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FINAL REPORT

STATISTICAL METHODS FOR THE QUALITY CONTROL OF STEAM CURED CONCRETE

by

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(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

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PREFACE

This project was initiated at an early stage in the development of nation-wide interest in the application of statistical concepts to the evaluation of highway materials and processes. The goal was to evaluate the applicability of several statistical techniques to the processing of concrete for prestressed elements. The goal was not to influence the production on which the data were being gathered. The production was being evaluated conventionally; i.e., on the basis of attainment of the detensioning strength within a specified time period. In a few cases, the application of the evaluation techniques described in this paper during production would have suggested action which may or may not have been taken under the existing and conventionally accepted criteria being used.

The developing emphasis on statistical techniques, and the ultimate indication of the need for corrective action using the conventional approach to evaluation and control enabled inspection personnel to correct most deficiencies although the necessary action might have been apparent earlier from use of the procedures suggested from this project. Despite the fact that the objective of this report was not to influence the production, concern for values which did not conform to the statistically established limits was inevitable.

Although not a part of the project, data obtained subsequent to the study were analyzed to ascertain the degree to which corrective actions taken by project personnel had been effective. These data are included for information as appendix material and are not a part of the project report.

SYNOPSIS

Concrete strength test results from three prestressing plants utilizing steam curing were evaluated statistically in terms of the concrete as received and the effectiveness of the plants' steaming procedures. Control charts were prepared to show trends in the data, the batch-to-batch variability of the strengths for both the 28-day moist cured and the steam cured samples (age approximately 20 hours), and the fluctuations in the efficiency of the processing.

The moving averages for range were computed to supplement the information provided by the control charts.

Analysis of variance were used as a means of examining the flow of variations within and between batches and for comparisons of steam cured versus moist cured strength variations.

The statistical techniques employed in this study revealed considerable promise as a means of aiding the production of uniform, high quality, steam cured concrete for prestressing. It is hoped, therefore, that this study may form the basis for the development of statistical plans, programs, and procedures for effective and economical quality control in the production of steam cured concrete.

While the techniques have been applied to concrete, they are equally applicable to other materials such as bituminous and pug mill mixtures, and stabilized materials that are subjected to processing.

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INTRODUCTION

All the concrete prestressing plants in Virginia and most of those throughout the nation use a steam curing process or other source of heat to accelerate the strength gain of their products. When problems associated with low strength steam cured concrete arise at the plants, the underlying cause is not always recognizable. It is often easy to attribute the problem to the steaming procedure, because of the tendency to assume that concrete delivered to the plant is reasonably uniform and of adequate quality. But many factors, such as the characteristics of concrete materials, proportioning, and mixing can reduce the uniformity of the incoming concrete. Atmospheric conditions, production schedules, steam generating equipment, etc., all can contribute to the lack of uniformity in concrete cured under the steaming process. Consequently, when low strengths have been a problem, it has been difficult to definitely determine whether the concrete or the steaming procedure has been faulty.

It is easily seen that the complexity of the variables associated with the production of steam cured concrete make absolute uniformity impossible; however, excessive variations in concrete strengths signify inadequate control. The application of statistical evaluation procedures to the strength results of the steam and moist cured companion specimens provides a means by which the uniformity of both the incoming concrete and the steaming procedures can be examined independently and the general quality of the production of prestressing plants thus evaluated. The use of statistical methods should lead to a more uniform quality product, since the producers can apply the statistical techniques to their own processing and the consumers can use the evaluations to assess the producers' adherence to reasonable standards of uniformity and quality.

PURPOSE AND SCOPE

The purpose of this study was to investigate the feasibility of using certain accepted statistical techniques to aid in the administering of a quality control program for prestressed concrete producers and consumers. It was believed that the utilization of these statistical procedures would assist the producers in more readily recognizing and understanding the causes for out of control processes and provide the consumers with a means of checking the quality of the product.

The study was primarily directed to an examination of the data by control charting and variance analysis. A less widely used technique, variation flow analysis, was also studied.

Regression analysis of steam and moist cured strengths was applied but the results are not reported; instead a numerical value termed "strength efficiency" is included. This value of strength efficiency provides more information for the producer and is more amenable for use by both the producers and consumers than are data provided by regression analysis.

The use of control charts for steam and moist cured strengths and efficiency should provide the producer and consumer sufficient information to recognize any need for correction in the production process. If additional information regarding the causes of unusual variation is desired, some insight may be gained by employing control charts of the moving average for the range, and analysis of variance and variations flow analysis.

To illustrate the use of these procedures, data from three prestressing concrete plants in Virginia were secured and processed. Variance analysis and variation flow analysis were not applied to the data from these plants; however, an example using these procedures is shown for illustrative purposes.

PROCEDURE

All data were taken from Virginia Department of Highways stressing and pouring reports (Form TL-62), which are generated by VDH inspectors at the prestressing plants. A copy is shown in the Appendix (see Figure A-1). A sample was comprised of two steam cured and two moist cured specimens from the same batch of concrete. The strength values plotted and analyzed are the result of averaging the strengths of two similarly cured specimens; thus steam and moist strength values are provided for each batch of concrete sampled. Both the steam and moist cured specimens for a particular plant were tested on the testing machine located at that plant. This is a normal procedure that was of particular importance to the minimization of testing (principally, machine and capping) error in this study. The test reports were arranged chronologically and from each report data were extracted and tabulated as shown in Table I.

The column headed "Eff'y" indicates the above mentioned strength efficiency value, which represents the ratio of the strength of a steam cured sample to that of a 28-day moist cured specimen in percent. This value provides an index of the efficiency of the steam curing process in developing the strength potential of the concrete as measured by the 28-day moist cured tests. While the steam cured strength is not generally expected to equal the 28-day moist strength, the degree to which such strength is attained should indicate the efficiency of the steaming process when other factors remain unchanged. Not all the data tabulated as shown in Table I were analyzed statistically. Data such as temperature, slump, water content, etc. were collected and examined to monitor any changes in concrete characteristics occurring at the plants. Typical results used in this report are shown in Table II.

Control Charts

The use of control charts[1] permits a manufacturer to distinguish trends in data and to make adjustments in his production process if the trends are undesirable. For this project, control charts were prepared to show chronologically the trend in variability between batches of concrete for steam cured strength, 28-day moist cured strength, and strength efficiency. To show the trend of variability within the two-specimen samples, control charts of moving average range were plotted. The variability between batches is a measure of overall differences in materials and testing. The within test variability is primarily a measure of differences in the sampling, storing and testing of specimens. The charts were prepared after all of the data were compiled. The procedures are, of course, intended for concurrent plotting and interpretation. The grand average of sample averages ($\bar{\bar{X}}$) is commonly used in control chart construction; however, it was used only in constructing the charts for strength efficiency in this project. In order for a producer to initiate the use of control charts, he must have previous strength results available from which to compute or estimate the standard deviation, (σ), a measure of data dispersion discussed in detail later that is necessary for satisfactory production. This standard deviation is used to establish the lower and upper control limits (LCL and UCL). Thirty to fifty reliable strength results are generally sufficient for calculating the upper and lower limits of control charts. The control limits shown in this paper were calculated by using the first fifty strength results from the one-hundred total (see Table III).

From a survey of available literature[2] it was concluded that a realistic standard deviation for compressive strength of moist cured specimens was 525 psi. Had this value been used for initial establishment of the control limits, the indications would not have been significantly affected. It appears from the very limited data in Table III that the standard deviation of steam cured concrete would generally fall between 400 and 450 psi.

TABLE I

TYPICAL DATA

Plant: ____________ Project No: ____________ Bridge Over: ____________

Contractor: ____________ Cement: ____________ Route No: ____________

Sample No.	Report No.	Date Cast	Min. Air Temp.	Max. Air Temp.	Min. Conc. Temp.	Max. Conc. Temp.	W/C	Slump	Air Content	Retarder	Moist Cured Str. #1	Moist Cured Str. #2	Moist Cured Avg.	Moist Cured Range	Steam Cured Delay Hrs.	Min. Delay Temp.	Max. Delay Temp.	Steam Hrs.	Min. Steam Temp.	Max. Steam Temp.	Total Age	Str. #1	Str. #2	Avg.	Range	Eff'y, %
		1965																								
1	136-1	10-12	72	81	79	81	.649	2.25	2.1	3	5950	6270	6110	320	8.25	78	98	12.0	153	158	20.75	4780	4640	4710	140	77.1
2	-2	10-14	76	81	78	82	.648	3.0	1.9	3	5910	6230	6070	320	7.5	90	94	12.0	150	154	20.0	4180	4180	4180	0	68.9
3	-3	10-16	64	70	80	82	.667	2.0	1.9	3	7260	7120	7190	140	7.75	80	90	16.0	150	158	24.2	4810	4380	4595	430	62.5
4	-5	10-21	66	72	79	80	.652	1.5	2.6	3	6620	6300	6460	320	6.5	78	91	15.0	152	158	22.0	4420	4460	4440	40	68.7
5	-6	10-22	70	73	80	81	.652	2.0	2.6	3	7260	6900	7080	360	7.25	84	100	12.0	150	158	19.25	4960	4880	4920	80	69.5
6	-7	10-25	57	63	73	76	.652	2.25	2.7	3	6830	6410	6620	420	7.25	70	82	12.0	154	159	19.75	4570	4750	4660	180	70.4
7	-8	10-26	60	68	73	75	.652	2.25	2.6	3	6660	7220	6940	560	7.5	76	90	12.25	151	157	20.25	4750	4780	4765	30	68.7
8	-9	10-29	48	48	67	70	.652	1.25	2.5	3	7010	6300	6655	710	7.5	67	108	12.0	150	158	20.0	5270	5520	5395	250	81.1

TABLE II

TYPICAL RESULTS USED IN THIS REPORT

PLANT ____________

Sample No.	Moist Cured Strengths, psi Spec. # 1	Spec. # 2	Avg.	Range	Steam Cured Strengths, psi Hrs. Steamed	Spec. # 1	Spec. # 2	Avg.	Range	Eff'y, %
1	5,950	6,270	6,110	320	12.0	4,780	4,640	4,710	140	77
2	5,910	6,230	6,070	320	12.0	4,180	4,180	4,180	0	69
3	7,260	7,120	7,190	140	16.0	4,810	4,380	4,595	430	63
4	6,620	6,300	6,460	320	15.0	4,420	4,460	4,440	40	69
5	7,260	6,900	7,080	360	12.0	4,960	4,880	4,920	80	70

TABLE III

PRESTRESSING PLANTS — STANDARD DEVIATIONS AND GRAND AVERAGE OF STRENGTH EFFICIENCY
(Computed from first fifty samples)

Prestressing Plants	Standard Deviation, σ, psi			Grand Average ($\bar{\bar{X}}$) Strength Efficiency, %
	Steam Cured	Moist Cured	Efficiency	
1	560	520	12	82
2	430	520	6	70
3	420	480	8	65

These values appear to be close to those found in accelerated curing work.[3,4] The remaining fifty results comprise the sample points shown on the control charts. The control charts were constructed as described below.

Steam and Moist Cured Strength

The average strength in psi from the two specimens (sample size, n = 2) was plotted for the successive samples. Upper and lower control limits were drawn at a distance of four standard deviations apart. (See Table A-I of the Appendix for example of these calculations.) The LCL of the steam data was located at 4,200 psi and that of the moist data at 5,200 psi, which is 200 psi above the minimum specification limit. The customary procedure of constructing the control limits at ±2 standard deviations from the grand average of sample averages was not used in this report because it caused the LCL to frequently fall below the specification limit (SL); thus the examples displayed would seem to indicate that the process was in satisfactory control when values were plotted below the SL. For the purpose of this study, 4,000 psi and 5,000 psi were used as lower specification limits for steam and moist strengths, respectively. The 4,000 psi SL represents the minimum detensioning strength for prestressed members, and 5,000 psi the minimum 28-day moist cured strength for the control specimens. If the LCL had been located on these SL's, values would fall out of control and below the SL simultaneously and provide no warning for the user of the chart. On an arbitrary basis, the LCL was therefore placed at 4,200 psi and 5,200 psi for the steam and moist values, respectively, to allow the user a margin of 200 psi between the LCL and the SL. With this buffer zone, (about 1/2σ) corrective action can be taken when values fall near the LCL so as to prevent future values from falling below the SL. The placing of the UCL and LCL four standard deviations apart permits the user to assume confidently that there is a 95 percent probability that the process is in control when the values fall between the control limits. In other words, if action is taken when a value falls outside the control limits (these values are shown as black dots) one should understand that 5 percent of the time this action would be taken without cause.

UCL's are significant in the examples because in the production of prestressed concrete control of the camber (the upward sway) of members is important. It is known that the amount of camber depends upon, among other factors, the strength of the concrete. It is generally desirable to maintain a uniform camber in the members on any particular job. By employing UCL's, the chart user places constraints upon the use of excessively high quality concrete and can thereby manufacture structural members with more uniform strength values and reduce differential camber problems.

In some of the examples used steam values fell below the lower specification limit of 4,000 psi. However, this does not mean that subpar concrete was being accepted, but only that after a given duration of steaming (12 to 16 hours for the data in this paper) the strength of the concrete had not yet risen above 4,000 psi and further curing of the member and remaining test specimens was necessary.

Strength Efficiency

The procedure used in establishing control limits for strength efficiency were the same as those used for the steam and moist cured strength, except that the control limits were placed at ±2 from the $\bar{\bar{X}}$ of the first fifty samples.

Moving Average For Range

The moving average for range is plotted for the average range of the previous ten groups of companion cylinders. The maximum average range allowable for fair to good field control is plotted.(1)

Concrete quality will be penalized unnecessarily if tests show greater variation than actually exists. The range between two companion cylinders from the same sample can be assumed to be the responsibility of those who make, handle, and test the specimens, and a control chart for ranges will thus provide a check on the uniformity of these operations.

The relationship establishing the value of maximum average range is expressed by the following equation:

$$\bar{R}_m = V_1 d_2 f_{cr}$$

where $\bar{R}_m$ = Allowable maximum average range.

V_1 = Within test coefficient of variation expressed as a decimal. In this study, a value of 0.05 was used, which is classified by the American Concrete Institute as fair to good control.

d_2 = A constant depending on the number of specimens per sample. In this study, with 2 specimens per sample, d_2 is given as 1.128 (see the American Concrete Institute reference for d_2 values for greater numbers of specimens per sample).

$$f_{cr} = \frac{f'_c}{(1 - tV)}$$

where

f_{cr} = Required average strength.

f'_c = Design strength specified, 5,000 psi used in moist cured charts and 4,000 psi used in steam cured charts. The latter value is the minimum detensioning strength required and, when reached, steam curing is generally discontinued.

t = A constant depending upon the proportion of tests that may fall below f'_c and the number of samples used to establish V. A value of t of 1,282 was used in this study which provides a chance of 1 in 10 tests falling below f'_c and is established for a number of samples greater than 30.*

V = Coefficient of variation expressed as a fraction. In this case a value of 15 was used (expressed as a fraction = 15/100), which is classified by the American Concrete Institute as fair to good control for the overall variation in general construction.

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*In the calculation of f_{cr}, the use of the constant "t" implies a proportion of test results will be expected to fall below the value of f'_c used in the equation. If a value of 4,000 psi is used for f'_c of steam strength, as is done in this report, then it must be accepted that under satisfactory control a certain number of strength values should be expected to fall below the 4,000 psi level. If strength values of less than 4,000 cannot be accepted, then additional steam curing would be necessary. Likewise, in the use of 5,000 psi for the f'_c of moist strength, a certain proportion of strength values should be expected to fall below the value of 5,000 psi. If moist strength values of less than 5,000 psi are unacceptable (in reality it is impossible to guarantee against this condition) then a larger "t" value must be used (i.e., a higher average strength must be maintained) to lessen the chance of moist strength values falling below the value of 5,000 psi.

Analysis of Variance and Variations Flow Analysis

Analysis of Variance

Data are subjected to an analysis of variance[5] in order to isolate and trace the flow of the sources of variation present. The principal terms used in the analysis and an example of analysis of variance are presented below.

Standard Deviation

The standard deviation is probably the most widely used measure of variability. A group of data usually contains within a range of ±3 standard deviations (3σ) around its average the total items or other units under study.

Variance

The squared standard deviation yields the variance. In an analysis of variance, the use of variance is generally preferable to the use of standard deviation because of the relationship known as vectorial addition in which:

$$\sigma^2_{total} = \sigma^2_{within} + \sigma^2_{between}$$

so that,

$$\sigma_{total} = \sqrt{\sigma^2_{within} + \sigma^2_{between}}$$

Coefficient of Variation

The standard deviation, expressed as a percentage of the average ($\bar{X}$) or mean of the data, yields the coefficient of variation, V. Thus:

$$V\% = 100 \frac{\sigma}{\bar{X}}$$

Analysis of Variance Example

The analysis of variance for within batch, between batch, and total variances for steam or moist cured strengths may best be discussed by use of the sample matrix of data shown in Table IV.

TABLE IV

EXAMPLE OF COMPUTATIONAL PROCEDURES FOR PERFORMING AN ANALYSIS OF VARIANCE

Sample Data Steam (or Moist) Cured Strength, psi

Sample No. 1	Sample No. 2	Total
4,390	4,360	8,750
4,530	4,550	9,080
4,070	4,200	8,270
4,600	4,680	9,280
4,530	4,600	9,130
Total (ΣX)		44,510
Average ($\overline{X}$)		4,451

Computational Steps	Sources of Variation: Between batch Variation	Within batch Variation	Total
a. Enter squared values	$8750^2 + 9080^2 - 8270^2$		$4390^2 + 4530^2$
	$+ 9280^2 + 9130^2$		$+ 4680^2 + 4600^2$
b. Sum of "a"	396,877,100		198,543,300
c. No. of tests per each entry in "a"	2		1
d. Crude sum of squares "b"/"c"	198,438,550		198,453,300
e. Correction factor, C $C = (\Sigma X)^2/N$	198,114,010		198,114,010
f. Corrected sum of squares	$d_1 - e$ 324,540	$f_3 - f_1$ 14,750	$d_3 - e$, 339,290
g. Degrees of freedom	n - 1 4	$g_3 - g$, 5	N - 1 9
h. Mean square "f"/"g"	81,135	2950	37,699
k. Component of Variance	$(h_1 - h_2)/c_1$ 39,093	h_2 2950	$k_1 + k_2$ 42,043
l. Std. Deviation, $\sqrt{k}$	198	54	205
m. Coef. of Variation $V - 1/\overline{X} \times 100$	4.4	1.2	4.6

Variations Flow Analysis

Variations flow analysis (6) is used to trace the relationship among the components resulting from a variance analysis. Greater insight into plant operations is gained by applying variations flow analysis procedures to the variance components. A sample of the variations flow anlaysis concepts applicable to the conditions of this study is given in Table V. The interpretation should be considered theoretical and tentative at present.

TABLE V

INTERPRETATION OF VARIATIONS UNDER VARIATIONS FLOW ANALYSIS PRINCIPLES

Type of Variation	Moist Cured	Steam Cured	Interpretation of the Variations Observed
Within batch	low	high	Inconsistencies in equipment, methods, and operators during production of each batch.
	high	high	Excessive fluctuation in raw materials from which each batch was produced.
	high	low	Unlikely in many processes and faulty testing or calculations or inadequate data would be suspected. But steam curing appears to have a modulating effect on the within batch variation of early compressive strength that results in this configuration of within batch variation.
Between batch	low	high	Excessive differences, from one batch to the next, equipment, methods, and operators.
	high	high	Excessive differences in quality of raw materials from shipment to shipment.
	high	low	Unlikely. Look for faulty testing or calculations or inadequate data.
Total	low	high	Raw materials generally seem to be uniform but there are processing problems in steam curing.
	high	low	Unlikely. Look for faulty testing or calculations or inadequate data.

Notes: There usually is no need to interpret total variations, since any fluctuation within batches or between batches will — if it is high — be best interpreted at that state.

Probably the best measure of variation is the variation coefficient, in percent, which accounts for the difference in average strength. It should be pointed out, however, that there is increasing evidence by a relatively large number of investigators that indicates that the standard deviation of concrete strengths, regardless of the strength level, remains comparatively constant, while under the same condition the coefficient of variation changes considerably with the strength average ($\overline{X}$) changes. Note that average strength is a factor of great importance, but it is not of importance in evaluating the flow of variations from raw materials or in looking primarily for fluctuations in strength.

If the variations for both moist cured and steam cured specimens are high, but those for the steam cured specimens are significantly higher, then the results should be interpreted as though moist cured were low relative to the very high steam cured.

DISCUSSION OF EXAMPLES

The examples of control charts to be discussed were constructed from raw data collected in 1964 and 1965 that emanated from operating prestressing plants. At the time the data were collected, no statistical quality control procedures were in effect at the plants, thus the data represent production free from any processing controls other than that of attempting to keep the strength results above the minimum specification limits. Table III showed the statistical parameters computed from these data and used in establishing the control charts for the respective plants.

Plant No. 1

Figure 1a — Steam Strengths

From this figure, the process appears to have been in fair control; however, the process average (the grand average of the fifty samples) was low. Recognition of the low process average brought about a substantial change in the process during production of the last ten samples.

Figure 1b — Moist Strengths

This figure indicates the process was obviously in a state of change during the last thirty to forty samples as may be seen from the progressive increase in strength of these samples. The data showed the process was out of control during much of the time when the last twenty samples were taken. These excessively high strengths were probably costing the producer unnecessarily, but these strength magnitudes were needed to improve the companion steam strengths.

Figure 1c — Strength Efficiency

The wide fluctuations shown in this chart (as compared to those of Figure 2c) reveal, as does a comparison of Figures 1a and 1b, that seldom did the steam strengths reflect the inherent quality of the concrete as received by the plant (the moist strengths). It looks as if the problem was in the steaming process since the higher moist strengths of samples twenty to forty did not show up in the companion steam samples.

The spread between the control limits as compared to those of Figures 2c and 3c indicate considerably less uniformity in the curing processes. It appears, however, that the process improved during the last fifty specimens because the control limits and grand average shown were predicated on the first fifty specimens and the UCL so computed appears extremely high in relation to the data plotted.

Figures 1d and 1e — Moving Averages for Range

These figures, Moving Averages for Range of Steam and Moist Strengths, respectively, show that a considerable portion of the problems of this plant was due to less than good handling and/or testing of specimens. High variations occasioned by handling and testing of structural concrete are not particularly unusual, as attested by the paper by Baker and McMahon,[7] who in a discussion of data supplied by the State Road Commission of West Virginia say, "A significant indication from these data is that the combined testing and sampling variations are usually greater than the materials variation." Figures A-2 and A-3 of the Appendix give an indication that this plant discovered the source of its problem disclosed in Figure 1d and 1e and instituted corrective action soon afterwards. The appended Figures A-2 and A-3 both reveal a substantial improvement in the handling and/or testing of specimens subsequent to the time the data for this report were collected. The data shown in these two figures were collected during 1966 and 1967.

Plant No. 2

Figure 2a — Steam Strengths

No problems with steam strengths are evident from this chart. The process average was where it should have been, near midway between the control limits.

Figure 2b — Moist Strengths

Good control and uniformity in moist strengths are indicated; the process average was slightly high.

Figure 2c — Strength Efficiency

The comparatively narrow band formed by the closeness of the control limits and the fact that in only three instances did the process fall out of control indicate that the quality of the incoming concrete (moist strength) was usually reflected in the steam strengths and that both the steam and moist curing processes were in good control.

Figures 2d and 2e — Moving Averages for Range

Figure 2d indicates that good control was exercised over the handling and/or testing of the steam cured specimens. A problem with the handling and/or testing of the moist cured specimens was evident early in the sampling program. That problem was subsequently corrected and the process appears to have run without problems thereafter.

Plant No. 3

Figure 3a — Steam Strengths

The steaming process changed in that the last two-thirds of the samples indicate a strength level higher than that of the first one-third. The process was comparatively variable in that it appears to have bounced from high to low strengths and back again.

Figure 3b — Moist Strengths

The strength level of the moist cured concrete appears to have been excessively high and to have resulted in an unnecessarily high quality concrete.

Figure 3c — Strength Efficiency

The great amount of fluctuations shown by this chart reveal that frequently the steam strengths were not reflecting the quality of the concrete being used, since the process average of the moist strengths was fairly constant.

Figures 3d and 3e — Moving Averages for Range

These figures show that handling and/or testing procedures for the steam and moist specimens were in need of improved control. This problem certainly contributed to part of the control problem for strengths (Figures 3a and 3b) for both types of specimens. Inadequate care or faulty testing of the specimens required that the moist strength level be unduly high in order to reduce the possibility of failing steam strengths. This plant is not now in operation, therefore there was no chance to check subsequent control.

SUMMARY AND RECOMMENDATIONS

The compressive strength data emanating daily from three prestressing concrete plants producing steam cured concrete were evaluated in terms of the concrete as received and the effectiveness of the plants' steaming procedures. The purpose was to demonstrate the application of certain statistical techniques to the improvement of quality control in the production of prestressed concrete and as a means of monitoring prestressed concrete quality by the consumer. The statistical concepts applied were as follows.

Strength Efficiency

In order to measure the efficiency of a plant in utilizing the inherent strength of the incoming concrete, an index number termed "Strength Efficiency" was used. This number is arrived at by dividing the average strength of the two steam cured samples by the average strength of the companion moist cured samples and expressing the result as a percentage. The higher this percentage, the more effective a plant is in preserving the concrete's as-received quality in the steaming process. The strength efficiency can generally be raised by employing longer periods of steam curing; however, the steam strength data used in the illustrations given in this report were all collected from steaming periods of 12 to 16 hours.

Control Chart Analysis

Control charting methods are illustrated in the report and it is shown how these charts can detect out of control conditions from moist cured strength data (faulty raw materials), steam cured strength data (faulty raw materials or steaming process), and strength efficiency (steaming process). In addition, control charts for the moving averages for ranges were plotted. These charts provide a check on the fabrication, handling, curing and testing of the concrete specimens.

Analysis of variance and variations flow analysis were applied to some typical steam strength data and are also presented in the report. Relatively complex calculations are required for variance analysis, the objective of which is to isolate and trace the flow of the sources of variation present in the data. Variations flow analysis is used to trace the relationship among the components resulting from a variance analysis. Due to the rigorous calculations involved, analysis of variance and variations flow analysis are not deemed particularly useful in everday operations, but are presented as auxiliary statistical methods to be used only when supplemental information is needed.

In addition to the use of these procedures by the Virginia Department of Highways for better monitoring of its prestressed concrete suppliers, it is recommended that groups within the Construction, Maintenance and Materials Divisions examine these statistical methods for possible application in their particular work areas. Of interest should be most operations where raw materials are molded, treated, or processed in some fashion.

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(7) Baker, Wesley M., and Thurmul F. McMahon, "Quality Assurance of Portland Cement Concrete," Quality Assurance in Highway Construction, Part 3, U. S. Government Printing Office, Washington, D. C.

APPENDIX

TABLE A-I

COMPUTATION OF STANDARD DEVIATION, GRAND AVERAGE AND CONTROL LIMITS

Date	Strength, psi Sample No. 1	Strength, psi Sample No. 2	Strength, psi Average	Deviation from Grand Average, psi	Squared Deviation
10/1	4,320	4,390	4,355	257	66,049
10/2	4,170	4,170	4,170	442	195,364
10/4	4,600	5,090	4,845	233	54,289
10/5	4,810	4,530	4,670	58	3,364
10/7	4,950	5,090	5,020	408	166,464
Total			23,060		485,530

Grand Average of Sample Average ($\bar{\bar{X}}$) = $\frac{23,060}{N} = \frac{23,060}{5} = 4,612$ Psi

Average of Squared Deviation $= \frac{485,530}{N-1} = \frac{485,530}{5-1} = 121,383$

Standard Deviation of Sample Average (σ) = $\sqrt{121,383} = 348$ psi

Lower Control Limit (LCL) = 4,200 psi, steam (arbitrarily set)
5,200 psi, moist (arbitrarily set)

Upper Control Limit (UCL) = 4,200 + 4 σ(steam) = 4,200 + 4 (348) = 5,592 psi
5,200 + 4 σ(moist)

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Form TL-62
Rev. 11/1/64

DEPARTMENT OF HIGHWAYS
MATERIALS DIVISION
PRESTRESSED CONCRETE PLANT
STRESSING & POURING RECORD

Sheet ________ of ________

Date ______________________ Route No. ______________________

Report No. ______________________ Project No. ______________________

Bridge Over ______________________ County ______________________

Contractor ______________________ Plant ______________________

Date & Time Stressed ______________________ Date & Time Stress Released ______________________

Stress Released on Cylinder Nos. ______________________ Date Cast ______________________

Time of Casting-From __________ (A.M.-P.M.) - To __________ (A.M.-P.M.) Conc. Temp. at Stress Release ______________________

Max./Min. Air Temp. During Pour __________/__________ Max./Min. Conc. Temp. During Pour __________/__________

Total Moist Cure Time (If Used) ______________________ Temp. at Time Stressed ______________________

DESIGN MIX (Per Cu. Yd.): (Shown on Report No. 1 Only)

Cement (Sks.) __________ Sand (Lbs.) __________ No. __________ (Lbs.) __________ No. __________ (Lbs.) __________

Water (Gals.) __________ AEA (Oz.) __________ Retarder (Oz.) __________

CYLINDER RECORD:

Cylinder Number	%Moist. Sand	%Moist. C. A.		W/C Ratio	Slump Inches	% Air	Retarder Oz./Sk.	Cluster No.	Strength Psi.	Cyl. Age Hrs.-Days			
		No.	No.							1st. Delay	Steam	2nd. Delay	Total

Prestress Unit No.	L-Meas.	Camber

STEAMING CYCLE RECORD			
CYCLE PHASES	Time Started	Time Ended	Total Hrs.
Delay Before Steam			
Temperature Rise			
Sustained Cure (between 130°F. - 155°F.)			
Delay before release			

Max./Min. Temp. During Delay __________/__________

Max./Min. Temp. During Sustained Cure __________/__________

HORIZONTAL STRANDS:

Nominal Diam. (In.) __________ No. of Strands __________ Overall Lgt. (Ft. & In.) __________

Tension Per Strand (Lbs.) __________ Total Tension (Lbs.) __________

Initial Tension (Lbs.)	Allowance for (In.)		Computed Elong. Req'd. (In.)	Computed Elong. Inc. Allowance (In.)	Gage Readings (Psi.)			
	Temp.	Vises			No. 1	No. 2	No. 3	No. 4

Max./Min. Elong. Measured (In.) __________/__________ Average Releasing Gage Reading (Psi.) __________

DEFLECTED STRANDS:

Nominal Diam. (In.) __________ No. of Strands __________ Initial Tension (Lbs.) __________

Tension Per Strand (Lbs.) __________ Total Tension (Lbs.) __________

Overall Lgt. Partial Trajectory (Ft.-In.) __________ Overall Lgt. Full Traj. (Ft.-In.) __________

Length Difference (Ft.-In.) __________ Allowance For Temp. & Vises (In.) __________

Req'd. Elong. Part. Traj. (In.) __________ Meas. Elong. Part. Traj. Incl. Allow (In.) __________

Req'd. Elong. Full Traj. (In.) __________ Meas. Elong. Full Traj. Incl. Allow. (In.) __________

Avg. Stressing Gage Reading (Psi.) __________ Avg. Releasing Gage Reading (Psi.) __________

Checked By: Remarks: ______________________

cc - Materials Engineer - Prestressed Concrete Section Inspector: ______________________

Figure A-1. Sample Form TL-62.

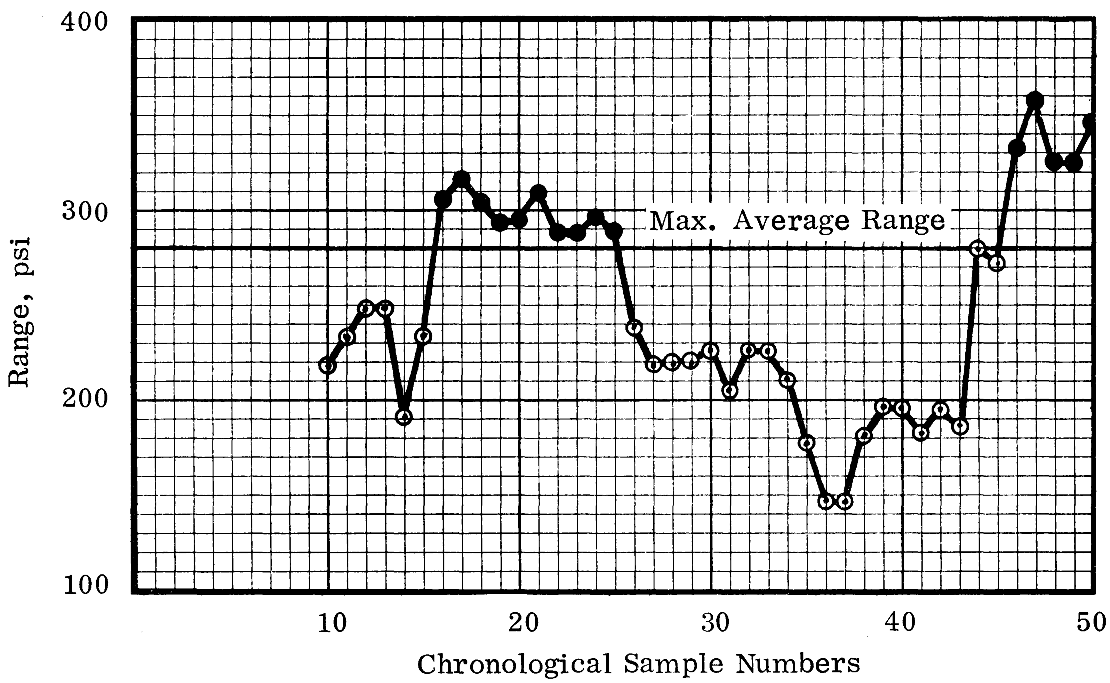

Figure A-2. Moving averages of range for steam strengths.

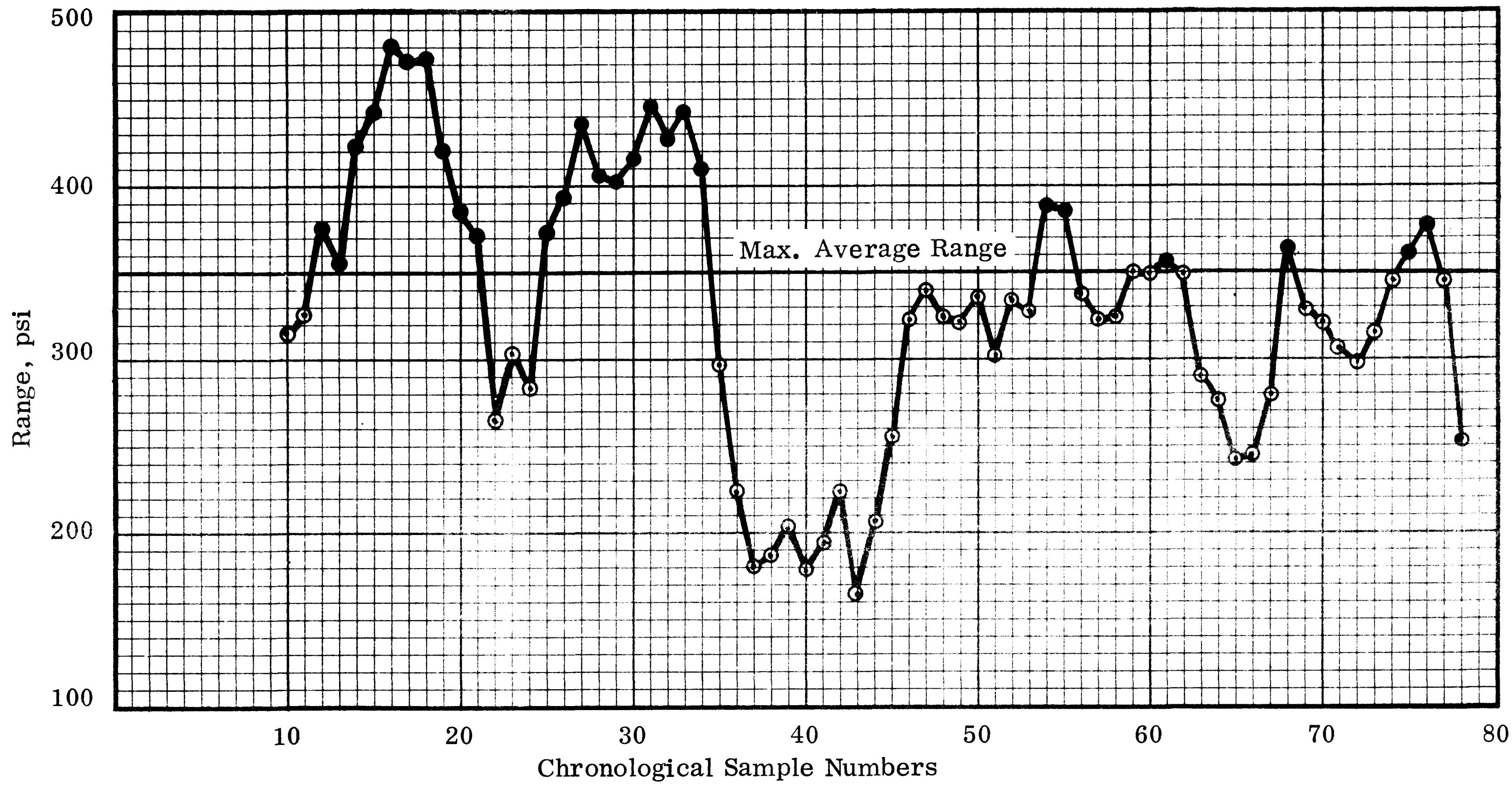

Figure A-3. Moving averages of range for moist strengths.