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## 3 Reports

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# Foreword

Quality concrete is not an accident. Construction and materials engineers are constantly striving to produce a product which will perform as required. At the same time, the researcher is hard at work developing methods of measuring concrete quality and establishing quality control concepts. There are areas in which our knowledge of concrete quality is limited. The work reported here is part of the continuing effort to improve this knowledge and will ultimately lead to concrete quality commensurate with performance requirements.

The first report deals with the measurement of the quality of portland cement paving concrete accepted by present methods of quality control. The concrete, which was accepted by the state's regular control procedures, was further sampled and tested in a statistically valid study to determine the average quality and variations from this average.

The study is a part of a nationwide program of measuring the quality of present construction being performed by state highway departments in cooperation with the Bureau of Public Roads. The report contains information concerning the average level—and the standard deviation—of the results of tests on three construction project studies. The tests performed were (a) the air content by pressure meter, (b) air content by Chace meter, (c) slump and (d) unit weight. The study was so designed as to allow the reporting of the variance due to sampling and testing as well as the material variance.

The second report is concerned with the anchorage mass concrete and the deck slab of the Verrazano-Narrows Bridge which crosses New York Harbor. This bridge has a span of 4,260 feet, the longest span in the world. The paper covers design and construction problems and solutions. Of particular interest to the reader will be the discussions of the control of temperature of the concrete and the placing of the deck slabs. Particular precautions must be taken in the construction of a concrete deck on a suspension bridge.

The third report is concerned with the study of the effect of mixing time and blending of aggregates on the quality of concrete for various large central plant mixers. The studies were conducted by the Bureau of Public Roads in cooperation with state highway departments and contractors. The objectives were to identify and evaluate operating plant variables which affect the mixing time required to produce satisfactory quality concrete. Data were obtained from three samples per batch at the plant and two or three samples per batch at the plant and two or three samples per batch at the roadway. Conclusions of the study are based on the results of slump, air content, compressive strength and coarse aggregate variations with mixing time. The authors present their recommendations concerning the obtaining of quality concrete.

# Contents

# Application of Statistical Quality Control Procedures to Production of Highway Pavement Concrete

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This investigation deals with the collection of data by a systematic procedure for the purpose of evaluating the variability present in the manufacture of portland cement concrete for highway pavements. Data were analyzed to provide information concerning the magnitude of the variance components for the Bureau of Public Roads' data system, and to provide information and illustrate procedures for the establishment of a quality control program that could be used by the Indiana State Highway Commission.

•OVER the years many specifications have evolved through trial and error without reference to the actual variability of the product or process. In theory it is possible to improve the product by narrowing the specification limits, but if the process itself is incapable of operating within those limits then they are of little use.

Specification requirements are of little use unless some means of testing and control are exerted. With estimates of the variability at hand, it is possible to develop a quality control program based on a thorough understanding of the capabilities of the process. Also, it is possible to establish a realistic system and schedule of acceptance tests, number of samples, etc.

The construction of a highway may be compared to an industrial manufacturing process. There is a manufactured product, the highway, and like industrial production there is a need to control the quality of the product. This need arises from the desire of the manufacturer, the contractor, to produce a product for the purchaser, the state, in the most economical manner possible while meeting the specifications for the product. The purchaser in turn is interested in seeing that he obtains a quality product.

Statistical quality control provides a means whereby a manufacturer can derive maximum benefit from control testing of the manufactured product. The basic concepts are applicable whether the product be piston rings or highway pavements. Inherent in statistical analyses is the ability to make estimates of population parameters from sample statistics and to associate with them estimates of the probability of being in error. By using statistical quality control procedures, a manufacturing process can be investigated to determine the range in values that one can expect under existing conditions. This information is valuable to both producer and purchaser. It can be used not only in determining compliance with specifications but also to judge whether the construction or manufacturing process is capable of producing the product within them. If existing specifications are unrealistic with respect to an end result or are economically unattainable, quality control data can provide a basis for the development of revised standards.

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Paper sponsored by Committee on Construction Practices—Rigid Pavement and presented at the 45th Annual Meeting.

## OUTLINE OF WORK

The investigation was limited to plastic portland cement concrete used in concrete paving projects under contract in Indiana. Tests for air content, slump and unit weight were made on the concrete. Air content was determined using both the pressure type air meter and the Chace air meter. These tests were conducted by a research team from Purdue University and all tests were made independent of highway commission control tests.

Three paving projects were selected with each project performed by a different contractor. The projects were chosen on the basis of their geographic location in the state and the paving schedules of the contractors.

Three replicate determinations of each attribute (slump, air content and unit weight) were made on fifty samples obtained on each project. Thus, 150 individual tests were performed for each test method on all projects for a total of 450 observations. The replicate determinations were selected rather than two samples tested twice from each location because of the time involved in making a test and the number of different tests being performed.

On each project, sampling began at the start of paving operations for any one day by the random selection of a batch and then continued throughout the day at time intervals dictated by the time required for each setup. This provided a random procedure that eliminated bias in the sampling procedure. The time for each setup varied due to variations in the distance from sampling point, and ease of equipment movement. A typical setup from start to finish required approximately one hour.

The data were collected during the 1964 summer construction season. Data were placed on IBM punch cards with appropriate coding to indicate job number, sample number, replicate number, time of test and date test was made. The data were then analyzed using standard statistical techniques and procedures. An IBM 7094 computer was utilized in the analysis.

## FIELD PROCEDURES AND TESTING

The nature of the investigation required a highly mobile operation. The equipment had to be transported to each of the three projects and then moved along the paving operation from test point to test point. The best way to handle mobility was through the use of a pickup truck outfitted with a few attachments to facilitate the testing program. To make the operation self-sufficient a supply of water was provided by a 55-gal water drum mountedon the truck. Water was thus available for the air meter and for clean up.

When a test site was selected, a team of operators began the testing program. (Since the testing program was limited to the summer months of 1964 only sites with paving in progress were considered.) Teams consisted of two men for the first site and a part of the second, but was expanded to three men for the remainder of the second site and all of the third. The two persons doing the actual testing were never changed, and they performed the same tests throughout the research project. Operator A performed the slump and unit weight tests while Operator B performed both types of air content tests.

Each site was surveyed to determine where and how to begin the testing program. Pertinent information was obtained concerning the mix design, sources and types of materials, any correction factors and other data needed for the testing.

All testing was performed on the right side of the forms in the direction of pouring. The dual-drum pavers and auxiliary equipment were located on the median side and a setup there would mean disturbing the concreting operations. The one guiding principle was to stay completely out of the way of the paving operations. Working on the right shoulder created one problem in that temperature steel was frequently unloaded on the shoulder. In some cases this meant a longer distance from sampling point to where the equipment was set or, where the subbase was especially wide, working to the right of the steel.

The setup for testing was placed as close to the forms as possible without interference. The setup took about 5 min and involved placing three square pieces of plywood and positioning the testing equipment; the plywood served as working platforms for the scale, slump tests and air tests.

A concrete sample from the batch which had been deposited on the grade was placed in a wheelbarrow and a large pan. Approximately 3 cu ft of concrete were required for each sample. The sample was obtained before the batch was spread by the first spreader in the case of an operation using twin-barrel mixes, and after the initial spread in the case of a central mix operation. The distance between samples was arbitrary and depended on how far the paving train progressed between setups and how long it took the team to perform the tests. The sampling operation required a maximum of 5 min.

After obtaining the concrete sample, operators A and B started performing their tests. Equipment was positioned so the testing could begin immediately to provide the maximum amount of time before the concrete began to stiffen.

## ANALYSIS OF DATA

At the completion of the testing program all data were tabulated and recorded on IBM punch cards. Information regarding job number, sample number, replicate number, time of test and date was coded and placed on the punch cards along with the appropriate data for ease of identification. The statistical analysis of the data was accomplished using standard computer programs for analysis of variance, correlation and distribution. In addition, standard statistical techniques and procedures were used to determine confidence limits and control limits and in significance testing. A majority of the analyses and plotting of data was accomplished using an IBM 7094-1410 computer system.

The data collected from each of the four tests were analyzed separately and the sum of squares, mean squares and standard deviations computed for each test method. The first analysis was based on a 2-factor factorial design model with three replicate observations for one factor (samples). In addition, correlation coefficients were determined for all combinations of the tests. Sample means were used in the correlations and data plotting.

In the development of a quality control program it is necessary to obtain data from a process which is "in control," i.e., from a process in which the variability is due to chance causes alone and not to assignable causes. From observations in the field, such as noting obvious errors in air-entraining agent content, water content, etc., it can be said that at certain times a portion of the variability noted in the present investigation was due to assignable errors. For this reason a one-way analysis of variance was conducted for each project site separately in addition to the factorial analysis.

In certain analyses the magnitude of the variance components differed from site to site. Analyzing the data for each site separately allows the computation of these variance components and makes it possible to compare the magnitude of the components from site to site. A factorial analysis averages the variances from the three sites and hence if at one or two sites the process is out of control, there is no estimate available for the variance of a process in control. In fact the factorial analysis is invalid if the variances are not homogeneous (i.e., variances are not statistically equal).

The factorial analyses are included in this paper to illustrate this type of statistical procedure. If other variables such as operator or equipment were included in an investigation a factorial design model incorporating these variables could be used.

Operators and testing equipment were not considered as variables in this investigation. Using one operator and one testing device limits data interpretation. The values of standard deviations and confidence limits cannot be applied directly to a project on which several operators and several pieces of testing equipment are used.

A time dependency was observed as samples were tested in the field for air content by the pressure meter. This led to statistically testing the differences between replicates and calculation of the correlation coefficient associated with the third pressure replicate vs the sample mean of the Chace tests. Results of this investigation will be discussed later.

Test results were also used to illustrate techniques and procedures that may be employed in a quality control program. Control limits are illustrated in the section on quality control.

For simplicity and ease in handling the large amount of data, a discussion of each test method will be presented separately. Sections concerning correlations and quality control applications follow.

## Field Observations

Dual-drum pavers were used on Sites 1 and 3 and a central mix plant was in operation on Site 2. These were quite different sets of conditions depending on the type of paving operation being employed. The basic difference between the sites was the method of mixing and initial placement, with all other operations being essentially the same.

In the central mix project there were fewer adjustments. The plant was started up and checked at the start of the project but then almost complete reliance was placed on the automatic features of the plant. Thus, there was less checking and less control of the concrete. The major problem was control of air content. By the time a low air content was noticed and a message relayed to the plant to make the necessary changes, many concrete trucks were either dumping or already on their way to the grade with their 8 cu yd of concrete. There was a large lag-time between catching a low air reading and effecting a correction. This was an unfortunate characteristic of the operation.

The less the paving operation is changed, the more constant the concrete product. This was evident at Site 3 where very few adjustments were made in the way of water content, air entraining agent or batch changes. This fact is substantiated by the statistical analysis. Site 3 had the best grouping of data and distribution of results.

## Air Content by Pressure Meter

The analysis of variance (ANOV) for the air content measured by pressure meter is given in Table 1. The sources of variation as determined by the factorial model are: (a) site-to-site variation, (b) sample-within-site variation, and (c) the error term. Table 2 gives a summary of the statistical analysis results based on a factorial design model over all project sites.

A standard test for significance, the F-test, indicates that at the 0.05 $\alpha$-level (0.05 probability of rejecting the hypothesis when it is true) the site-to-site variation is not significant, but the sample-within-site variation is significant. The concrete is manufactured in batches and a sample comes from a single batch; hence the sample-within-site variation is a measure of the batch-to-batch variation. Therefore, at an $\alpha$-level of 0.05 the batch means are different.

When first viewed, these results may appear to be reversed from what one would expect. However, consider the manufacturing process. The sample-within-site variation is the batch-to-batch variation for a particular site. Changes in moisture content of the aggregate, adjustments in the amount of water per batch and adjustments in the amount of air-entraining agent can occur from batch-to-batch and one would expect the

TABLE 1

ANALYSIS OF VARIANCE—FACTORIAL MODEL AIR CONTENT BY PRESSURE TEST

| Source of Variation | df | SS | MS | EMS | F |
|---|---|---|---|---|---|
| Site | 2 | 8.19000 | 4.09500 | $\sigma_\epsilon^2 + 3\sigma_{\text{sample}} + 150\,\sigma_{\text{site}}^2$ | 2.72 |
| Sample within site | 147 | 221.21985 | 1.50490 | $\sigma_\epsilon^2 + 3\sigma_{\text{sample}}^2$ | 19.09 |
| Error | 300 | 23.64664 | 0.07882 | $\sigma_\epsilon^2$ | |

$\alpha = 0.05$

$F_{2,147} = 3.07$ 2.72 $\therefore$ site not significant

$F_{147,300} = 1.30$ 19.09 $\therefore$ sample within site significant

TABLE 2

SUMMARY OF STATISTICAL ANALYSES FOR ALL SITES (FACTORIAL MODEL)

| Standard Deviations (all sites) | Air Content Pressure | Air Content Chace | Slump | Unit Weight |
|---|---|---|---|---|
| Site Std. Dev. | 0.10 | 0.11 | 0.14 | 0.15 |
| Sample Mean Std. Dev.[a] | 0.16 | 0.32 | 0.21 | 0.62 |
| Sample-Within-Site Std. Dev. | 0.69 | 0.69 | 0.98 | 0.89 |
| Error Term (all sites) | 0.079 | 0.30 | 0.14 | 1.15 |

[a] Consists of variation due to variance among determinations but not among samples.

air content to change. Site-to-site variation would also be expected to be significant (different).

It is necessary to understand the composition of the site-to-site variance, or in statistical terms, the expected mean square (EMS) components of variance. The EMS from Table 1 is ($\sigma_\epsilon^2 + 3\sigma_{\text{sample}}^2 + 150\,\sigma_{\text{site}}^2$) for the site-to-site component; ($\sigma_\epsilon^2 + 3\sigma_{\text{sample}}^2$) for the sample-within-site component and $\sigma_\epsilon^2$ for the error term. The error term ($\sigma_\epsilon^2$) is observed to be small in comparison with the sample-within-site term ($\sigma_\epsilon^2 + 3\sigma_{\text{sample}}^2$), leading to the conclusion that sample-within-site variation is significant or that sample means are different. The $\sigma_{\text{sample}}^2$ term is large compared to the $\sigma_{\text{site}}^2$ term, and when a significance test is performed ($\sigma_\epsilon^2 + 3\sigma_{\text{sample}}^2 + 150\,\sigma_{\text{site}}^2$)/($\sigma_\epsilon^2 + 3\sigma_{\text{sample}}^2$), the site-to-site component is determined not significant. If the distribution of sample means was smaller (i.e., $\sigma_{\text{sample}}^2$ smaller) and $\sigma_{\text{site}}^2$ remained the same, a significance test might indicate the site-to-site component significant. In other words, distribution of sample means is so large that it overshadows the spread among site means.

The distribution of air content for all sites measured by the pressure meter is shown in Figure 1. Values tabulated are sample means. The overall mean air content is 4.40 percent. The distribution over all sites approximates a normal distribution. The air

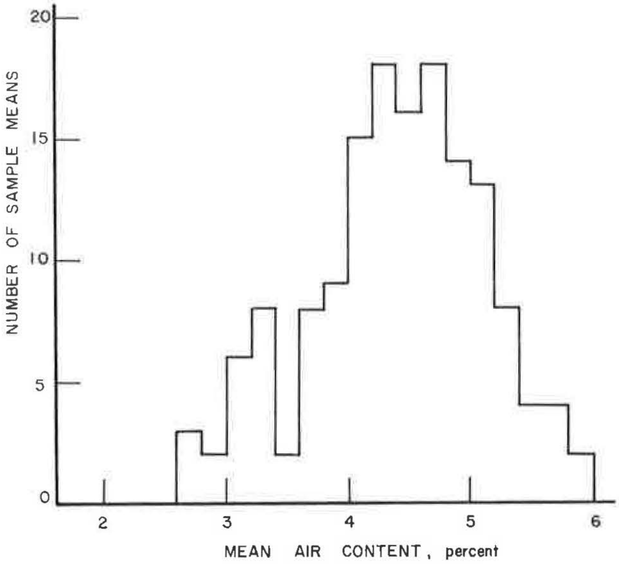

Figure 1. Histogram for the distribution of air content measured by pressure meter, all sites.

TABLE 3

SUMMARY OF STATISTICAL ANALYSES FOR EACH SITE ANALYZED SEPARATELY

| Source of Variation | Mean Square | | |
|---|---|---|---|
| | Site 1 | Site 2 | Site 3 |
| (a) Air Content, Pressure Meter | | | |
| Between Samples | 1.1345 | 2.5686 | 0.8116 |
| Within Samples | 0.1387 | 0.0558 | 0.0419 |
| (b) Air Content, Chace Meter | | | |
| Between Samples | 2.6093 | 2.0215 | 0.6044 |
| Within Samples | 0.4775 | 0.2356 | 0.1962 |
| (c) Slump | | | |
| Between Samples | 4.0191 | 1.8208 | 3.1446 |
| Within Samples | 0.2262 | 0.1133 | 0.0704 |
| (d) Unit Weight | | | |
| Between Samples | 3.4949 | 4.6644 | 2.4261 |
| Within Samples | 1.6434 | 1.3496 | 0.4437 |

content determinations for Sites 1 and 3 indicated a tendency towards normality, but for Site 2 the distribution was definitely not normal. This may be accounted for by the fact that a number of difficulties arose with the plant operation on Site 2. The aggregate varied considerably in its moisture content and a number of failures occurred in the air-entraining agent dispensing equipment. These factors combined to produce a large range in air contents and a non-normal distribution.

The observed error term from Table 2 is 0.079, or from a practical viewpoint 0.1 percent, indicating that an error of 0.1 percent can occur in the air content determination due to chance alone. Placing 95 percent confidence limits on the site mean gives a range within which we are 95 percent confident the true site mean lies. For example, the mean for Site 1 is 4.48 percent; therefore, we are 95 percent confident that the true site mean lies between 4.28 percent and 4.68 percent.

As mentioned previously, it was observed that assignable causes in several instances added to the measured variation and thus a one-way ANOV was performed on each test method for each site separately. A summary of the results is given in Table 3.

If the mean square terms (MS) for the three sites as analyzed separately are averaged, the result is equal to the corresponding mean square as determined by the ANOV of the factorial model. This provides an accuracy check of the computation and illustrates how the mean square terms are related.

Note the differences in the MS and the standard deviations from site to site.

## Air Content by Chace Meter

The ANOV for air content by Chace meter is similar to that for air content by pressure meter (Table 1). The statistical sources of variation are the same as those associated with the pressure meter. A summary of results from the statistical analyses is given in Table 2. The overall mean air content is 4.40 percent. Air contents by the Chace meter were determined in the field to the nearest one-half percent. Corrections for mortar content of the mix were computed and the appropriate adjustment made in the air content. The calculations in the statistical analysis portion of the investigation were carried to hundredths of a percent for purposes of handling the computation and for comparison with other tests.

The F-tests indicate that both site-to-site components and sample-within-site components are significant. This is in contrast to the previously discussed pressure meter results where the site-to-site components were not significant. The standard deviations computed for the Chace test are 0.11 percent for the site means and 0.32 percent for the sample means. The standard deviation for the Chace meter sample means is twice that of the pressure meter. Air contents by Chace meter are determined to the nearest one-half percent in the field; the Chace test might well be used as an indicator of the relative air content, but not as a test to determine the precise air content. The sample-within-site standard deviation is 0.69 percent, which is the same as the pressure meter.

A histogram showing the distribution of air content by the Chace meter for all sites is shown in Figure 2. The values plotted are sample means. This distribution does approach a normal distribution, but an interesting observation may be made. The figure shows three distinct small peaks. These peaks occur at the mean Chace air content for each site or if one were to locate the means of each site on Figure 2, they would fall at

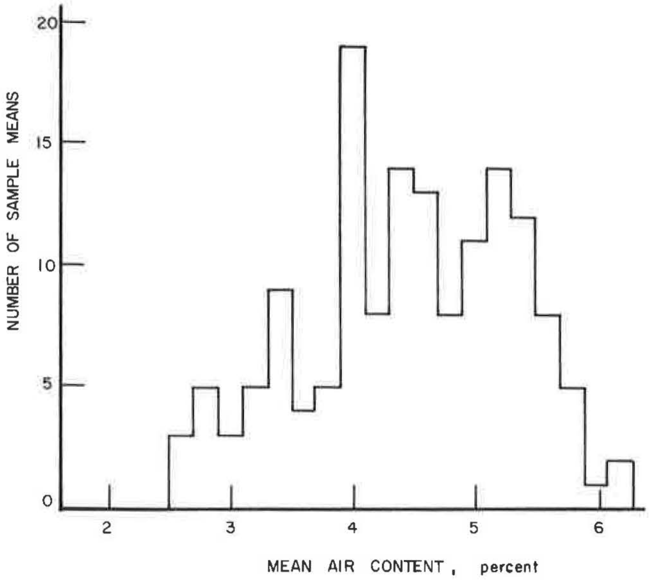

Figure 2. Histogram for the distribution of air content measured by Chase meter, all sites.

each peak. This does not happen in the case of pressure meter results, as Figure 1 clearly shows. The pressure meter distribution is nearer to a normal distribution. The distribution for Chace is more dispersed, thus showing its higher variability as indicated by the higher standard deviation calculated for sample means.

In Table 2 the site-to-site standard deviation is 0.3 percent. Confidence limits placed on the site mean indicate that there is a confidence of 95 percent that the site mean lies between $\overline{X}_{site}$ + 0.2 percent and $\overline{X}_{site}$ - 0.2 percent. Also, the 95 percent confidence limits on a sample mean is $\overline{X}_{sample} \pm 0.6$ percent. This last figure is interesting when it is compared to the pressure meter results. The 95 percent confidence limits for the pressure meter data were determined to be $\overline{X}_{sample} \pm 0.3$ percent. This, once again, indicates the pressure air content test to be statistically more reliable than the Chace test.

In comparing the three sites in an effort to check dispersion of data, Site 3 stands out as being more consistent than the other two sites. This is true because there were few adjustments made in the air entraining agent and also less changing of the water content. Site 2 shows a sort of sinusoidal shape indicating trends which were not immediate but occurred over a number of samples. A plot of the pressure air content data also substantiates this. Site 2 was a central mix project and this operation had difficulties with its air dispenser which resulted in the distribution indicated. Site 2 also has the greatest amount of dispersion of the three sites.

As in the pressure meter analysis, a one-way ANOV was conducted (Table 3). Observable differences occur in the MS and standard deviation terms from site to site. As in the pressure method analysis, the within-sample mean-square term for Site 1 is at least twice that of Sites 2 and 3 which are very nearly equal.

## Slump Test

The ANOV for the slump test is similar to that in Table 1. The sources of variation (site-to-site variation, sample-within-site and error terms) are the same used for the two air content tests. Table 2 gives a summary of the statistical analysis of the slump phase of this investigation for the factorial model.

The F-test indicates that at a 0.05 $\alpha$-level the site-to-site variation is not significant but the sample-within-site variation is. This is what would be expected in view of the

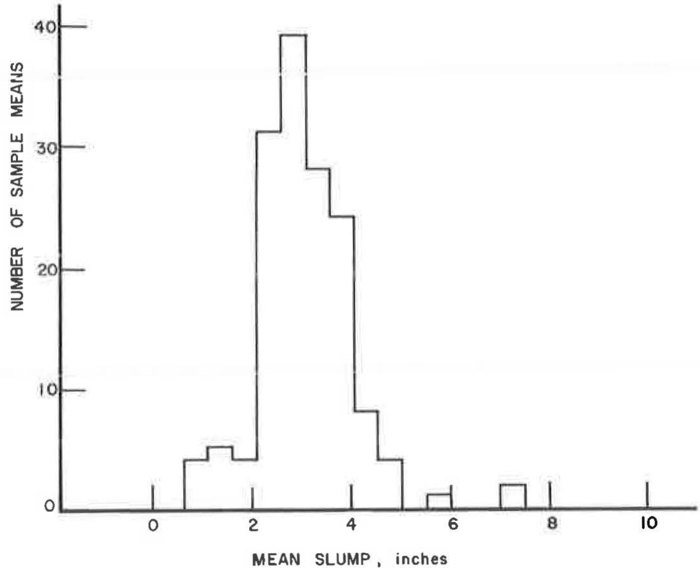

Figure 3. Histogram for the distribution of slump, all sites.

characteristics of the slump test. The slump test is a measure of water content and therefore will vary as the water content varies. The more one changes the adjustment on the water indicator of a mixer the more the slump should change. Thus, one would expect Site 2, the central mix project, to show the least variation in slump, which it does. Both the dual-drum paver sites show more spread in slump than Site 2. In the central mix operation there were relatively few changes in water content compared to the operations using dual-drum pavers.

The distribution of slump for all sites is shown in Figure 3. The values plotted therein are sample means. The histogram shows a close grouping of data which is a tight, almost normal, distribution. The overall mean of the slump is, for all practical purposes, 3 in. There is a slight tendency for each site to approximate a normal distribution which becomes more pronounced when all three sites are lumped (Fig. 3). The histogram for Site 2 is tighter than those for Sites 1 and 3 which substantiates what was said concerning the central mix plant.

The 95 percent confidence limits on the site mean are ± 0.3 percent, while 95 percent confidence limits on the sample mean are ± 0.4 percent. Site 2 had the smallest range in slump values, i.e., it exhibited both the highest minimum and lowest maximum slump.

As in the previous analyses, a one-way ANOV was performed on the slump data for each site and a summary of the results is given in Table 3. The between-sample standard deviation is lowest for Site 2, bearing out the observation made from the factorial analysis that the variances for Site 2 were smaller, i.e., Site 2 exhibited better control as far as slump measurements were concerned.

## Unit Weight

The distribution of unit weight from all sites is shown in Figure 4. As with the other three test methods, sites, sample-within-site and the error term were the components of variation. Noting the site means and comparing these with the histogram, it can be seen that the three peaks in the overall distribution correspond very closely to the three site means. Evidently changes in materials from site to site cause a definite and obvious shift in the individual site distributions that is reflected in the overall distribution.

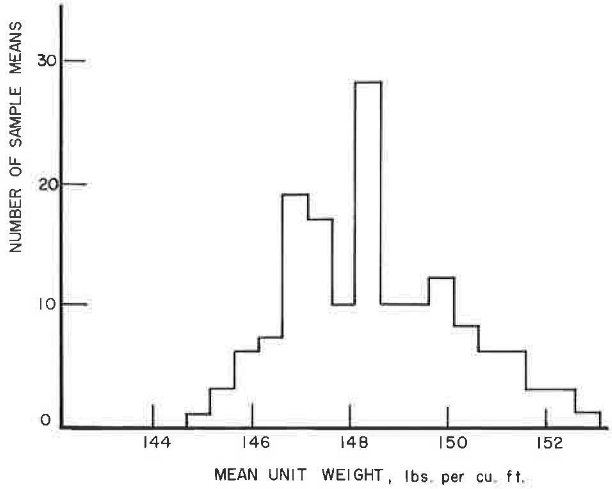

Figure 4. Histogram for the distribution of unit weight, all sites.

A summary of the results from the statistical analysis is given in Table 2. From the ANOV it was determined by F-tests that both the site component and the sample-within-site component are significant. The site component is highly significant as would be expected since from site-to-site the aggregate used varied in specific gravity and the unit weight reflected this change.

The observed error term (Table 2) is 1.15 lb indicating that a unit weight determination can have an error of 1.15 lb due to chance alone. The 95 percent confidence limits on the sample mean are ± 1.2 lb (i.e., 95 percent confident that the true mean lies between $\overline{X}_{sample} \pm 1.2$ lb). This shows that there is a great deal of variability involved in the performance of this test. This wide range might be due to variation of air content, water content of concrete or the amount of stiffness allowed to occur before testing. The longer the concrete is allowed to set, the more difficult it will be to compact it into the yield bucket. This also may lead to large voids of entrapped air in the stiffening concrete.

As in the analysis of the other three test methods, a one-way ANOV was performed on the unit weight data; a summary of the results is given in Table 3. Site 2 exhibits a greater variability than do Sites 1 and 3. This is consistent with the observations made on the results of the analysis of air content data and is what would be expected since variations in air content cause the unit weight to vary accordingly.

## Correlations

With the amount of data available and since the tests for air, slump and unit weight were made on the same sample, it was considered advantageous to obtain information regarding correlations between the tests (Table 4). Significant correlations were found between the pressure meter air content test and the Chace meter air content test as well as with unit weight. Since both the pressure meter and the Chace meter measure air content and the air content influences the unit weight of the concrete, these significant correlations were expected. Also, there was a correlation between air content measured by the pressure test and slump; however, the correlation coefficient is not large. The correlation between air content by Chace meter and slump is not significant.

The correlation coefficients presented are the "r" values, and even though significant correlations do exist there is a large amount of scatter. The predictability is relatively poor in a number of the correlations.

The correlation between air content measured by the Chace meter and unit weight is highly significant. This is in agreement with the significant correlation between air content by the pressure meter and unit weight previously noted. The correlation coef-

TABLE 4

TABULATION OF CORRELATION COEFFICIENTS AND SIGNIFICANCE TESTS

| Variables | r | $t_{148}$ | $\alpha = 0.001$ | Significance |
|---|---|---|---|---|
| (a) All Sites | | | | |
| Pressure vs Chace | 0.6060 | 9.2675 | 3.29 | Highly significant |
| Pressure vs slump | 0.3368 | 4.3516 | 3.29 | Significant |
| Pressure vs unit wt | -0.5491 | 8.6351 | 3.29 | Highly significant |
| Chace vs slump | 0.1296 | 1.5900 | 3.29 | Not significant |
| Chace vs unit wt | -0.6445 | 10.2540 | 3.29 | Highly significant |
| Slump vs unit wt | -0.1856 | 2.2977 | 3.29 | Not significant |
| (b) Pressure vs Chace by Sites | | | | |
| Site 1 | 0.5130 | 4.1405 | 3.51 | Significant |
| Site 2 | 0.7288 | 7.3744 | 3.51 | Highly significant |
| Site 3 | 0.7247 | 7.2861 | 3.51 | Highly significant |

(c) Interpretation of Correlation Coefficients[a]

| Correlation Coefficient | Relationship Demonstrated |
|---|---|
| 1.0 | Perfect |
| 0.9 | Very good |
| 0.8 | Good |
| 0.7 | Fair |
| 0.6 | Poor |
| 0.5 or less | Very poor |

[a] See reference (9).

TABLE 5

SUMMARY OF ANALYSIS OF DIFFERENCES BETWEEN REPLICATE OBSERVATIONS

| Site | Observation Difference = d | $\bar{d}$ | S | $t = \bar{d}/S$ | $t_\alpha$ | Significant |
|---|---|---|---|---|---|---|
| 1 | $X_1 - X_2$ | 0.256 | 0.03727 | 6.87 | 2.01 | Yes |
| | $X_1 - X_3$ | 0.398 | 0.07365 | 5.40 | 2.01 | Yes |
| | $X_2 - X_3$ | 0.142 | 0.07022 | 2.02 | 2.01 | Yes |
| 2 | $X_1 - X_2$ | 0.136 | 0.04452 | 3.05 | 2.01 | Yes |
| | $X_1 - X_3$ | 0.190 | 0.05049 | 3.76 | 2.01 | Yes |
| | $X_2 - X_3$ | 0.054 | 0.03360 | 1.61 | 2.01 | No |
| 3 | $X_1 - X_2$ | 0.208 | 0.03486 | 5.97 | 2.01 | Yes |
| | $X_1 - X_3$ | 0.302 | 0.03619 | 6.41 | 2.01 | Yes |
| | $X_2 - X_3$ | 0.024 | 0.02467 | 0.97 | 2.01 | No |

ficients are negative indicating that as air content increases unit weight decreases. Both Chace air content vs slump and slump vs unit weight are not significant.

## Differences Between Replicate Observations

As mentioned before, a time dependency was observed when the air content was measured by the pressure meter. As a result, an analysis of the difference between replicate observations was performed (Table 5). The differences between replicate 1 and replicate 2 is significant at the 0.05 $\alpha$-level for all three sites. This is also true for the difference between replicate 1 and replicate 3. Replicate 2 and replicate 3 differences are not significant except in the case of Site 1 where the results are extremely close to the borderline. These results indicate that signal change in air content occurred between the first and second replicate.

Consequently, correlation analyses of the third pressure reading vs the mean of the Chace meter were made. The mean of the Chace was used since these air contents were taken immediately after the third pressure reading and the time involved for three Chace readings is small.

A comparison of these coefficients with those of the mean pressure vs the mean Chace show a general trend to a lower coefficient for the case of third pressure vs the mean of the Chace meter reading. Considering the results of the analysis of differences, a higher correlation could be expected. One possible answer to the apparent contradiction is that the Chace meter air contents are measured to only the nearest one-half percent while the pressure meter readings are to the nearest one-tenth percent. A more realistic comparison might be to round the pressure meter readings to the nearest one-half percent and then make the analysis.

Basically the analysis of the differences indicates statistically significant changes in air content measured with the pressure meter as a function of time. However, the correlation of the third pressure meter reading with the mean of the Chace meter readings is inconclusive in this aspect of the analysis.

## QUALITY CONTROL APPLICATIONS

It is important to understand that a quality control system depends on the data used to establish the system. Control procedures therefore are no better than the data used to establish them and it is obviously necessary to obtain these data in some manner. There are two approaches to this problem. One is to rely on past data, data collected by examining records of construction, etc. The other approach is to obtain the data required via a preliminary testing program.

There are several problems associated with using past data. One is the lack of reliability. The possibility is always present that only test results that met specifications were recorded. This situation may not arise out of desire to falsify records but rather from a conscientious effort to maintain good control in the field. For example, a situation may arise when something in the manufacturing process goes awry, an acceptance test is made which detects the error and appropriate steps are taken to correct the situation following which another test on the product is made and recorded. The testing has served its purpose, an error was detected and corrected, but only the last test result was recorded.

For statistical evaluation of the process, the out-of-specification result is just as important as the within-specification result if a realistic estimate is to be made of the variation. For this reason the second method of obtaining the so-called historical data is used when there is a scarcity of information or there is reason to suspect the past data. This investigation is of the second type and operated independent of acceptance sampling.

There are certain limitations associated with the results of this investigation. Only one operator and one piece of testing equipment were utilized for each test method conducted. There is, therefore, no estimate available of operator or equipment variability. It is a recognized fact that these variables may be significant. Another limitation arises from the fact that only three sites were checked and these were all Interstate-type construction.

In the section on analysis of data, the measures of central tendency and components of variability were presented. The problem is to apply these results to establish a realistic quality control program that may be implemented and used in the field.

The typical data plot in Figure 5 shows the fluctuation of the sample means. The variability of plastic portland cement concrete is represented by these fluctuations. One method of quality control is to establish control limits based on the data at hand and to use these limits to control the quality on future jobs. It is of no practical value to place the calculated limits on the data plots of the sites investigated since the calculated limits are based on the measured variability of these sites and therefore practically all of the data would fall within these limits.

To illustrate, a variation that is considered to be reasonable from analysis of the data will be used and the use of control limits demonstrated in the following pages. A

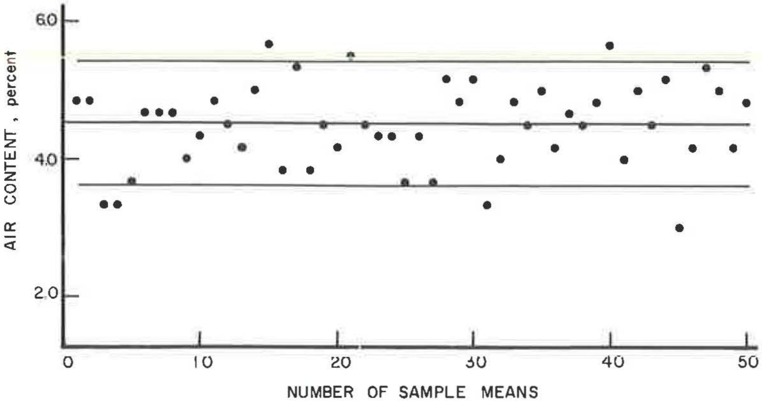

Figure 5. Data plot for air content measured by pressure meter, Site 1.

point should be made here concerning the distribution of the sample means. It is possible that the population of sample means is not normally distributed and normality is one of the assumptions underlying the concepts of control limits. If subgroups of 4 or 5 are used, the central limit theorem comes into play and the normalization effect is fairly strong. It is therefore better at times to use "moving means" in constructing control charts.

There are basically three types of control charts that are of use in the application of statistical quality control to the manufacture of fresh portland cement concrete. These charts are the $\overline{X}$-charts, R-chart and the $\sigma$-chart. All three charts provide a graphic representation of variation from point to point (i.e., sample to sample). An objective of using one or a combination of these charts is to keep track of the process so that some type of corrective action may be taken whenever the process goes "out of control" or a trend develops toward the control limits, indicating the possibility that an assignable cause is adding to the variation.

In concept, the control limits form a band within which fluctuations in the measured values are due to random or chance variation in the process. Observations which fall outside these limits more than a predetermined percentage of the time cannot be explained by chance causes alone and hence must be due to an assignable cause or a change occurring in the process. For example, having estimates of the components of variability associated with air content determinations, control limits may be computed and a control chart drawn. The air contents are plotted on the chart as the samples are tested during the manufacturing of the portland cement concrete. As the process proceeds, the air contents begin to decrease and fall outside the lower limit; hence, some assignable cause should be responsible for this change. A check of the process may show a defective dispenser, a change in sand gradation or some other recognizable cause that has resulted in the process going out of control. When this cause has been identified and corrective action taken, the process should again come into control.

If specifications have been written so that maximum and minimum values are given which form a band narrower than control limits based on the inherent variability of the process, it will be impossible to manufacture a product that will be within the specification all of the time (the percentage outside will naturally depend on specification limits and the known standard deviation).

To illustrate one use of control limits, sample means have been computed for the data and a plot is shown in Figure 5.

Assumed values used in the determination of control limits are based on the one-way ANOV and considerations of what is reasonable to expect based on field experience. The limits are for 3-$\sigma$ control limits which would include approximately 99.7 percent of data if a job were operating in control. Note that even if a job were operating in control, 0.3 percent of the data could fall outside the control limits due to chance variation alone. If the limits were based on a 0.05 $\alpha$-level, then 95 percent of the data would fall within the limits in the long run and 5 percent could fall outside the limits due to chance variation alone. This illustrates the point that because one or two observations fall outside the control limits does not necessarily mean the process has gone "out of control."

Assuming a $\sigma'_{\bar{X}}$ of 0.60 for air content by pressure method, 3-$\sigma$ control limits are: $\bar{\bar{X}} \pm 1.732\ (0.52)$ or $\bar{\bar{X}} \pm 0.90$. Applying these limits to the data plot of Figure 5, it may be noted that for Site 1 about 15 percent of the sample means are outside control limits, and thus one could conclude that some adjustments should be made. A similar plot of the data for Site 2 would show approximately 40 percent of data outside the limits. The job is in poor control and action should be taken. By contrast Site 3 exhibits the best control—only 4 percent of the data fall outside the limits. If the moving average concept is used, the same general conclusion may be reached and additional information concerning trends in the data may also be noted which may be valuable in field control.

With estimates of the components of variance available it is possible to take a critical look at present specifications. As mentioned previously, even though a process is "in control," if the variability of the process is high it may be incapable of producing a product always inside the specification limits. If this is the case, there are several possible avenues of action. The specifications should be examined to determine if the limits actually need to be as tight as they are. Also, the process itself should be examined to determine if any adjustments or changes are possible which will reduce the inherent variability of the process itself. This situation also points the way toward acceptance testing. A process may be operating in control and still have the product falling outside specifications. Operating in control does not insure that a product will meet specifications.

There are other ways of providing control procedures and one such method is to use tolerance limits. For example, if air content is desired to be between 4 and 7 percent and the variance is known, then a range of means may be used. If the variation on a site is known and 3-$\sigma$ limits determined to be 5.5 percent ± 0.90 percent, then the average air content can be 5.5 percent ± 0.60 percent for a process in control and the material will meet the specified 4 to 7 percent air content providing the process remains in control. Another approach is to specify a mean and allow a standard deviation range. For example, specify a mean of 5.5 percent; the standard deviation may then be $\leq 0.5$ percent for 3-$\sigma$ limits and the product will pass the 4 to 7 percent specification limits. Tables can be set up for various means and various standard deviations, allowing a contractor operating with a known standard deviation a certain latitude in mean air content. The same may be accomplished by testing standard deviation and then stating that if a standard deviation of so much is occurring then the mean air content must be within certain limits for the product to meet specification limits.

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# Concrete in the Verrazano-Narrows Bridge

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This paper describes the use of ice in the concrete mix to reduce the maximum internal temperatures in the mass concrete of bridge anchorages. It shows the effect of varying amounts of ice on the initial concrete placing temperature. It also gives some data on the maximum achieved internal temperatures (150 and 110 F), and the variation of temperature with time and ambient temperatures.

The effect of the use of ice in the bridge pavement concrete is discussed. A novel type of concrete pavement for bridges is described. The difficulties of control of the surface of the pavement on a flexible structure are explained as well as the method used to solve this problem.

•THE Verrazano-Narrows Bridge across New York Harbor has the longest span in the world—4,260 ft between main towers. With a total of 729,330 cu yd of concrete, a degree of care in the solution of design and construction problems was implicit. This paper will cover two phases of construction, the anchorage mass concrete and the deck slab on the suspended structure (Fig. 1).

Figure 1. General view of Narrows Bridge.

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## ANCHORAGES

In a suspension bridge the function of the anchorage is to resist the pull of the main cables. It does this by friction developed on the supporting soil; hence mere weight is important. The design pull exerted by the four main cables of this bridge is 136,000 tons. Due to differences in topography at opposite ends of the bridge the two anchorages were not identical, their respective contents being: (a) Brooklyn anchorage, 205,980 cu yd; and (b) Staten Island anchorage, 172,400 cu yd.

With weight at a premium, the heaviest economically available coarse aggregate (trap rock) was selected. Its average specific gravity was 2.90. The restriction to crushed stone in the specifications led to a strong protest from other aggregate producers. However, they were able to understand and accept the necessity for this restriction once it was explained.

The mix proportions for one cubic yard for the Brooklyn anchorage were:

| Class of Concrete | A | B |
|---|---|---|
| Required 28-day strength | 3,000 psi | 2,500 psi |
| Number of cubic yards | 56,440 | 149,540 |
| Portland cement | 493 lb | 410 lb |
| Natural cement | 63 lb | 53 lb |
| Sand | 1,150 lb | 1,100 lb |
| $^3/_4$-in. crushed stone | 1,363 lb | 983 lb |
| $1^1/_2$-in. crushed stone | 907 lb | -0- |
| $1^1/_2$- to $2^1/_2$-in. crushed stone | -0- | 1,353 lb |
| Water | 29 gal | 31 gal |
| Darex (for air entrainment) | About $^3/_4$ liq oz per sack | |
| Plastiment (retarder-densifier) | About 2 liq oz per sack | |

The class A concrete was for buttresses, columns, beams and structural slabs, the class B for mass concrete.

The anchorage is made up of large interlocking concrete blocks whose size depended upon: (a) the daily concrete plant capacity, (b) shrinkage considerations, and (c) the geometry of the anchorage. With a plant and delivery capacity of about 120 cu yd per hr, the maximum practical volume of block was about 1,000 cu yd. For a perfect cube this would give an edge dimension of 30 ft. Blocks of this size and shape present real problems in the dissipation of heat during the summer months. Actually, the blocks were considerably flatter than a cube and occasionally as thin as 7.5 ft. This flatness is an advantage since this shape presents a larger surface area to permit cooling, by exposure to air and contact with other (cooler) blocks which were previously placed.

Given the daily plant capacity of 800 to 1,000 cu yd, the shape of each block was largely controlled by the geometric details of the several masses of each anchorage. However, an effort was made to limit the maximum horizontal dimension to 75 ft to minimize shrinkage in the individual blocks. Of course, a skip sequence of day's work was adopted to minimize overall shrinkage.

The anticipated maximum temperatures were judged low enough not to require internal cooling by circulation of cooling water in embedded pipes. The specifications required that, except for winter concreting, the temperature of the concrete at time of depositing should not exceed 60 F. With this specification, a relatively low starting temperature is achieved which has the additional advantage of a slow initial heat development, since the rate of hydration of the cement depends in part on the temperature of the mass.

The maximum achieved internal temperature should depend upon:

1. The amount of and rate of heat developed vs
2. The rate of heat dissipation.

Number 1 depends upon: (a) the initial concrete temperature, (b) the type of cement used, and (c) the number of bags of cement per cubic yard.

Number 2 depends upon: (a) the spread of temperature between highest internal and the ambient temperature, or temperature of an adjacent block in contact; (b) the rate of heat conductivity of concrete; and (c) the distance from the center of the block to the cooling surface. From information given later in this paper it will be apparent that the conductivity coefficient of concrete must be low.

The physical constants of the problem for summer conditions in New York reveal that in a cubic yard of class B concrete:

| | Approx. Wt (lb) | Specific Heat | Temperature (F) |
|---|---|---|---|
| Coarse aggregate | 2,336 | 0.2 | 75 |
| Sand | 1,100 | 0.2 | 75 |
| Cement | 463 | 0.2 | 75 |
| Water (city mains) | 258 | 1.0 | 60 |

For these assumed conditions, the resulting concrete temperature (discounting heat developed by grinding action in mixing), would be 71.3 F and even if the 258 lb of water were cooled to 32 deg, the concrete temperature would be 64.3 F. The mass of mixing water, even with its high specific heat, is too much smaller than the mass of the solid materials to have much cooling effect. Some means other than cooled water is necessary.

Figure 2. Ice crushing machine—Brooklyn.

## TABLE 1

## ICE REQUIREMENT

| Air Temp (F) | | Ice per Cu Yd (lb) | Concrete Temp (F) | Remarks |
|---|---|---|---|---|
| Low | High | | | |
| 66 | 83 | 100 | 59 | With no ice: 72 F |
| 66 | 83 | 90 | 61-64 | |
| 70 | 79 | 90 | 60-62 | |
| 69 | 82 | 125 | 60 | |
| 73 | 88 | 115-145 | 60-65 | With no ice: 80 F |
| 76 | 84 | 145-165 | 58-62 | |
| 72 | 90 | 130-145 | 60 | |

On the Narrows Bridge additional cooling was achieved by using ice in place of some of the mixing water. Since the amount of heat necessary to change one pound of ice to one pound of water is 144 BTU (as contrasted with one BTU to heat water from 32 to 33 F), the large cooling effect of the heat of fusion of ice is apparent. The heat required to melt the ice must come from the concrete itself.

The mixing plant for the Brooklyn anchorage consisted of two Smith turbine mixers of 3 cu yd capacity each, plus an ice crusher capable of handling about 2 tons of ice per hour (Fig. 2). The crushed ice moved from the crusher to the mixer in a pipe. Because turbine mixers have not been in general use in this country many years, it may be useful to note that, even with a short mixing time of 1¼ min per 3-yd batch, and with lump ice in the mix, the resulting concrete was entirely satisfactory.

The temperature of the concrete at placing time depends on the ambient temperatures prevailing during the previous days due to their heating effect on the stockpiled aggregates and cement. To meet the 60 deg specified maximum placing temperature for the concrete, the amount of ice required was varied by trial. Some idea of how pertinent factors varied may be seen in Table 1 from records selected at random.

The net added mixing water per cubic yard of concrete was determined by subtracting the weight of ice added from the design value of 258 lb. Normally one would assume that flakes would be required to assure thorough melting and mixing; actually pieces from one to 3 in. were used to avoid the jamming in the feed pipe which occurred when flakes were used. The turbine mixer (with high speed blades) handled this size satisfactorily, although conceivably standard concrete mixers might not. The cost for the addition of ice was approximately $0.75 per cu yd of concrete. The ice itself cost 50 cents per 100 lb.

To determine the maximum internal concrete temperatures achieved, a series of remote-reading thermocouples were embedded in the concrete. These were read at approximately daily intervals for two to three months after placing (Figs. 3, 4). While it may not be reasonable to generalize from the small sample shown, certain facts seem significant:

1. The difference in cement content per cubic yard (556 to 463 lb) did not produce a very significant difference in maximum temperatures reached internally.
2. The influence of nearness to a cooling exterior surface exercises a profound influence.
3. Other readings too numerous for reproduction here gave evidence of the effect of ambient temperatures on the rate of cooling. In the summer months the highest internal temperature recorded was about 150 F, whereas during the cooler weather the highest temperature was 110 F.
4. There was some evidence that when the internal concrete temperature was approaching the ambient temperature (about 60 F) and another concrete block was placed

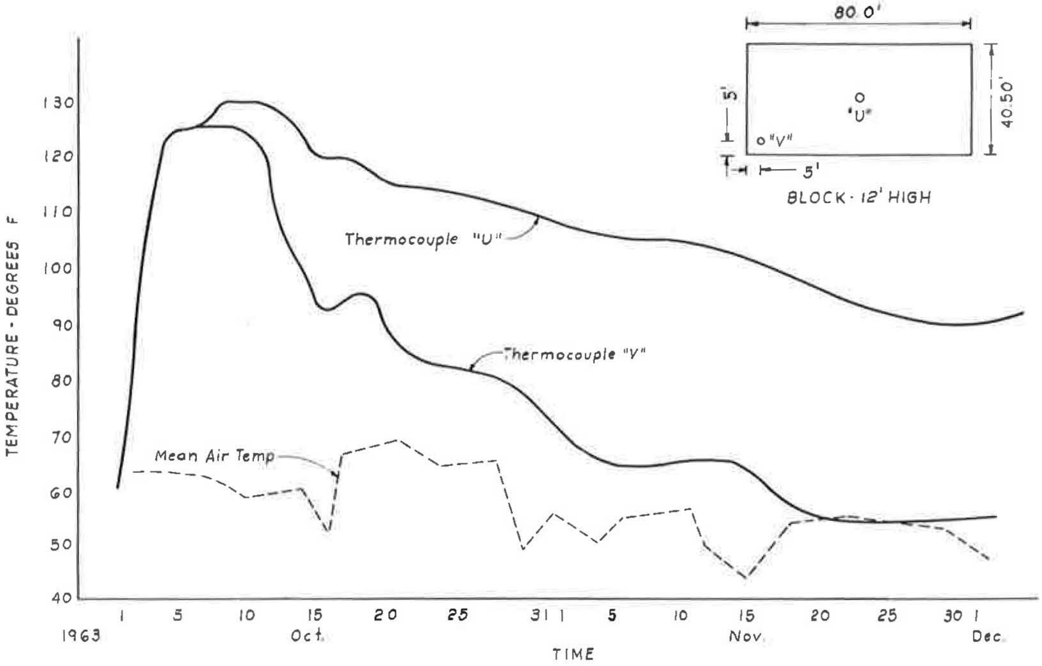


Figure 3. Curve showing internal concrete temperatures—class A concrete, Brooklyn anchorage.

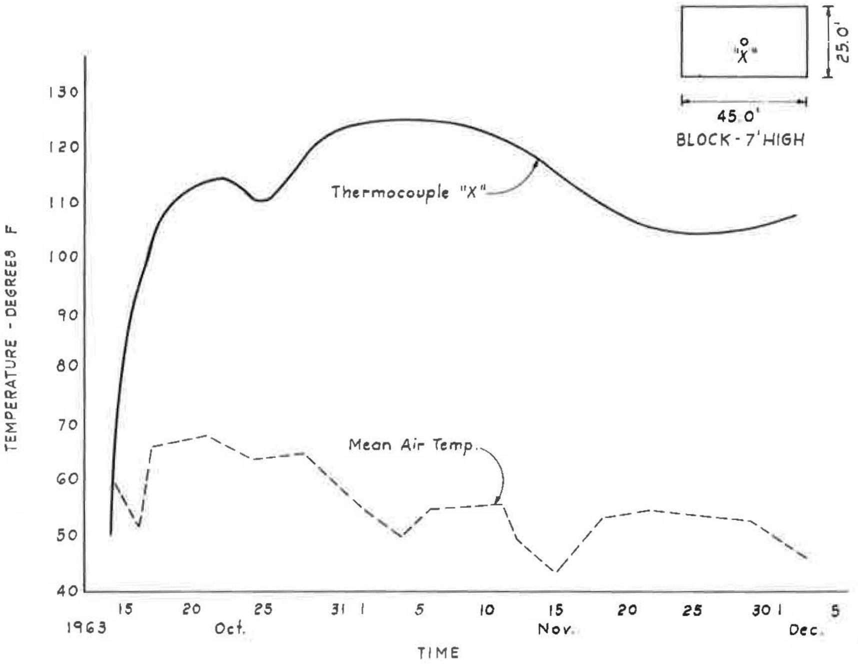


Figure 4. Curve showing internal concrete temperatures—class B concrete, Brooklyn anchorage.

over the first, thus insulating it from the cooling air, the internal temperature in the first block rose again as much as 20 F.

It may come as a surprise to the uninitiated how long higher temperatures persist internally in mass concrete. Low ambient temperatures often result in surface temperature cracks, which later disappear as the inner concrete contracts on cooling and a more uniform distribution of internal temperatures is reached with the passage of time.

## CONCRETE PAVEMENT ON SUSPENDED SPANS

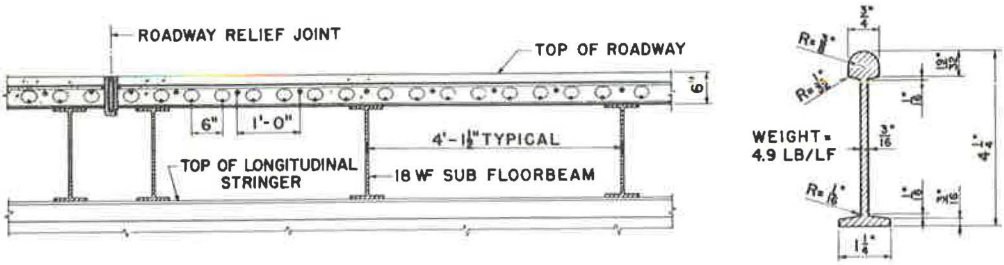
The concrete pavement slabs on the suspended spans are of interest because of: (a) their complete freedom from surface cracks; (b) the unusual slab design to meet unusual requirements; and (c) the uncommon method of screeding.

In recent years there has been an unusual amount of surface cracking in concrete bridge slabs. This is probably due not to any inherent characteristics of concrete, but to bad field practices which have evolved during the greatly enlarged highway construction program.

It was important to avoid surface cracking in this structure because (a) the very high frequency of traffic on this toll structure requires that maintenance operations be kept to a minimum, and (b) leakage of the upper deck slab would be troublesome for vehicles on the lower deck. These factors and necessary weight reduction led to an unusual deck slab design.

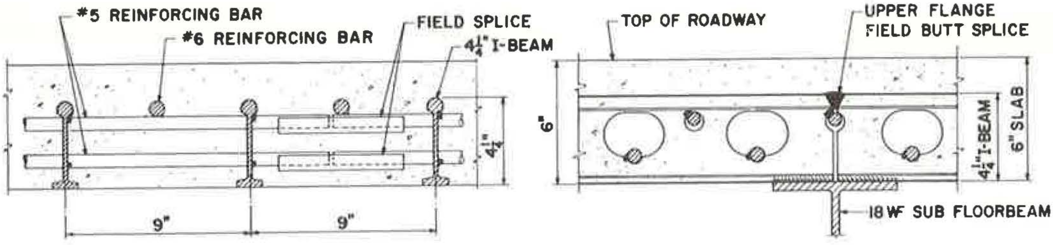
In long-span bridges there is a great emphasis on reduction in weight of slab and all other suspended elements since these directly affect the size of the main cables, the towers, the tower foundations and the anchorages. In fact, for every pound of weight carried there is required nearly a pound of more expensive materials to carry it.

Opposed to this requirement of weight reduction for the slab is the absolute need for a slab sufficiently strong to meet an extremely heavy load both as to intensity and frequency. The design which was developed had been used in slightly modified form on two of our previous suspension bridges. It is a 6-in. concrete-filled grid (Fig. 5). The principal slab reinforcement is longitudinal, consisting of specially rolled $4\frac{1}{4}$-in.



TYPICAL LONGITUDINAL SECTION OF FLOOR

GRID FLOOR I-BEAM



TYPICAL CROSS SECTION

SECTION AT I-BEAM SPLICE

Figure 5. Details of pavement slab.

I-beams spaced 9 in. on centers with a top $^3/_4$-in. bar between each beam. The transverse top and bottom reinforcement, which is threaded through the beam webs, consists of $^5/_8$-in. bars. The top transverse rods proved useful during construction in a way not contemplated during design. Since the bottom beam flanges are flush with the bottom of slab, there are $1^3/_4$ in. of concrete over the top of the embedded beams, thus providing sufficient cover to minimize the tendency to crack over the beams.

There are several significant peculiarities inherent in the paving of a flexible structure such as a long-span suspension bridge. Among them:

1. It is necessary to distribute the pavement load during placement by skipping several panels between successive pours in order to spread the load and so minimize angular distortions of the suspended structure and cables.
2. Transit mix trucks are too heavy to run on the grid so the concrete must be conveyed long distances in light buggies (up to 3,700 ft).
3. Because of the inevitable large deflections of the suspended structure during loading with the pavement, it is not possible to screed the concrete to a surveyed profile.

For a detailed treatment of conventional deck paving operations refer to "Smooth-Riding Bridge Decks," HRB Bull. 243. It will be seen that allowance in setting screed rails for the support deflection, due to the addition of the concrete, is only 4 to 5 in. for even a 200-ft span. For the Narrows Bridge, the pavement slab was over 45 percent of the weight on the main cables and would cause deflections during placement of several feet, as well as appreciably change the shape of the roadway profile curve. For this reason it was not practical to run in a profile curve by survey, but rather to rely on some other means of controlling the screeding of the pavement surface.

The construction contractor proposed using, as a control, the top transverse reinforcing bars which were 12 in. on centers. These rods were welded to the upper surface of the holes punched in the webs of the embedded small beams. Their conformity to a smooth curve was tested in place and found to be surprisingly good. Accordingly, the contractor constructed a metal sled of $^3/_8$-in. steel plate about 5 in. high and 42 in. long. These sleds were framed into and supported the screed. In use, these metal sleds rode on the top surface of the upper transverse reinforcing rods and were continuously embedded about $2^3/_4$ in. deep in the wet concrete. Because of the small volume displacement by this $^3/_8$-in. plate, there was no need to add concrete to fill the space previously occupied by the metal sled. Of course, the screeding is only a strike-off, but this operation has always had a marked effect on the smoothness of a completed pavement slab.

It is apparent that the effectiveness of using the upper surface of the transverse reinforcing steel as a control depends on the exactness of the positioning of these rods. In this instance the shop punching of the holes in the webs of the small I-beams (through which the rods were threaded) produced a degree of regularity sufficient for the purpose. With respect to the possibility of long waves in the pavement surface, this was apparently eliminated by the nicety of the stiffening truss and floor system fabrication as well as by the uniform distribution of weight suspended from the cables. In any case, the riding quality of the surface is completely satisfactory.

## PAVING OPERATION

No heavy vehicles were permitted to ride on the grid so the transit mix trucks had to discharge at a point on the bridge approach before reaching a suspended side span. They rotated for 5 min before adding the retarder in order to permit better dispersion of the cement. After mixing another 10 min the truck then discharged into a holding hopper which was used to load $^1/_3$-cu yd motorized buggies, which conveyed the mixed concrete along the suspended structure to where the paving was in progress. Since this distance was as great as 3,700 ft, as many as 21 buggies had to be used for maximum runs. The concrete slump was held very uniformly at $2^1/_2$ in. to prevent segregation in the buggies. After deposit, electrically driven vibrators were pulled along in each 9-in. space between the small longitudinal beams. The double screed was then pulled manually to strike off the fresh concrete. Each screed consisted of a double beam 19 ft long carrying two gasoline driven vibrators (Fig. 6).

Figure 6. Paving operation.

The customary successive operations of luting, testing with a straight-edge, burlap drag, and curing by spraying a white pigmented compound are too well known to require description here. All operations following the screeding were carried on from cross-bridges to assure positively no walking in the wet concrete after strike-off. This is a simple and most essential requirement which is often not enforced.

Tests of pavement smoothness by a rolling "bump meter" confirmed compliance with the specified tolerance which was $\frac{1}{8}$ in. in 10 ft. This is also borne out by the experience of many critical automobile riders.

Since the entire pavement operation of 107,000 sq yd was carried out between June 22 and September 30, 1964, hot weather was a factor which could have had a seriously damaging effect on the pavement concrete. In addition to the heat, this bridge is in a location continuously exposed to wind which has a bad evaporation effect. The specifications made no mention of a maximum concrete placing temperature. However, to achieve a maximum temperature of 72 F, flake ice was added to the mix in amounts varying from 60 to 70 lb per cu yd. In this instance it was flake ice and not chunks, such as were used in the turbine mixers for the anchorages.

It is believed that the lower placing temperature contributed to the lack of surface cracks. Other favorable factors were: (a) the low slump, (b) the use of some natural cement, (c) the use of a retarder, and (d) the proper application of the sprayed curing compound. The fact that no stripping of slab forms was permitted before seven days had a favorable curing effect on the underside of slab. This may be the first time ice has been used in a concrete pavement mix.

The mix design for one cubic yard of pavement concrete was:

| | |
|---|---|
| Portland cement | 535 lb |
| Natural cement | 69 lb |
| Sand (surface dry) | 1,220 lb |
| ¾-in. crushed trap rock | 1,990 lb |
| Water | 31 gals (less ice) |
| Plastiment | 2 liq oz per sack |
| Darex (for 6% air) | 2.5 oz per cu yd |
| Ice | 60 to 70 lb |
| Concrete placing temp | 72 F (max) |

The strength of the pavement concrete as measured by 57 test cylinders at 28 days averaged 4,524 psi.

Considering the many problems which arose in placing this concrete pavement on a flexible structure during the hot months under a very rapid schedule, the resulting slab has proved to be eminently satisfactory.

# Mixing Performance of Large Central Plant Concrete Mixers[1]

F. M. BOZARTH and W. E. GRIEB, Highway Research Engineers, Office of Research and Development, U.S. Bureau of Public Roads

•FIELD TESTS of central plant concrete mixers of the tilting-drum type on four projects lead to the conclusion that good blending of aggregates on the belt during charging of the mixer, and good parallel timing and uniformity in charging of cement and water are essential to production of good quality concrete with minimum mixing time. Two of the four makes of mixers tested produced satisfactory quality concrete at mixing times ranging from 30 to 180 sec. Results and evaluations of factors contributing to poor quality suggest that all four of the mixers tested could probably perform equally well when the plants are properly adjusted. Also, it was found that visual determinations of good blending and timing can be misleading.

As a result, it is recommended that mixing time be determined by mixer performance tests where reasonably possible, and in all cases involving 20,000 cu yd or more of concrete. In the absence of performance testing a mixing time of 75 sec is recommended. However, with the performance tests, mixing time may be reduced (or increased) to that which test results indicate to be a satisfactory mixing, but not less than 40 sec.

Test results also indicate that a specified maximum mixing time may be desirable, e.g., 60 sec in excess of the minimum permitted. Concrete mixed with a set quantity of air-entraining agent incurred substantial increases in air content as mixing time was extended—at least within the range of mixing times tested. For example, concrete on one test job with a specified mixing time of 50 sec was found after 180 sec mixing time to possess air content sufficiently high to account for numerous plant test strengths which were below 3000 psi (Fig. 1).

These tests were conducted by the Bureau of Public Roads in cooperation with state highway departments and contractors on four projects in Connecticut, Virginia, Wisconsin and Wyoming. Study objectives were to identify and evaluate operating plant variables which affect the mixing time required to produce satisfactory quality concrete.

The study effort embraced multiple sampling at plant and roadway of nearly 400 test batches, nearly 2000 tests each for slump, air, unit weight and washout, plus nearly 4000 compressive strength tests. Each sample was tested for (a) slump, (b) air content, (c) unit weight of fresh concrete, (d) coarse aggregate retained on the No. 4 sieve after washout, and (e) 28-day compressive strength of molded 6- by 12-in. concrete cylinders. This abridged report briefly covers the major test results and discusses the factors and causes contributing to the results.

One plant which failed to produce good concrete at 30-sec mixing time needed from 70 to 90 sec to mix passable concrete. This concrete still had some deficiencies due to inadequate blending of all three batch ingredients—aggregates, water and cement—during charging of the mixer. Another plant using a mixer with experimental mixing blade configurations did not produce acceptable concrete even at 180-sec mixing time, based on test results obtained at the plant. However, roadway tests of the same concrete yielded satisfactory minimum compressive strengths at the specified 90-sec

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Paper sponsored by Special Committee on Highway Equipment and presented at the 45th Annual Meeting.

[1] This is an abridged version of a longer report.

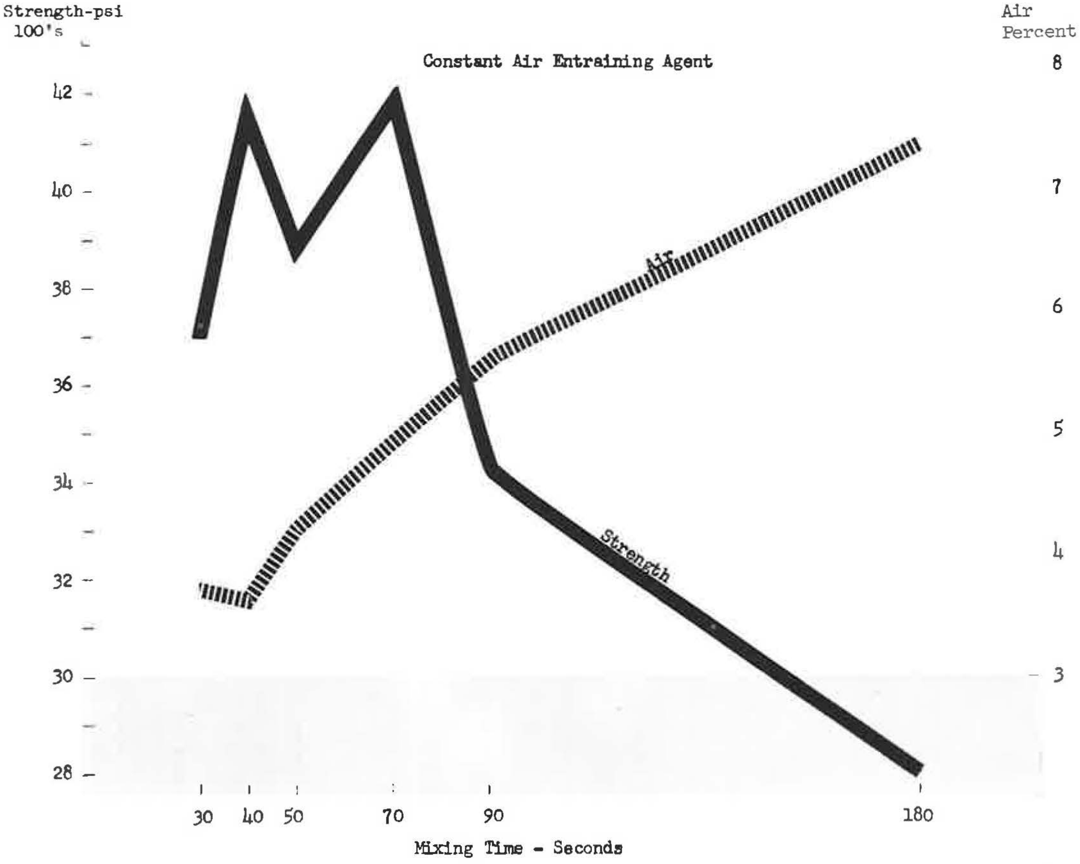

Figure 1. Strength and air vs mixing time.

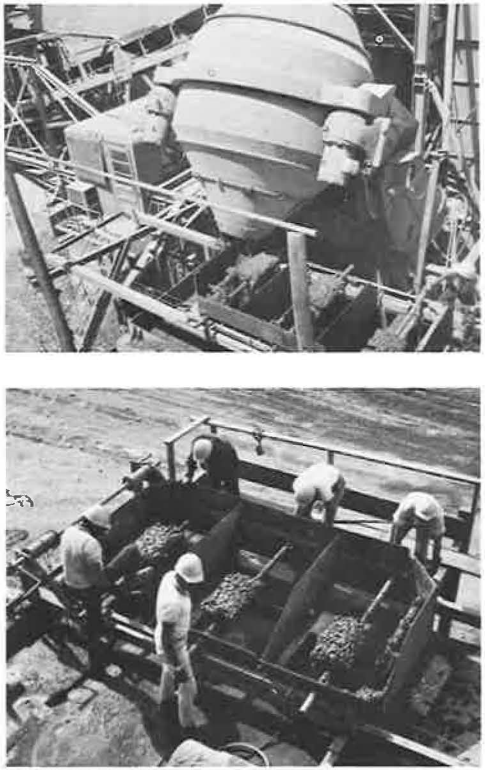

Figure 2. Sampling rack.

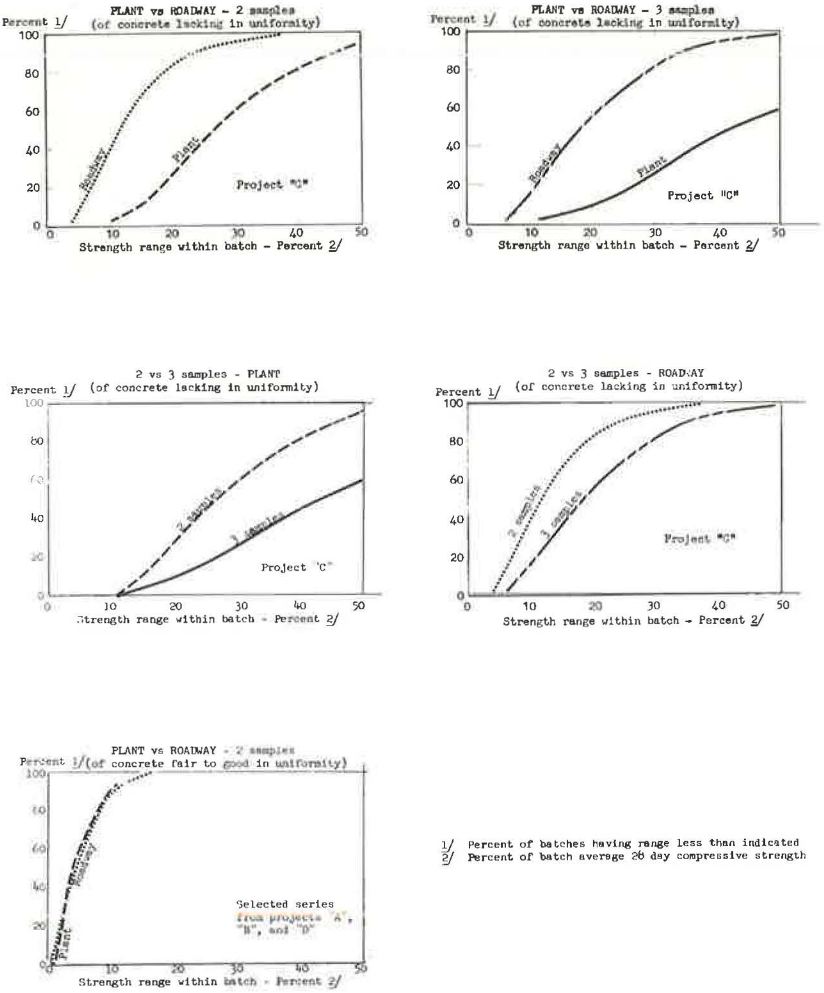

Figure 3. Contrasts in uniformity.

mixing time. The plant using experimental mixing blades had good distribution of aggregates within the batch at all mixing times tested based on aggregate washout tests, but the cement distribution within the batch was unsatisfactory.

Tests at all four plants were made from three samples, identified as Nos. 1, 2, and 3, obtained by intercepting the mixer discharge at approximately the one-sixth, one-half and five-sixth points of the discharge with a specially designed sampling rack (Fig. 2). Tests of the same concrete obtained from roadway samples indicated that poor uniformity when found in sampling at the mixer is less pronounced at the roadway after the concrete has been discharged into the hauling unit, dumped again, and put in place at the paving site. The contrasting uniformity in these tests makes it appear logical that a large proportion of historical test data on paving concrete should be compared to roadway tests rather than plant tests as identified in this report.

Roadway data on three of the four test projects were obtained from two samples per test batch, whereas on the remaining test project three roadway samples were taken per test batch. This difference in number of samples taken at the plant and roadway is important when evaluating the relative uniformity of concrete or when comparing uniformity at the two locations, because data ranges obtained from two samples must be expanded by a factor of 1.5 to facilitate comparison with data ranges obtained from three

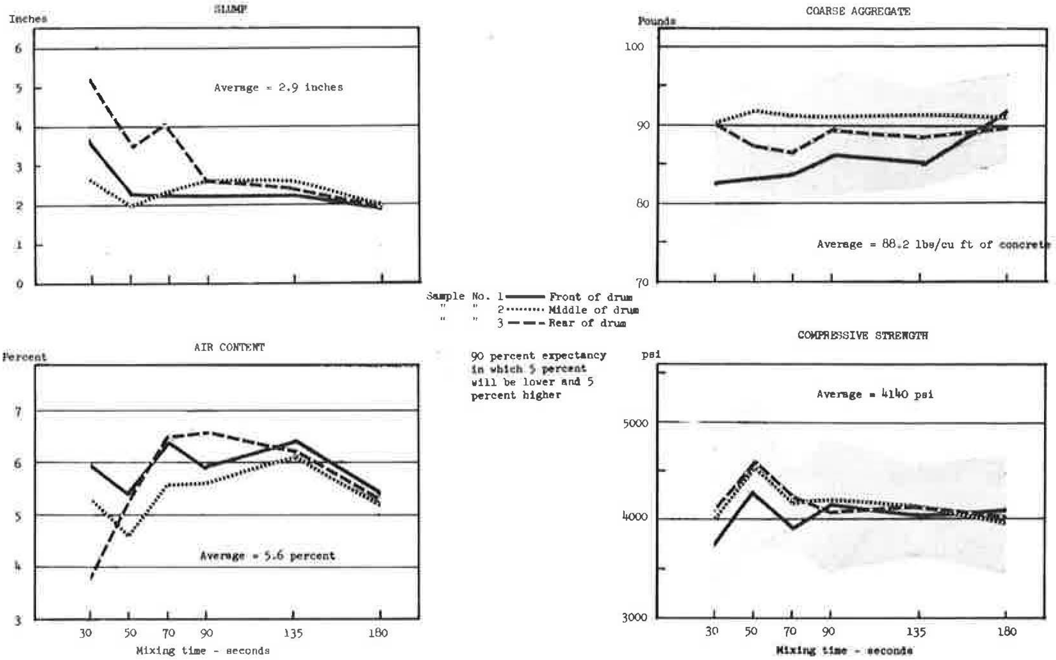

Figure 4. Plant data, project "A."

samples. Figure 3 shows the difference in compressive strength data ranges for two and three samples from the same concrete as well as showing the contrasting test results between plant and roadway data for marginal quality concrete, and the similarity of results between plant and roadway data for good quality concrete.

The broad composite patterns shown in Figure 4 for project "A" are those of inadequate blending during charging of the ingredients. This is particularly evident for mixing times under 90 sec. Slump uniformity leveled out beyond 70 sec. Apparently, much of the water entered the drum too late, causing excessive slump in the rear of the mixer. Air uniformity improved significantly beyond 30 sec mixing time and the sample-to-sample spread became very narrow beginning at 135 sec. Blending of aggregate on the belt appeared to be good but, evidently, this was an illusion. Uniformity of the coarse aggregate in the mixer improved quite slowly. Coarse aggregate range between samples 1 and 2 was consistently in excess of 7 lb per cu ft of concrete, until mixing time exceeded 135 sec. This suggests that indiscriminate charging of materials into large tilting mixers, with the expectation that the mixer will solve the problem, is inherently conducive to nonuniformly mixed concrete. The efficient method of obtaining uniformly mixed concrete is thorough blending of all ingredients during charging of the mixer.

It will be noted that sample 1 for project "A" shows a consistent pattern of relatively lower strengths for mixing times under 90 sec. This appears to be a case of poor timing of cement charging. On seven batches mixed for 30 sec, cement was observed to lag during charging of the mixer because of clogging in the scale hopper. The consequent maldistribution of cement in the mixing drum failed to correct itself during the 30-sec mixing time. Strengths of the three samples taken at the mixer from these seven batches, which are separated from the 30-sec test series summaries, gave an average range, or spread, of 2200 psi. In other words, sample 1 had an average of 3100 lb as compared to 5300 lb for each of samples 2 and 3.

On projects "B" and "D" (for which data are given in the full report), concrete mixed for 30 sec was essentially as good as any of the concrete mixed for longer periods. The good concrete obtained on project "D" is of interest when compared with the concrete

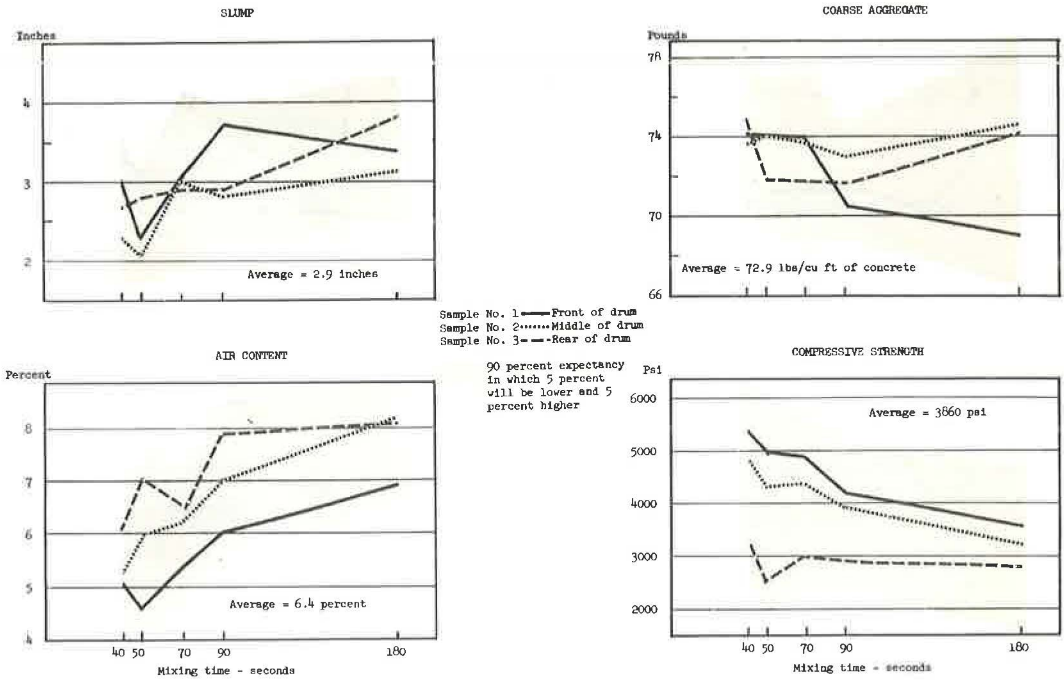

Figure 5. Plant data, project "C."

obtained on project "A." Both projects "A" and "D" utilized similar aggregates and mix designs, and the plant and mixer equipment had similar physical characteristics and features, although built by different manufacturers. Those test criteria which indicated questionable quality on project "A" were consistently good on project "D" for all mixing times tested.

An experimental mixer was tested on project "C," but its use was limited to the one job. However, some test data on this mixer are of significance (Fig. 5). Although maldistribution of cement was present after 180 sec mixing time, uniformity of aggregate distribution at all mixing times tested was generally comparable to the best obtained on the other projects. The cement maldistribution is manifest in the extremely low strength for sample 3, which provides strong evidence that blending of the cement with other batch ingredients during charging of the mixer was critically poor. Also, visual evidence suggested that samples 1 and 2 might be high in cement content. The graphic trend of sample average strengths if extrapolated beyond 180 sec appears to converge at about 270-sec mixing time. The downward trend is essentially accounted for by the progressive increase in air content, with constant air agent and increasing mixing time. Although compressive strength for much of sample 3 at 90-sec mixing time fell below 3000 psi, roadway samples show there was only one chance in 20 of this concrete having pavement compressive strengths less than 3400 psi.

Although control of slump uniformity during mixing of test batches on project "C" was fairly successful, minor adjustments in charging the water always carried the risk of failure. The water charge was relatively fast and a small adjustment in the water timing could cause a large change in slump uniformity. The soupy end of the drum could be reversed easily by making only moderate changes in timing of the water. Experience suggested that catching and holding the optimum slump uniformity was akin to the problem of walking a tight rope. A very slight off-center move in either direction could throw the situation out of balance.

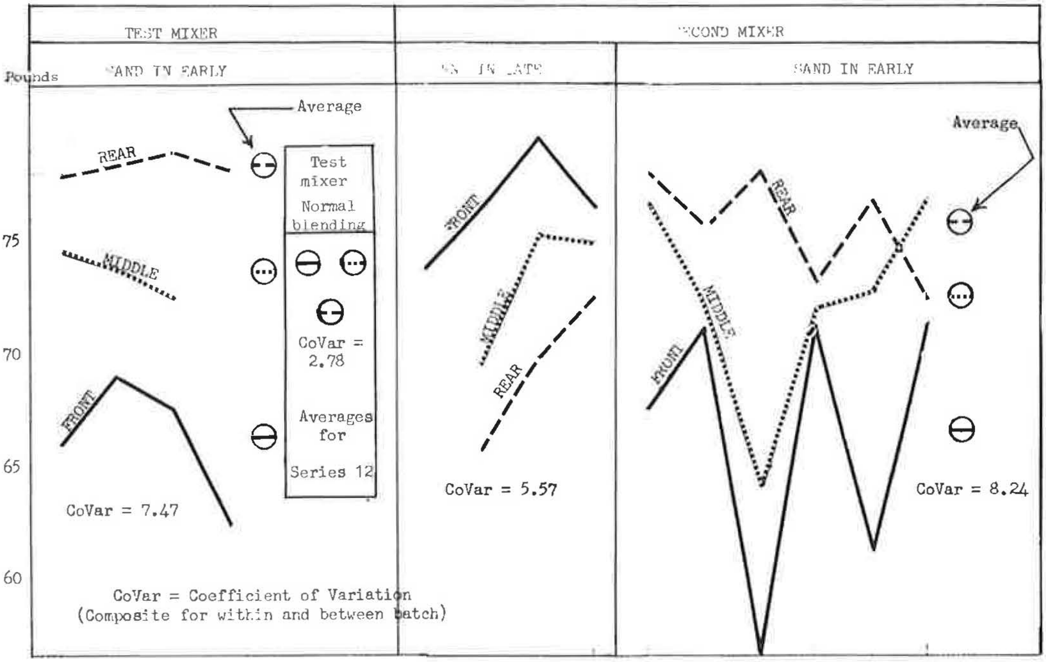

Figure 6. Project "C" special tests at plant—coarse aggregate retained on No. 4 sieve.

Test variations in the uniformity and timing of water and cement flow during charging of the mixer were not intended; nevertheless, their apparent lack of uniform blending on two of the four projects strongly contributed in specific cases to the marginal or poor quality of concrete. Although the critical nature of this deficiency might vary for different mixers, there is evidence that proper charging of water and cement (i.e., timing and uniformity) is more important than blending of aggregates during charging. In the case of the mixer on project "C," proper charging of water and cement to match the good aggregate uniformity might have resulted in uniformly mixed concrete for any of the test series. Subsequent to completion of the scheduled series of tests on this project, a representative of the manufacturer attempted to trouble-shoot the cause of the obviously poor quality of concrete obtained from the freshly completed tests. He modified the belt loading in an effort to improve the blending of aggregates on the belt. Results from four batches, shown at left in Figure 6, clearly show that uniformity of coarse aggregate content, which had been good, with a coefficient of variation of 2.78, was made worse instead of better. The new coefficient was 7.47. The logical inference from the modified blending test results is that sample 1 was heavy on sand. The previously described cement imbalance was still apparent.

Two series of additional special tests on project "C" were run on a second mixer of standard design, operated by the contractor from a separate setup in the same plant yard. Preliminary investigation indicated that too much sand was held back and fed onto the charging belt late. Although mixing action provided vigorous cascading of the materials, the high proportion of raw sand visible in the rear of the mixing drum was very slow in becoming dispersed, and obviously was not uniformly distributed after 50 sec mixing. Four of these batches were sampled at the plant after being mixed for 60 sec. Results for coarse aggregate distribution are shown at center in Figure 6. An excessive proportion of sand in the rear of the mixer is apparent from the low proportion of coarse aggregate. This is accompanied by an excessive proportion of coarse aggregates in the front of the mixer. Blending of aggregates on the belt was then altered in an attempt to improve uniformity of the mixed concrete. Plant samples confirm the changed blending pattern on the belt, but the changes resulted in a problem of incon-

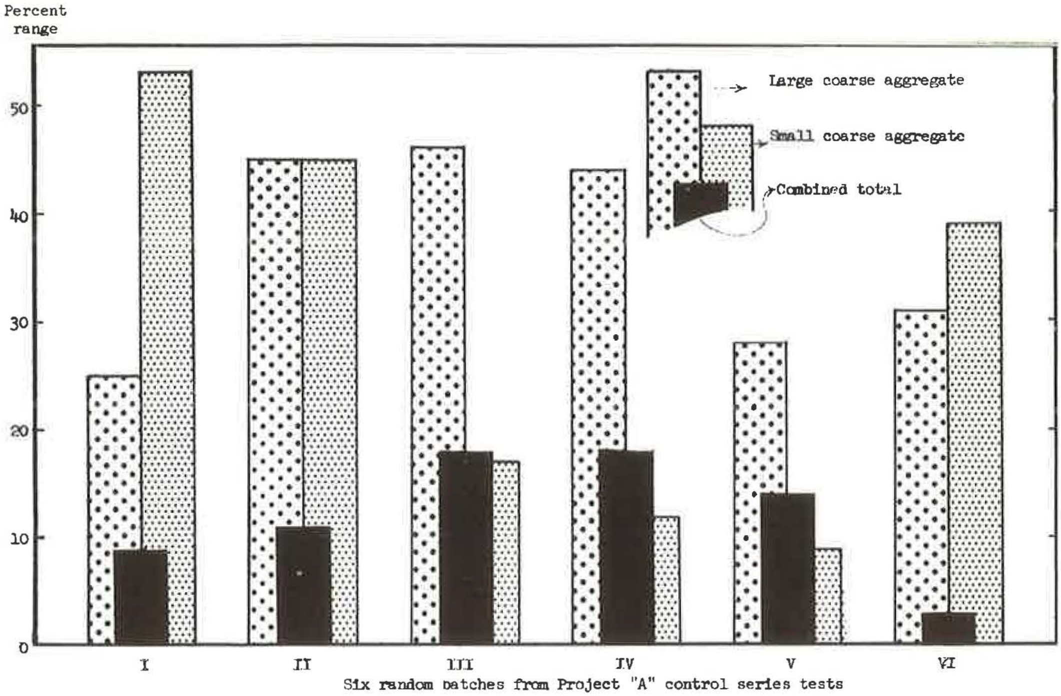

Figure 7. Range of coarse aggregate within batch—3 samples.

sistency which was not fully apparent at the time. The results are shown at right in Figure 6. This time the heavy concentration of sand, except for one batch, had changed ends in the mixing drum. The erratic behavior during charging is evident, both from variations in coarse aggregate weights, and from the coefficient of variation, which went up to 8.24.

Figure 7 was prepared from sieve data for coarse aggregate retained on the No. 4 sieve from washout tests, where partial or no blending of aggregates on the charging belt was deliberately planned. Coarse aggregates for the project were stockpiled in two sizes. One consisted of material passing the 2-in., but retained on 1-in., while the other size consisted of material passing the 1-in., but retained on No. 4 sieve. Total weights retained on the No. 4 sieve can falsely indicate within-batch uniformity without the two sizes of coarse aggregate being present in equal proportion in each sample. For example, batch VI shows a range of only 3 percent for total retention on the No. 4 sieve but this is misleading. The two sizes had ranges of 31 and 39 percent, respectively.

## RECOMMENDATIONS

The following recommendations are based on the authors' evaluations and observations relative to test results covered by this report.

1. Minimum mixing time for large central plant mixers should be determined by plant-mixer performance tests where reasonably possible and in all cases involving 20,000 cu yd or more of concrete. Mixer performance data should be based on three concrete samples per test batch taken at the mixer during discharge, from approximately the one-sixth, one-half, and five-sixth points of the batch discharge.
2. Product uniformity aspects of concrete acceptability should be based on roadway test results from not less than two and preferably three samples from each test batch taken after dumping the concrete from the hauling unit.

TABLE 1

| Test Criteria[a] | Permissible Range Within Batch From Three Samples (not to be exceeded by 6 out of 7 batches) | |
|---|---|---|
| | Plant | Roadway |
| Slump, in inches | 2.25 | 1.75 |
| Air content, percent by volume of concrete sample | 2.0 | 1.5 |
| Weight per cubic foot of plastic concrete, in pounds | 4.0 | 5.5 |
| Coarse aggregate retained on No. 4 sieve, expressed as a percent of three-sample average weight retained | 11.0 | 9.0 |
| Compressive strength, 28-day, based on average of two cylinders per sample, expressed as a percent of three-sample average | 25.0 | 20.0 |

[a] Tests to be made in accordance with AASHO methods.

3. Determination of coarse aggregate uniformity within the batch where concrete ingredients are batched from separate stockpiles of more than one size of coarse aggregate should be made using sieves of appropriate size to identify the quantity of coarse aggregate coming from each of the separate stockpiles. This is particularly helpful in the case of mixer performance tests.
4. Air-entrained concrete mixed greatly in excess of the specified time which the intended air content allowed for may have excessive air content to the point of reducing a high proportion of compressive strengths for plant samples below the design minimum. This risk should be either controlled or compensated for by one of the following options: (a) a specified maximum mixing time which should not exceed the specified minimum by more than, for example, 60 sec; or (b) a substantial increase in the safety margin provided for in the design strength of the concrete.
5. Where mixer performance tests are made on given project setups and concrete mixtures, the acceptable mixing time for drums of 6- to 10-cu yd capacities may be reduced (or increased) for those particular circumstances to the mixing time which test results indicate to be satisfactory mixing. In no event, however, should mixing time be less than 40 sec. Where mixer performance tests are not made, minimum mixing time should be 75 sec, providing that apparent blending of materials during charging is achieved to the satisfaction of the engineer.

To define satisfactory mixing a minimum of seven production batches of concrete should be tested for the proposed minimum mixing time, unless the engineer determines on the basis of prior tests that a different number of batches is adequate for the purpose. When any change occurs in size of the batch, the operating process, conditions affecting mixing or hauling, the ingredients of the concrete, or other conditions which in the opinion of the engineer will affect the quality of the concrete incorporated in the pavement, an additional seven production batches of concrete should be tested.

Each sample of concrete should be tested and differences in test results for the three samples from each batch should not exceed those given in Table 1 where any of the listed criteria are applied. It is recognized, however, that 28-day strengths and even 7-day strengths are not a realistic answer to the need for quick test criteria for job control purposes.