times \left(-\frac{a_{13}}{a_{11}} \right)$			$\frac{-(a_{13})^2}{a_{11}} = -43,104,535$	$\frac{-a_{13} \times a_{10}}{a_{11}} = -43,715,235$	
(7) = (5) $\times \left(-\frac{a_{23,1}}{a_{22,1}} \right)$			$\frac{(a_{23,1})^2}{a_{22,1}} = - 3,858,675$	$\frac{-a_{23,1} \times a_{20,1}}{a_{22,1}} = - 3,064,596$	
(8) = (3) + (6) + (7)			$a_{33,12} = + 3,720,545$	$a_{30,12} = + 2,798,434$	
			$b_3 = 0.75216$		$b_3 = \frac{a_{30,12}}{a_{33,12}}$
		$b_2 = 0.06433$			$b_2 = \frac{[(a_{20,1}) - (a_{23,1} \times b_3)]}{a_{22,1}}$
	$b_1 = 0.57146$				$b_1 = \frac{[a_{10} - (a_{13} \times b_3 - a_{12} \times b_2)]}{a_{11}}$
Regression Equation:					
$Y = \bar{Y} + b_1 (X_1 - \bar{X}_1) + b_2 (X_2 - \bar{X}_2) + b_3 (X_3 - \bar{X}_3)$			CHECK = $a_{13} \times b_1 + a_{23} \times b_2 + a_{33} \times b_3 = a_{30}$		
or $Y_{365\text{-day}} = 0.60 X_{7\text{-day}} + 0.06 X_{28\text{-day}} + 0.75 X_{90\text{-day}} + 797$					

future, the compressive strengths at one year could be predicted from those at 7, 28, and 90 days. A quick glance at Tables 2-2 and 2-3 should convince even the most skeptical engineer that in these types of analyses the use of a computer becomes mandatory when the number of test results exceed 20. It should be emphasized that apart from the speed at which the calculations are carried out by a computer, the probability of making an error is minimal whereas in manual computations the chances of making errors and repeating them are always present.

Case History 3 -- Fitting of a Hyperbolic Curve This analysis problem originated during the research work being carried out by the Construction

Materials Section on the development of a satisfactory accelerated test for determining the 28-day compressive strength of concrete.⁷ This test procedure is different from the one discussed earlier; in this method 6x12-in. concrete cylinders are moist-cured 24 hr in a standard manner and are then boiled for 3-1/2 hr. The cylinders are then removed from the boiling water tank and are tested 1 hr later.⁸

A total of 792 6x12-in. cylinders was tested in compression at 7 and 28 days, an average of three test cylinders at each age comprising one test result. The nature of the data necessitated the fitting of a curvilinear function to the plot of the accelerated versus 28-day standard-cured compressive strengths. The data were fed into an IBM 1620 computer, and various types of curves were tried using a trial and error method. The best-fitting curve was of the type:

$$Y = \frac{X}{AX + B}$$

where X = accelerated-cured strength, psi; Y = 28-day standard-cured strength, psi; and A and B are constants.

A plot of the test results is shown in Figure 2-8, together with the hyperbolic curve of the above form.

It was concluded from this investigation that the 28-day standard-cured strengths could be predicted from the accelerated strength with an accuracy of about ± 12 percent (Figure 2-8).

CONCLUSIONS

Digital computers can be used with advantage in the quality control of concrete. Furthermore, the case histories discussed effectively demonstrate that when a large number of test results are available for interpretation and analysis it becomes very necessary to make use of the electronic computing facilities.

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PAPER SP 16-3 An integrated system employing computer-based techniques for data processing and analysis and information storage and retrieval is described. This system serves for the evaluation of concrete quality, the selection of concrete to best match a structural design, and for the study of performance

Digesting Concrete with a Computer

By PETER SMITH

THERE MAY BE LITTLE POINT in refining structural designs with a computer unless we can improve our ability to build them. In recent times those concerned with concrete as a material have become increasingly aware of two problems. First, information arising from experience, performance studies, and research has tended to accumulate faster than it can be appraised and incorporated in future work, through better specifications. Second, the speed of construction often outstrips the conventional means of controlling quality.

In looking for a way out of these difficulties the Department of Highways, Ontario decided to see if computer-based techniques for data processing and analysis, and for information storage and retrieval could help. This, in turn, requires a reorganization of the fact-gathering processes, principally for those used in quality control testing at the time of construction. The objective of this reorganization is to produce the facts in a form that can be handled quickly, and to insure that only those facts are collected which are of direct use in defining quality in materials and the effects on design, specification, control, and performance.

The project to be described is concerned with concrete, specifically with the half-million cu yd of concrete used each year by the Department of Highways, Ontario. Depending upon the use made of the stored and evaluated information, the project falls into one of three main phases.

The first phase of "the new look in concrete quality control," as the project has become known, is that concerned with day to day operations during construction. A computer is being used for the analysis of test results, in particular for strength, so that the effectiveness of control of the product and its compliance with specification can be better judged as the work proceeds.

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Concrete acceptability, in many specifications, is governed by minimum 28-day compressive strengths. Both "minimum" and "28 days" are probably unrealistic concepts if the inherent variability of concrete and the need to be able to make corrections before construction has proceeded too far are truthfully considered. Adjuncts to the new look have, therefore, included the development of accelerated test procedures and consideration of more realistic specifications based upon statistical concepts.

The two remaining phases require, in addition, the storage of information about the concrete materials and mixtures used and the construction operations employed, in such a manner that any fact can later be retrieved readily. The stored information may be retrieved to assist in the selection of concrete or its constituent materials to meet specific design criteria or to match materials and structural design in an over-all design-construction theory based on the probability of failures. Or it may be compared with observations made during performance studies or other investigations to determine the governing variables. This should result in the long-term improvement of portland cement concrete technology and specifications.

The first phase is now in operation and the second and third phases will be developed as the inventory of data accumulates.

PHASE 1 -- COMPUTER ANALYSIS OF CONCRETE TEST RESULTS

It is beyond the scope of this paper to discuss the inadequacies of many concrete specifications with respect to the properties, limits, sampling procedures, method of test, testing frequency, responsibility for quality (or product) control, and basis of acceptance specified or the alternatives that are currently being advocated. It appears that the computer project to be described could readily be modified to suit future changes;

indeed the project itself may provide the facts necessary to justify the changes. The project has been based on the Department of Highways' present practice, which is to test concrete for both control and acceptance purposes at the same time, against the requirements of a specification that is a fairly typical example of those that are on a partially statistical basis.

One feature of such an approach to quality control should be emphasized--that is, the time occupied by testing and evaluation of the results often prevents the information from being used to the fullest extent as the work proceeds. This is particularly true of concrete strengths; in addition to the long testing time, evaluation of the results takes considerable time and effort.

Statistical parameters appropriate to the analysis of concrete strength results have been in common use for many years. They are probably best described in ACI 214-65.¹ The problem is not with the evaluation, as such, but with the tedious mathematics involved. In spite of simplifications suggested in the standard referred to or by the use of graphical methods,² results can rarely be conveniently analyzed as the work proceeds and hence statistically based specifications lose a lot of their meaning. Southworth³ and Clague and Evans,⁴ among others, have all recently demonstrated that the computer can, by its ability to make many calculations rapidly, take the hard work out of the determination of mean strength, standard deviation, coefficient of variation, required or desired strength, and within-test variations.

The full value of such an analysis is, however, only obtained if the results are presented immediately to the person in a position to take action on them, along with other supporting data that he may need on what went into the concrete and what happened when it was placed. This is achieved in the Ontario program by presenting a summary of such information and a collation of all other test results on the computer printout sheets showing the strength analysis.

One of the axioms of computer technology is that only that which is put in can be got out. Therefore, it is necessary to devise an input system which, along with appropriate storage and retrieval, will contain all the needed information. Information could be manually abstracted from conventional reporting procedures and placed on punch cards; however, this would be an extra step requiring much clerical effort. Instead, report forms, filled in at the time the concrete is placed, have been devised which contain the requisite information for direct card punching.

Much thought has been given to the question, "What is the requisite information?" No two people will precisely agree on which records it is essential to preserve, bearing in mind that these same records will also have to serve the other phases of the program that deal with performance studies and the matching

of materials to design. Figure 3-1 shows those selected for recording on the concrete construction report. An interesting feature of this form is that many items involve multiple choices. This has the great advantage of aiding the inspector in producing the correct information and it also cuts down on the manual coding required prior to processing of the data. When completed, copies of this report are sent immediately to others concerned with quality control so that they know what happened when the concrete was placed.

The concrete construction report is dual purpose; when enclosed in a waterproof envelope it also serves as the cylinder shipping tag. The original of the report, completed in full with all the information on the day's placement and a summary of all tests, is sent in for each concrete placement, accompanied by a set of cylinders for compression testing at 28 days. The results of these tests are the ones analyzed. All other cylinders or beams submitted for test are accompanied by the same form but only completed sufficiently to record identifying data and the results of tests made on the plastic concrete represented by that particular set of specimens.

Another source of input information is the mix design card shown in Figures 3-2, 3-3, and 3-4, which contains all the basic background information on the concrete mixture and on the materials used. Additionally, this card serves to record one set of quality and gradation information about the aggregates used. This information comes from results of tests on the samples of aggregate upon which either original quality approval or mix design was based. This is an interim step in order to have some information on the quality of aggregates that can be retrieved for performance and other studies. When the whole of the department's granular inventory and test result recording is computerized, there will be cross reference simply through sample numbers, to every piece of information about any material used.

The third input source is the strength results obtained from the testing laboratory. The report of concrete strengths used for this purpose, is shown in Figure 3-5. The recipient of this report first matches and attaches it to the corresponding construction report so that he now has all the information about that particular concrete placement on a single sheet.

The originals of the corresponding reports on concrete construction and strength are then checked over for errors and to make sure that no changes have been made in the mix or materials that would invalidate an analysis. Certain items, against which numbers cannot be conveniently placed in the field, are coded and the reports are then filed until a significant number of new sets of information (usually five) is accumulated.

COPY FOR LABORATORY

DEPARTMENT OF HIGHWAYS - ONTARIO

CONCRETE CONSTRUCTION REPORT NO.

TYPE OF CONCRETE WORK

CONCRETE PLACED

General Location

Pavement Lane

Stn. 46 51 To Stn. 52 57

or Description

DIST. NO. HWY. NO. CONT. NO.

Date Concrete Placed

Report above and to right of double line must be filled out for each set of cyls. or beams sent in for test. In addition, each time a significant quantity of concrete is placed, one report must be completed in full, accompanied by a set of 28-day cylinders. Place white original in waterproof envelope and attach to one cylinder or beam. Identify other cylinders of the set by attaching B and C tags using exactly the same field number. Also see notes on the back. Ship cylinders or beam to laboratory. Distribute other copies of report as shown in top left hand corner of each without delay.

SPECIAL INSTRUCTIONS

(1) When report of early breaks is urgent, to whom and how sent?

By Phone to Name Phone No.

By Teletype Attention of At

Cylinders or beam not from DHO contract report results and bill to;

FIGURE 3-1 CONCRETE CONSTRUCTION REPORT FORM

CARD 1 2 **Sheet No.** 4

DEPARTMENT OF HIGHWAYS - ONTARIO
MATERIALS AND TESTING DIVISION
DESIGNATED CONCRETE MIX DESIGN

MIX DESIGN No. _____ Class Cons. Mod 17

MIX SERIAL NUMBER _____

Dist. No. _____ Hwy. No. _____ Cont. No. _____

Designed by: Central Lab. 1 Contractor 2 Region 3 Field 4

Approved for issue
Signature _____

Issued: Phone _____
Teletype _____
Letter _____

Date of issue _____ Day _____ Month _____ Year 38 _____

Mix Originally Used in Dist. No. _____ on Cont. No. _____

MIX PROPORTIONS, OVEN DRY WEIGHTS PER CUBIC YD. CONCRETE

Coarse Aggregate 1 _____ lb.
Coarse Aggregate 2 _____ lb.
Fine Aggregate _____ lb.
Cement _____ lb.
Water _____ lb.
Total _____ lb.

CARD 2

Admixture _____ fl. oz./lb.; 100 lb. cement
_____ fl. oz./lb.; 87 1/2 lb. bag

Air Entraining Agent, Add amount to give specified air content _____

Remarks about mix _____

SOURCE

Granular Inventory No. _____

_____ CODE _____
_____ CODE _____
_____ CODE _____
_____ Type Mill _____

23 CODE 24
29 CODE 30

Mix proportions verified in Lab. by trial mixes at: effective W/C Ratio _____ slump ins. _____ air cont. % _____ unit wt. lb/cu. ft. _____ to yield cu ft. _____

(see forms 9-04-03 & 313-04-03, contract drgs. and special provisions for field requirements and limits.)

LABORATORY TRIAL MIXES - STRENGTH TEST RESULTS

Mix Eff. W/C _____ Mix Eff. W/C _____ Mix Eff. W/C _____

Accelerated _____
7 day _____
10 day _____
28 day _____

CARD 3

NOTES. (i) Use Form OB-MT-303 to convert the proportions given above to suit batch size used and to compensate mix for moisture in aggregates. Before each placement check aggregate gradations are similar to those used in mix design.

(ii) Designated mix was selected from trial mix in first column above.

(iii) Where strength results are not yet available when mix was issued, enter them from Form OB-MT-53 when separately reported.

FIGURE 3-2 MIX DESIGN CARD -- MIX PROPORTIONS

The new sets of information are then key punched and processed through the computer along with all the results to date for that particular class of concrete on the contract. The computer is also programmed to recall from storage any necessary background information. The program is written in Fortran IV and the specific computer used is an IBM 7044 32K.

The printout, on three standard attached sheets, contains the following information. Sheet 1 summarizes the five concrete placements, identifying the location and amount of concrete, how it was produced and placed, what materials and mix were used, and the maximum, minimum, and average results of all tests made on the plastic concrete. Sheet 2 specifically deals with the last five sets of cylinders. In addition to recording the strengths of individual cylinders it presents the statistical analysis for each set and the corresponding tests made on the plastic concrete. Sheet 3 is a graphical presentation of the strength analysis and shows the control chart for the last five sets of tests and a control chart for the whole job to date, averaging each group of five, and including the last five sets of results.

A complete copy of the printout is dispatched at once to those people concerned with quality control on the particular job so that, without reference to individual reports, they have a full picture of concrete quality from the beginning of the work, which is updated by the day after each fifth set of 28-day cylinders is broken.

The reaction of the recipients of the printouts has yet to be gaged. Two attitudes are possible; one would be to find that the evaluation of quality is of real worth to them in their job and as a side effect, because the results now appear to be used by somebody for something, greater attention will be paid to the frequency and accuracy of field testing, cylinder making, handling and curing, and preparation of reports. If, however, the field inspection staff does not accept this new look in quality control, it could become pointless and even dangerously misleading. Signs are hopeful that the former attitude will prevail, but any such project must include a selling job to explain what it is all about.

At present it is the 28-day compressive strengths that are being used in the analysis. This means it is over a month after the concrete placement before the engineer knows if it meets the acceptance requirement of the specification or not. This of course is far too late for the full value of the test to be realized. It is of no value for day-to-day control and therefore the 20,000 cylinders made each year by the department at a cost approaching \$100,000 serve only as a very costly and doubtful way of judging concrete acceptability. This has been recognized for some time and considerable effort has been put into the development of an accelerated strength test. One such test⁵ has been in use and

QUALITY OF MATERIALS UPON WHICH APPROVAL IS BASED.

	Coarse Aggregate 1			Coarse Aggregate 2			Fine Aggregate		
Lab. Sample No.	42	51	52	61	62	71			
<u>CARD 7</u>	5	14	15	24	25	34			
Field Sample No.									
Type of Sample	35 Prelim. 1 Routine 2 Prod. 3			36 Prelim. 1 Routine 2 Prod. 3		37 Prelim. 1 Routine 2 Prod. 3			
Los Angeles Abrasion	38 40			41 43					
MgSO ₄ Soundness	44 46			47 49		50 52			
P. N.	53 56			57 60		61 64			
Flat & Elongated %	65 67			68 70					
Absorption %	<u>CARD 8</u> 5 8			9 12		13 16			
Bulk Specific Gravity	17 19			20 22		23 25			
Clay Lumps %	26 28			29 31					
Freeze Thaw Durability Factor	32 34			35 37		38 40			
Alkali Aggregate Reactivity	41 Positive 1 Negative 2 43 Positive 1 Negative 2			42 Positive 1 Negative 2 44 Positive 1 Negative 2		45			
Organic Impurity						46 Positive 1 Negative 2			
Mortar Making Properties									
Passing No. 200	47 48			49 50		51 52			
"Problem" Agg.	53 Yes 1 No 2			54 Yes 1 No 2		55 Yes 1 No 2			

Remarks based on these samples and inventory record re potential quality problems and need for production samples as work proceeds. _____

District and Region advise: samples acceptable on Date _____ Signed _____

FIGURE 3-4 MIX DESIGN CARD--QUALITY OF AGGREGATES

is a specification requirement for certain work such as concrete pavement. This and other promising procedures are currently being evaluated by a subcommittee of ASTM Committee C9. Development of a standard accelerated strength test is one of the main needs of concrete technology at the present. A review of the subject⁶ suggests that this will probably happen in the not too distant future. While initially it may be used only as a control test to check the likely corresponding 28-day strength there is a very strong possibility that it will eventually replace the 28-day test. When confidence is sufficiently established to permit this, the whole concept of concrete strength testing and its value and use for both control and acceptance purposes will be completely revolutionized and the computer evaluating program will attain its full worth.

A valuable side effect of the program is that it includes information on the number of each kind of test made in relation to the amount of concrete placed. The result of this--especially when studied in relation to performance, control levels, and testing costs--may well be to show that some tests are more valuable than others and that each has an optimum frequency.

Lastly, the report forms provide information necessary for accountants to bill and recover the cost of tests. Also, to gladden their hearts and those of business efficiency experts, it may be remarked that three forms replace the twelve forms previously used to attain the same end.

PHASE II -- MATCHING CONCRETE MATERIALS TO STRUCTURAL DESIGNS

Lount⁷ has stated that "Among the principles that need to be reviewed is our conception of safety factors and load factors. As long as the same design structure can be built by two different contractors and have two different collapse loads, we cannot be satisfied that our concept of load factors is soundly based. Essentially, we want a structure to sustain the loads which it may reasonably be expected to carry--presuming that reasonable care will be exercised in its construction. This can be stated in terms of probability."

He continues by illustrating that there could be tight or wide probability curves for structural loadings, just as there are for good or poor inspection and quality control, with the end result being to pile the material and control probability on top of the design probability. In concluding, he suggests that the system should be considered as a whole. "..... On critical work, why should not the tightly controlled job be designed for a lower factor than the job with little control? The cost of control and inspection becomes then a real factor in design.

W. P. No. _____

Date by which Mix is Required in the Field _____ Contract No. _____

REQUIRED CONCRETE PROPERTIES _____ 28 29 Service _____ 30 31 Effective _____ 32 34

Type of Concrete Work _____ Conditions _____ W/C Ratio _____ 35 39

Class of Concrete : Comp. Strength _____ Flexural Strength _____ Quantity of Concrete in this class cu. yd. _____ 35 39

Cement _____ 40 Type _____ 41 42 Admixture _____ 43 44 Slump ins. _____ 45 46 Air Content % _____ 47 48

Remarks _____

Initialed _____ Date _____

MATERIALS USED IN MIX DESIGN		Coarse Aggregate 1		Coarse Aggregate 2		Fine Aggregate	
Lab. Sample No.	3	14	15	24	25	35	36
Field Sample No.	36	43	46	55	56	66	67
Nominal Max. size or F.M.		67	68	70	72	73	75
2"		3	7	9	10	3/8	11
1 1/2"		14	16	17	19	" 4	20
1"		23	25	26	28	" 8	29
Gradation		32	34	35	37	" 16	38
% Retained		41	43	44	46	" 30	47
Depl. Designated		50	52	53	55	" 50	56
Sieve		59	61	62	64	" 100	65
Size		68	70	71	73		74
No. 4		74	76	77	79		80
Passing No. 200							
Absorption %	Determined 1 5 6 9	Determined 1 10 11 14	Determined 1 15 16 19				
Bulk Specific Gravity	Assumed 2 20 21 23	Assumed 2 24 25 27	Assumed 2 28 29 31				

Mix Design Aggregate samples : _____ 32

meet specification and are acceptable _____ 1

or acceptable but outside limits _____ 2

Note of deficiencies _____

Signed _____ Date _____

Where Concrete is Ready Mixed, Name and location of Plant _____

33 - CODE _____ 41

Quality rating _____

FIGURE 3-3 MIX DESIGN CARD -- REQUIRED PROPERTIES AND AGGREGATE GRADATION

"The over-all probability of failure is a combination of many factors, which are not well considered in our present approach to design. The fact that an analysis based on the probability of failure becomes practical when the computer is used as a tool, means that our approach to many aspects of our work must be re-examined."

If Phase 1 of the program results in a reduction of one probability, that of concrete variability, and at the same time provides early assurance through accelerated strength testing as to the ultimate strength potential and quality of the concrete, much will have been done to build up the designer's confidence to examine this approach to design or at least to try more daring designs on conventional theories.

Daring designs, no doubt themselves refined by the computer, will demand the optimum materials for building the structure. A couple of examples may serve to illustrate what this may require in the selection of concrete and concrete materials.

The recently constructed Willows Creek Bridge in Toronto is a large structure (88 ft wide, 790 ft long, and composed of five spans) with several unusual features.⁸ The fifty prestressed concrete beams, each 158 ft long and 8 ft 3 in. high and containing 62 cu yd of concrete, are of specific interest to this paper. The designer specified that the concrete should have a minimum compressive strength at 28 days of 6000 psi. This was to be the first break through the 5000-psi barrier in the area and there was some concern as to how this might be achieved.

An initial meeting was devoted to trying to find out what the designer meant by "minimum compressive strength 6000 psi at 28 days." Was it 100 percent, 95 percent, or 90 percent of all test results? Was it to be judged on cylinders cast horizontally or vertically? In what sort of mold? Field cured or laboratory cured? Capped or with the ends sawn? Or did he really mean every little bit of concrete in the beam after steam curing, or after steam curing plus a period of normal curing or air drying? Did he care how far above 6000 psi some of the concrete was? and so on.

These questions having been somewhat resolved, the following steps were undertaken to determine how such concrete could be made:

1. Analysis of the capability of the ready-mixed concrete producer to attain a low coefficient of variation so that the required strength need not be set unduly high.
2. Selection of a concrete mixture of the required properties, principally excellent workability with high strength.

CARD 1

Sheet No. 2 Beams or Cyls. 5 No. Sets Today 6 Costs Recoverable 7

DEPARTMENT OF HIGHWAYS - ONTARIO

REPORT ON CONCRETE STRENGTHS

Dist. No. 11 Hwy. No. 13 Cont. No. 17

Date Placed 27 Day Month Year

Date Received 38 Day Month Year

Date Tested 58 Day Month Year

Age at Test 66 67

Specified Class of Concrete Compressive Strength p.s.i.

Flexural Strength p.s.i.

Cylinders or Beam not from D.H.O. contract report results and bill to: _____

Dist. Engineer _____

Copy for Principal Materials Engineer _____

Strength results on beams or cylinders sent in for test are reported to the left. Before assessing these results and to determine the location of the concrete represented first fold this report and attach over top right hand corner of the corresponding Concrete Construction Report carrying same report No.

FORM OF BREAK: for cylinders is indicated by:

1 Satisfactory break, e.g.

or 2 Unsatisfactory break, e.g. When a cylinder breaks as 2 the result may not be indicative of the strength of the concrete.

For beams form of break is indicated by:

3 Break mainly in paste or in aggregate bond

or 4 Coarse aggregate largely broken

or 5 Break is combination of 3 & 4

CONDITION: refers to cylinder or beam as received at Laboratory:

1 Specimen improperly made, testing not possible.

2 Specimen damaged, testing not possible.

3 Concrete Frozen.

4 Cardboard Cylinder Mold.

5 Heavy Metal Vertical Cylinder Mold.

6 Heavy Metal Horizontal Cylinder Mold.

7 Tin Cylinder Mold.

WEIGHT OF CYLINDER: The cylinder is weighed upon arrival in the lab. to provide early information on possible deficiencies in the quality of the concrete. Cyls. weighing less than 27 lb. warrant immediate investigation.

Remarks _____

Condition	Wt. of Cylinder	Form of Break	Field No.	Strength p.s.i.
5	6	8	10	11
28	29	31	33	34
51	52	54	56	57

71 A. Rutko Materials & Testing Eng.

FIGURE 3-5 CONCRETE STRENGTHS REPORT FORM

3. Selection of suitable constituent materials at the lowest cost.
4. Construction technique selection for placing, consolidation, and curing to suit the ideal concrete designed rather than the converse.
5. Consideration of the method of testing most indicative of the true strength of the concrete.

Using present manual methods, many hours of record searching, manual statistical analysis, visiting and sampling aggregate sources, making trial mixture designs, and several additional meetings between the parties concerned were required.

In the future the quality control phase of the computer project will build up an inventory from which the required information can be extracted to narrow down the possibilities. Obviously, previous mixture designs can be searched for those which, on the basis of laboratory trial mixes and subsequent field performance, show promise for high strength with good workability. Also, the producer's ability can be statistically analyzed on the basis of strength results on previous work. Less obviously, but of great help, because each aggregate or other material source is coded (see Figure 3-2) it will be possible to call forth the past physical and other test results on any likely constituent material. In this case, for example, it would be helpful for locating aggregates having a good shape and suitable maximum size, with constant and ideal gradings that have proved to have adequate strength and bond-to-paste characteristics. It would also be interesting to look at the strength-producing properties of the alternative cements in combination with various admixtures for different steam curing cycles.

The second example serves to emphasize the tie-in needed with research on materials. Shrinkage and creep, even after decades of study, are still a problem to designers since they do not know precisely what to expect and hence must make somewhat undue allowance for their effects. The materials used to make concrete, especially the aggregate, have a large influence on the amount of shrinkage. Following a recent over-all assessment of their influence by Tremper and Spellman⁹ detailed material investigations for specific projects are now becoming routine, especially in the San Francisco Bay area. A good example of the way a daring design benefits from this approach was in the construction of the Stanford linear accelerator described by Osgood and Keith.¹⁰

Concern with selecting aggregates, cements, and admixtures to minimize drying shrinkage and creep will undoubtedly become of increasing importance, and designers are going to demand

both more specific information and the better control of these properties. This will first require considerable applied research on local materials. If the results of this research are stored in the right form, they could be retrieved along with other significant information and quickly matched or compared through the computer with what is required to realize a design concept, so that undesirable side effects are minimized and the properties sought in the concrete are enhanced.

In the beginning, the second phase of the computer project will merely offer assistance to the designer through material selection and better control. In the long-term view it may result in a complete integration of material technology and structural design. This phase of the project will only become operable as inventory data accumulates with time. The alternative would be to speed up the process by feeding the system with data obtained from past experience. This would involve considerable work and is not contemplated.

PHASE III -- COMPUTER AND PERFORMANCE STUDIES

Like the weather, everybody talks about the performance of concrete, but in practice they are able to do little about it when it proves inadequate. Only when a problem reaches epidemic proportions--for example salt scaling, sulfate attack, or aggregate-alkali reactivity--do the results of performance investigations and research inspired by them receive adequate feedback to the designers and specifiers. Even then there is usually an unnecessary time lapse so that the original deficiencies continue to be repeated. There is, therefore, a need for better understanding of those factors which affect concrete performance, for greater ease in locating the results of applicable research from throughout the world, and for better correlation and dissemination of the conclusions reached. If the computer project can help achieve these things, tremendous advances in the understanding of concrete and application to future work through better specifications will result.

Performance studies of concrete in service involve five principal types of investigation:

1. Assembly of records
2. Condition surveys of structures
3. Sampling
4. Physical tests on samples obtained
5. Analytical techniques--physical, chemical and microscopical

In setting up the Department of Highways' computer and concrete project, it was decided to try to make it compatible with assisting such a study. Records for future retrieval will be automatically stored during Phases I and II of the project. They will therefore include: all the data on the concrete and concrete materials used; the analysis made of test results, especially strength; the location of particular concrete placements; and the general influences on concreting operations such as the weather conditions and the methods used.

The people who understand computers say this will permit such things as:

1. The record for any given structure to be called for and printed out.
2. Any factor common in performance to be identified for study; for example, a list of all structures that contain suspect aggregate "X" could be printed out.
3. Any variable under study to be compared with any other variable to see if it appears significant in relation to the observations made on the present condition of the concrete.

The recording of performance features is one of the areas of the project that is only just opening to study. There are many questions to resolve. These are largely concerned with the nature of the observation and how to set numbers against it. When the observation results from a test this is already done, but when it is visual or subjective it is another matter. How do you classify differences in exposure or a pattern of cracking with numbers? It would be very helpful if the present work of ACI Committee 201, Durability of Concrete in Service, could lead to a recommended practice in this respect.

The department has a pilot performance study currently under way but it would be premature to report upon it at this time. This aspect of the project is now receiving great attention since performance is the ultimate judge of the adequacy of everything that has been done to insure good quality concrete.

FUTURE DEVELOPMENT

The three phases described are the extent of the present scope of the department's computer project. This is by no means all that could be done, especially in the area of performance studies, if every modern aid were used regardless of cost.

Computers have proved invaluable in making sense out of full-scale research projects such as the AASHTO test road, and the data arising from almost any field or laboratory investigation

of any complexity are analyzed more readily by their use. It is possible, in the mind's eye, to see the intermediate step of manually recording and collecting data being replaced by a direct connection between the recording instrument and the computer. This would be of particular value in performance studies. Permanently installed measuring devices could maintain a constant surveillance on the behavior and environment of a concrete structure or pavement in service.

For example, using only techniques we know of at the moment:

1. Loads and frequency of application could be measured by load cells.
2. Strategically located strain gages could record the response of the concrete.
3. Ultrasonic testing could warn of the onset of cracking or deterioration indicated by a reduction in amplitude or pulse velocity.
4. Electrical potential readings could indicate the onset of corrosion in embedded materials.
5. Temperature changes, moisture conditions, number of freeze-thaw cycles in the concrete and ambient weather conditions could be recorded.

While similar things are being done every day as part of the space program, complexity, cost, and lack of a clearly established need preclude application to concrete at present. However, if the little black boxes were built into each structure now, the data could be collected during say the 1984 annual inspection for analysis by a computer at its leisure. This proposal, which is equivalent to the installation of such recorders in aircraft to monitor performance in case of accident, is within practical bounds.

The other areas for the future wider application of computer-based techniques to concrete are well known and beyond the scope of this paper. They include such things as the general problem of reference and information storage and retrieval and the application of critical path methods to design and construction programming which, when in general use, will also offer considerable help in taming the information-construction explosion.

CONCLUSIONS

The realm of concrete as king of construction materials is limited only by its own weaknesses. These stem from imprecision in structural design, lack of knowledge of many properties,

or uncertainties as to uniformity or performance in the structure. While many of the problems are widely recognized each of us tends to concentrate study only on one particular aspect without due thought that the factors involved are complex and other work must be taken into account to arrive at the complete answer.

The first thing that needs to be done is obvious. Designers, material experts, producers, and users should all work together more closely to identify problems, initiate the search for solutions, and then appraise and apply the results. This might best be done through greater participation in the work of ACI technical committees.

The second thing is that the use of computer-based systems for data processing and analysis and for information storage and retrieval may be the needed key to unlock many of the doors that are still closed in concrete technology.

The Department of Highways, Ontario has initiated such a system with the hope that one key may open three locks: construction quality control, material selection, and performance studies. This should permit the concrete engineer to better evaluate and use the information at his disposal for the control of concrete quality at the time of construction. Since it is essential to have the facts in time for them to be of practical value, accelerated tests, especially for strength, should be developed and used.

The information accumulated for quality control will also serve to provide a more realistic basis for selection of materials, performance studies, and improved specifications for future work.

The initial phase of the project is now in operation and is just starting to prove its value in day-to-day control. Though much remains to be done, especially in the area of performance studies, progress is encouraging and the possibilities for overall improvements in concrete technology appear immense and exciting.

Computer skeptics may at least be comforted to know that by making 20,000 concrete cylinders per year and analyzing the results, one computer can be kept out of other mischief for a couple of minutes per working day.

ACKNOWLEDGEMENTS

This project was initiated by the Materials and Testing Division of the Department of Highways, Ontario as part of its continuing program for the improvement of concrete quality. The staff of the computing center prepared the necessary program and are responsible for processing the data.

The paper is presented by permission of H. W. Adcock, Assistant Deputy Minister (Engineering).

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PAPER SP 16-4 In proportioning concrete mixtures with the aid of computers, due regard must be given to such parameters as rheological properties of the mix and intensity of vibration. Translation of given relations into mathematical formulas presented here makes it possible to use automatic computers to calculate parameters of the mix. Simple relations are summarized in flow chart and block diagrams, and the calculations necessary for checking and adjusting the mix are introduced. After a simplification of the theory, the derived relations can be applied in practical production of ready-mixed concrete and in batching plants of large construction firms which have computers available. The whole process of computation is demonstrated by practical examples.

Proportioning Concrete Mixes Using Digital Computers

By J. STORK

USE OF COMPUTERS for the proportioning of concrete mixes presupposes the derivation of theoretical relations that are necessary for the transition to automatic control in the production of precast concrete elements. The theoretical bases for the development of such production control have been published,¹ and now research workers are studying the possibilities of their practical application. The present paper covers only that part of the theory which can be applied for proportioning of the concrete mix.

To facilitate computer applications for mix proportioning problems, it was necessary to fulfill the following conditions:

- a. To derive a reversible relation between the mix composition and the consistency, established by a sufficiently precise method.
- b. To derive the relation between the mechanical properties--mainly that of strength--and the consistency of the mix, assuming that the same parameters are applied as have been used when determining the reversible relation between the composition of the mix and its consistency.
- c. To establish the relation between the consistency and the intensity of compaction (vibration) on one hand, and the

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time required for almost complete compaction of the concrete mix, given by the degree of compaction $H = 0.99$ (i.e. 1 percent of voids is tolerated) on the other.

d. To formulate all necessary relationships by means of mathematical equations, thus enabling the use of digital computers.

To fulfill the requirements of (a) and (b) it was necessary to introduce a whole series of new material characteristics which will be defined in the text. In doing so we have availed ourselves extensively of physical values that can be determined objectively, while empirical values have been applied only in a limited degree.

The relationships we have set up for proportioning concrete mixes are numerous, and we shall give here only the basic equations from which an entire series of other relationships can be derived. In doing so we have tried to use, as far as possible, those relationships which are familiar and well-established. Only when we could not find a required equation in published literature, did we derive a new relation. The reader may examine Reference 1 for further data.

The mathematical theory of mix proportioning does not exclude the use of other relationships besides those given here as long as they have been verified and as long as they are structurally similar to those we have applied, and provided that they are connected with other relationships of the material properties or with the considered parameters.

To obtain these connections many known relations had to be transformed, or adjusted in such a way as to conform to reversible connections. These known relations are not given here in their original form, because in that form they do not fit into our theory.