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 sucessfully, 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

G. B. SOUTHWORTH has been with Master Builders, Cleveland, for 28 years, the major part of which has been spent in field engineering and in training throughout the United States, Canada, and several other countries. Mr. Southworth has written numerous papers on concrete proportioning and control and is well known as a lecturer on the production and use of concrete. He is an ACI member.

NEIL M. MOSS, a recent graduate of Case Institute of Technology, is also an ACI member and a member of ASCE. Mr. Moss is the author of several papers concerning computer simulation. Since 1963, he has been with Master Builders as a computer programmer and statistical analyst. He is currently enrolled in graduate study at Harvard University.

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 RANGE	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	248	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	125	3.2112
18	4935	5094	5014	4925.6110	5177.0000	8.3600	3.3967	159	177	128	3.1886
19	5129	5414	5271	4943.7894	5184.1999	8.2517	3.4628	285	183	156	3.2786
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	3.5868
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	9.3898	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	3.3118
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	3.0908
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	186	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	3.6786
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	2.9406	89	192	285	3.5903
48	5041	5218	5129	4752.3541	4783.7999	8.5639	4.8656	177	192	260	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

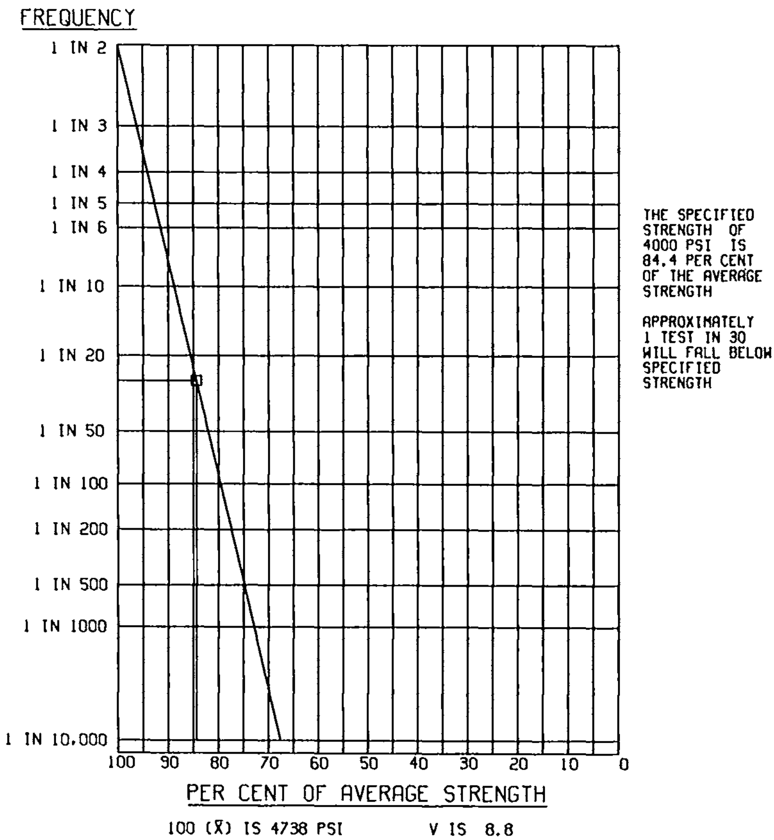

FIGURE 1-2

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.

V. M. MALHOTRA is a graduate of both Delhi University and the University of Western Australia. His experience in concrete technology and soils engineering includes work on hydroelectric projects and in the construction industry in Australia, India, and Canada. In 1962, Mr. Malhotra joined the Construction Materials Section of the Mines Branch, Department of Mines and Technical Surveys, Ottawa, Ontario, where he is engaged in applied research in the field of concrete and concrete aggregates. He is affiliated with both ACI and ASCE, and currently serves on ACI Committees 118 and 214.

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.:

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

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:

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

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	.11905714E+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