PROGRESS REPORT

APPLICATION OF STATISTICAL QUALITY CONTROL PROCEDURES TO PRODUCTION OF HIGHWAY PAVEMENT CONCRETE

MARCH 1965
NO. 5

by

S. J. HANNA
and
A. P. LOTT

Joint
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Project

PURDUE UNIVERSITY
LAFAYETTE INDIANA

Progress Report

APPLICATION OF STATISTICAL QUALITY CONTROL
PROCEDURES TO PRODUCTION OF HIGHWAY PAVEMENT CONCRETE

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To: K. B. Woods, Director
Joint Highway Research Project

From: H. L. Michael, Associate Director
Joint Highway Research Project

Attached is a report entitled "Application of Statistical Quality Control Procedures to Production of Highway Pavement Concrete." This report was prepared by Messrs. S. J. Hanna and A. P. Lott under the direction of Professor J. F. McLaughlin. The report contains the results of the first part of a projected series of quality control investigations on various aspects of highway construction and are a contribution to the Bureau of Public Road's Data System. In addition, the report provides information and illustrates procedures that can be used for the establishment of a quality control program by the Indiana State Highway Commission.

Respectfully submitted,

H. L. Michael /JFM
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HLM:kr

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PROGRESS REPORT

APPLICATION OF STATISTICAL QUALITY CONTROL
PROCEDURES TO PRODUCTION OF HIGHWAY PAVEMENT CONCRETE

by

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and

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Prepared as Part of an Investigation

Conducted by

Joint Highway Research Project
Engineering Experiment Station
Purdue University

Joint Highway Research Project

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ABSTRACT

Hanna, S. J. and Lott, A. P., "Application of Quality Control Procedures to the Production of Highway Pavement Concrete", Joint Highway Research Project, Report No. 5, HPS-HPR(1)-38, Purdue University, March 1965. Project Director: J. F. McLaughlin.

This investigation was concerned 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. The data were analyzed to provide information concerning the magnitude of the variance components and to provide information and illustrate procedures for the establishment of a quality control program which could be used by the Indiana State Highway Commission.

Plastic portland cement concrete was chosen as the area of investigation. The specific area was limited to concrete paving projects under contract in Indiana during the summer months of 1964. Three paving projects were selected and tests for air content slump and unit weight were made on the concrete. The projects were chosen on the basis of their geographic location in the state and the paving schedule of the contractors. Each project was performed by a different contractor all of whom were operating under the same specification requirements.

Three replicate determinations of each attribute, air content, slump and unit weight were made on 50 samples obtained on each project. Hence, for this investigation, 150 individual tests were performed for each test method on all projects for a total of 450 observations. Tests for air content by pressure meter, air content by Chace meter, slump and unit weight were performed using standard test procedures.

A team consisting of three men (two test operators and one cleanup man) collected the field data at each project site. One operator performed the slump and unit weight test while the other operator performed both types of air tests. The equipment and operators never varied. The 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. Six to ten samples were tested in a day.

The data were recorded in the field and at the completion of the testing program all data were tabulated and recorded on IBM punchcards. Information regarding job number, sample number, replicate number, time of test and date were also recorded for ease of identification.

The statistical analysis of the data was accomplished using standard computer programs for the analysis of variance, correlation and distribution. In addition, standard statistical techniques and procedures were utilized to determine confidence limits, control limits and for testing of significant differences. A majority of the analysis and plotting of data was accomplished using the IBM 7094 computer system. The components of variance for site, sample-within-site and error term were computed based on a factorial design model. In addition, each site was analyzed separately to obtain estimates of the components of variance for each site. Using the results of the analyses of variance 3- σ control limits were computed for each attribute measured and control charts developed to illustrate the use of this quality control procedure. The control limits were computed on the basis of values of components of variance that appeared reasonable in the light of present technology. Since operators and equipment never varied there is no estimate available of operator or

equipment variability. It is a recognized fact that these variables may be significant.

With the amount of data available and since the tests for air, slump and unit weight on the same sample information regarding correlations between the tests was obtained. It was determined that significant correlations existed between several of the methods but that the predictability was poor.

A time dependency was observed when the air content was measured by the pressure meter and an analysis of the difference between replicate observations was performed. Significant differences were found to exist between the first and second replicates for all sites and the first and third replicates for all sites.

During the field portion of the investigation assignable causes of variation were noted (such as faulty air dispensing equipment) which increased the variability. The use of a quality control program can provide evidence that some assignable cause is increasing the variability beyond that due to chance alone.

INTRODUCTION

This investigation was concerned 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. The 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 been 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. It is, as has been stated, one of the aims of this investigation to obtain estimates of the variability associated with the manufacturing of fresh portland cement concrete for highway pavement.

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 likened 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 these estimates of the probability of being in error. 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 the producer and to the 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.

THE BUREAU OF PUBLIC ROADS ACTION PLAN

The Bureau of Public Roads has, in recent communications to many of the states, has stressed the need for a statistical approach to quality control. There are several reasons why quality control is needed. One is that something more than judgment is frequently needed to support engineering decisions. In addition, it is difficult, and too often impossible, to say whether present sampling and testing procedures are adequate to control a construction project.

On November 4 and 5, 1963 a Quality Control and Compaction Workshop was held by the Bureau of Public Roads at Homewood, Illinois, with state personnel from Illinois, Indiana, Kentucky, Michigan and Wisconsin in attendance. The purpose of this workshop was to stress the need for statistical quality control of highway construction and to encourage the states to develop their own programs to participate in a quality control study.

It was brought out that the Bureau of Public Roads would organize sampling and testing programs to evaluate the selected criteria and the states would make measurements on the various items of representative acceptable construction. The Bureau of Public Roads, using the data thus obtained will set up a compilation of variance estimates for many construction items for use by all state highway departments. It was pointed out that the Bureau of Public Roads is not proposing this program in an attempt to institute another level of "record sampling," but rather to collect information that will be useful to the states in controlling present construction and which ultimately could be used in the preparation of better specifications.

The following are step-by-step guide procedures for implementing the program that were presented for consideration.

- Step 1. Select material or items of construction for which numerical acceptance limits are to be developed.
- Step 2. List significant quality characteristics of each material or item. Analyze historical data or otherwise obtain preliminary estimate of normal variation on which sampling plan will be based.
- Step 3. Design plan that will insure randomness of sampling. Specify in detail the methods of sampling and testing on which acceptance will be based.
- Step 4. Apply sampling plan to material or item of construction produced under acceptable routine conditions and usual job control. Take a minimum of 50 samples in duplicate of each of 3 representative locations.
- Step 5. Divide each duplicate sample into two portions as identical as possible. (600 portions from the 150 duplicate samples)
- Step 6. Obtain measurement of selected characteristics on each portion of routine methods which will be used in acceptance testing.
- Step 7. For each characteristic compute average level, overall variance, variance due to sampling procedure and variance due to testing error.
- Step 8. Classify the characteristics with respect to criticality and multiply the sigma of each characteristic by acceptance tolerance (T_s) appropriate to its classification.
- Step 9. Compare limit(s) obtained in Step 8 with existing limits and/or engineering requirements. Adopt if a reasonable comparison is obtained. If limits appear too wide, examine sources of variance to determine if construction or process controls must be tightened, or if variance due to sampling and tests can be reduced.
- Step 10. Apply statistically obtained limits on trial basis concurrently with governing current specifications. At end of construction season review results and adopt or revise new type specifications.

Principal areas to be included in the quality control study, also presented by Bureau of Public Roads at the Homewood Workshop for consideration by the states, were as follows:

AREAS TO BE STUDIED FOR STATISTICAL QUALITY CONTROL
AND TENTATIVE ASSIGNED CLASSIFICATIONS TO VARIOUS
CHARACTERISTICS OF MATERIALS AND PROCESSES

By

The Task Force Group on Statistical Quality Control
Office of Research and Development
U. S. Bureau of Public Roads

Portland Cement Concrete Pavement

<u>Item</u>	<u>Characteristics</u>	<u>Class</u>
Pavement Slab	Thickness	Major
	Air content of surface	Major
Plastic Concrete	Slump	Major
	Air content	Major
	Cement content	Major
	Cylinder strength	Major
Coarse Aggregate	Grading	Major
	Durability	Major
	Passing No. 200	Major
	Deleterious materials	Minor
	Los Angeles loss	Minor
Fine Aggregate	Grading	Major
	Fineness modulus	Major
	Passing No. 200	Major
	Sand equivalent	Minor
Cement	Alkali content	Major
	Strength	Major
	Air content	Minor

Hot Mix Asphaltic Concrete

Asphaltic Pavement	Density	Major
	Temperature at compaction	Major
	Thickness	Minor
	Surface tolerance	Minor
	Roughness	Minor
Asphaltic Base	Density	Major
	Thickness	Minor
Asphaltic Mix	Gradation of aggregate	Major
	Dust ratio	Major
	Asphaltic content	Major
	Mixing temperature	Major
	Stability and flow	Minor

<u>Item</u>	<u>Characteristics</u>	<u>Class</u>
Asphalt Cement	Penetration or viscosity	Major
	Retained penetration of thin residue	Major
	Thin film test loss	Minor
Aggregate	Los Angeles loss	Major
	Gradation	Major
	Liquid limit and plastic index	Major
	Durability	Minor
	Deleterious material	Minor
	Flat and elongated particles	Minor
	<u>Base Course</u>	
Soil Aggregate	Stability	Major
	Plasticity	Major
	Thickness	Minor
	Gradation	Minor
	Density	Minor
	Line and Grade	Minor
Stabilized Base	Stability	Major
	Additive quantity	Major
	Thickness	Minor
	Plasticity	Minor
	Gradation	Minor
	<u>Soils</u>	
Subgrade	Density	Major
	Stability	Minor
	Moisture content	Major
Embankment	Density	Minor
	Moisture	Minor

These tables are subject to additions and changes as the project develops.

WORK IN INDIANA

Plastic portland cement concrete was chosen as the area of investigation. The specific area was limited to concrete paving projects under contract in Indiana. Tests for air content, slump and unit weight were made on the plastic portland cement. Air content was determined by using two different types of air meters. One was of the pressure type and the other was the Chace air meter. These tests were conducted by a research team from Purdue University and all tests were made independent of ISHC control tests.

Three paving projects were selected in cooperation with the ISHC. Each project was 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. Hence for this investigation 150 individual tests were performed for each test method on all projects for a total of 450 observations over the three projects. 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 paving 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 set-up. It is considered that this provided a random procedure that eliminated bias in the sampling procedure. The time for each set-up varied considerably because of variations in the distance from sampling point, and ease of movement of equipment. A typical set-up from start to finish required approximately one hour.

The data were collected during the summer construction season of 1964. The raw 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 analyzed using standard statistical techniques and procedures. The IBM 7094 computer was utilized in the data analysis.

FIELD PROCEDURES AND TESTING

After the four tests had been selected (air content by both pressure meter and Chace meters, slump and unit weight) equipment and personnel were organized. It was quite obvious at the outset that the whole operation had to be a highly mobile one. 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. It was felt the best way to handle the problem was through the use of a pick-up truck. Upon request, the Indiana State Highway Commission provided a maintenance pick-up for use during July and August of 1964. The truck was outfitted with a few attachments to facilitate the testing program. A plywood box was bolted to the body of the truck and used for storage of various small items such as tamping rods, trowels, etc. It was also noted that the testing program would be such that it would be necessary to have a supply of water on hand at all times. A 55 gallon drum with a hose and spigot attached was strapped to the left side of the truck body. This drum proved to be quite handy and made the operation extremely self sufficient.

With the equipment and vehicle in order, job sites were selected. Each site selected was selected on the basis of geographic location in the state and on the basis of their paving schedules. (Since the testing program was limited to the summer months of 1964 only sites with paving in progress were considered). As soon as a site was selected, a team of operators went to the site to begin the testing program. The 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 whole research project.

Operator A performed the slump and unit weight tests while Operator B performed both types of air content tests.

The site was surveyed to determine where and how to begin the testing program. Also, pertinent information was obtained as to the mix being used, sources and types of materials, any correction factors and other data needed for the testing. All this information was duly recorded.

The testing of a single sample of concrete required anywhere from 30 minutes to an hour and fifteen minutes. Four different tests were performed in triplicate on each sample so there was little time to waste before the concrete would begin to stiffen. Since the testing time varied depending on whether there were two or three men, the following discussion will use a time of one hour per sample with three men working. After some experience, this procedure became a highly efficient operation.

All the testing was performed on the right side of the forms in the direction of pouring (see Figure 1). The dual-drum pavers and auxiliary equipment were located on the median side and a set-up there would mean disturbing the concreting operations. The one guiding principal was to stay completely out of the way of the paving operations. Working on the right shoulder created one problem in that this was where the contractor normally laid out his steel. In some cases this meant a longer wheelbarrow run or, where the subbase was especially wide, working to the right of the steel. Figure 2 shows the set-up as it was located between the sheets of steel mesh on the shoulder. It was more convenient to conduct the test at or near these openings which occurred at each contraction joint.

FIG. 1 PICTURE OF PAVING OPERATIONS

Figure 1 is a view looking down the right shoulder with the paving train heading toward the camera. In the middle left side of this picture is the testing team. This figure illustrates how far away from the paving operation the team was and the small disturbance it caused the paving.

The set-up for the testing was placed as close to the forms as was possible without interference. The set-up took about 5 minutes and required 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.

After setting up there normally was a short wait of approximately 5 minutes to allow the paving train to catch up to the team. The batch

selection was arbitrarily chosen by the testing team and upon request the mixer operator would place the batch on the subbase near the testing set-up.

Concrete was sampled from the batch which had been deposited on the grade. The sample of fresh concrete was placed in a wheelbarrow and a large pan. Due to the type and number of tests to be performed, approximately three cubic feet 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 quite arbitrary and depended upon how far the paving train progressed between set-ups and how long it took the team to perform the tests. The sampling operation required approximately 5 minutes at the most.

With the concrete sample having been obtained, the tests themselves were performed. Both Operators A and B started simultaneously performing their respective tests. The equipment was positioned so the testing could begin immediately to provide the maximum amount of time before the concrete began to stiffen. Operator B immediately started performing the air content test by the pressure method while Operator A started on the slump tests. These tests were performed in accordance with ASTM standards and later will be described in greater detail. With both operators working together, the three slump tests could be performed while one pressure air content and half of another could be done. Each slump test required approximately 5 minutes while an air pressure test required 10 minutes to be performed. (These times include cleaning of equipment). Figure 3 shows the testing already in progress.

As soon as Operator A was finished with the slump tests, he immediately started in on the unit weight tests. Each unit weight test required approximately 8 minutes to be performed.

After Operator B completed the three air content by pressure meter tests, the three air content by Chace meter tests were begun.

The Chace air test can be performed quickly, the three tests taking no more than 10 minutes. The testing program worked out quite well. Both operators usually managed to complete their respective tests at or about the same time.

While the tests were being performed there was a constant problem of cleaning the equipment for the next battery of tests. Each operator had a 5 gallon bucket of water with which to rinse off the test apparatus. Also, there was excess concrete to get rid of. This was the job of the third man. The tested concrete was thoroughly dispersed over the shoulder and slope with all big clods of concrete being broken up. Concrete was tested only once, the portion of concrete used in the air test was not re-used for the slump or other tests.

After the tests were completed, the testing set-up had to be torn down, placed on the truck and driven up the grade to the next testing site. The truck was kept as close as possible to the set-up so as to facilitate loading and unloading of equipment. The wheelbarrow and pan were cleaned thoroughly after each sample to avoid intermingling of samples. Most of the equipment was reloaded on the truck except the wheelbarrow, shovels and pan. This latter equipment was wheeled up to the next test area. At the next test area the truck was unloaded and equipment was set-up thus starting the cycle all over again. The tear-down and transportation phases required about 5 minutes.

Table of Relative Times for Each Phase

Set-up	5 min.	
Wait	5 min.	
Sampling	5 min.	
3 Pressure tests	30 min.	3 slump = 15 min.
3 Chace tests	10 min.	3 unit wt. tests 25 min.
Tear down	<u>5 min.</u>	
	60 min.	

Test Descriptions

The concrete tests were all performed in accordance with test methods of the American Society for Testing and Materials (ASTM).

The pressure air meter used was a Techkote White Air Meter chosen because of its compactness and ease of use. This meter is not in complete accordance with ASTM as the lid is not curved as specified in ASTM C 231-62. The test was performed by placing the concrete in the material container in three layers. Each layer was rodded 25 times and the excess concrete was struck off. The strike-off was accomplished in 2 or 3 passes and no effort was made to obtain a mortar-smooth finish as it is not necessary for the test. After the container lip was cleaned, the lid was secured in place and water added until bubbles ceased rising out of the center petcock. Pressure was built up in the pressure chamber by means of the hand pump and the dial needle was set on the initial mark. Air pressure was then released onto the concrete and the gross air content directly read off the dial. This gross air content was adjusted by an aggregate correction factor determined in advance for each project. ,
Two meters were taken along on the all field work with one being a backup for the other. The meters were carefully calibrated before each project and carefully cleaned at the end of each day's testing.

The Chace Meter was a Concrete Air Indicator Model CT-158 as produced by Soiltest Incorporated. These meters are quite fragile and so three of them were made available for the program. The cup was filled with mortar paste exclusive of any particles greater than those passing a No. 10 sieve. The excess mortar was struck off with a trowel. Holding a finger over the stem opening, a solution of water and 20 percent isopropyl alcohol was poured in the large end of the meter. The rubber stopper with the filled mortar cup was inserted in the large stem end. The meter was inverted and isopropyl alcohol added to adjust the liquid level to the top line of the small stem. Placing a finger over the small stem, the meter was rolled and rocked until all the mortar had dispersed into the liquid. After the mortar was dispersed, the finger was carefully removed from the small stem and the number of graduations that the liquid had fallen were counted. For this type of meter each graduation represents 1 percent of air for some specific mortar content of the concrete. For concretes having different mortar contents, this figure was to be corrected. The manufacturer supplied the necessary correction factors with the meters.

The slump test was performed in accordance with ASTM C 143-58. The slump cone was filled in three layers of equal volumes with each layer being rodded 25 times. The top was struck off and, after cleaning the area immediately around the cone, the cone was pulled in a smooth, steady motion. The test was performed on an eye-level piece of plywood, and the slump was measured with a carpenter's rule using the cone itself and a straight rod. The slump was measured to the average height of the slumped concrete.

The unit weight test was performed in accordance to ASTM C 138-63. A one-half cubic foot bucket was used which was calibrated before the testing began. The concrete was placed in the bucket in three layers

with each layer being rodded 25 times. The top was carefully struck off with a strike-off bar and the bucket plus concrete were weighed on a platform scale. The scale was on a piece of plywood which was layed down and leveled by eye. The empty bucket was weighed at the start of each day's testing so as to have an accurate tare weight.

The results of the tests were recorded on data forms along with other pertinent information such as time of test, station and weather conditions (see Figures 4 and 5).

QUALITY CONTROL RESEARCH

Contract No.: _____

Sheet No.: _____

Project No.: _____

Date: _____

Operator: _____

SOURCE OF MATERIALS AND LOCATION OF SOURCE

	Remarks on Materials	Batch Weights
Cement (Type ____)	(C)	
Water		
Fine Aggregate		
Coarse Aggregate U.		
Coarse Aggregate L.		
Total Weight of Batch (B)		

AIR CONTENT

PressureTest
1Test
2Test
3

Station Number			
Time of Test			
Air Meter Used			
Mixing Time			
Temperature of Concrete			
Air Entraining Agent			
Percent of Air Gross			
Aggregate Correction Factor			
Percent of Air Net			

Chase Meter

1

2

3

Percent of Air Gross			
Aggregate Correction Factor			
Percent of Air Net			

FIG. 4 DATA SHEET FOR AIR CONTENT

QUALITY CONTROL RESEARCH

Sheet No.: _____

Contract No.: _____

Date: _____

Project No.: _____

Operator: _____

GENERAL WEATHER INFORMATION

Atmosphere Temperature _____

Weather: _____

YIELD TEST

	1	2	3
Station Number			
Time of Test			
Weight in Pounds of 1/2 cu. ft. measure full of concrete			
Total Gross Wt.			
Ave. Gross Wt.			
Wt. of Container			
Net Wt. - 1/2 cu. ft.			
Weight per cu. ft. (A)			
Barrels of Cement per cu. yd.			

SLUMP TEST

	1	2	3
Station Number			
Inches			

YIELD TEST FORMULA

$\frac{C}{376}$ = Barrels of cement per batch.	$\frac{C}{376} \times \frac{27A}{B}$ = Bbls. of cement per cu. yd.
$\frac{B}{27A}$ = Cubic yards of concrete per batch	= .0718C $\times \frac{A}{B}$
Then	

FIG. 5 DATA SHEET FOR SLUMP AND UNIT WEIGHT

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 utilized to determine confidence limits, control limits and in significance testing. A majority of the analyses and plotting of data was accomplished using the IBM 7094-1410 computer system.

The data collected from each of the four tests (air content by pressure meter, air content by Chace meter, slump and unit weight) were analyzed separately and the sum of squares, mean squares and standard deviations computed for each test method. The first analysis was based upon 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 above mentioned 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," that is, 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 site separately in addition to the factorial analysis.

In certain of the analyses it was noted that 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 an in control process. In fact the factorial analysis is invalid if the variances are not homogeneous (i.e., variances are not statistically equal).

The factorial analyses have been included in this report for the purpose of illustrating this type of statistical procedure. If other variables such as operator or equipment were included in an investigation the factorial design model could be used in the analysis of the data.

It should be noted that operators and testing equipment were not considered as variables in this investigation. Only one operator and one piece of testing equipment was used throughout the investigation for each test method. This necessarily limits the interpretation of the data. 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.

As a sample was tested in the field for air content by the pressure meter, a time dependency was observed. This led to testing the differences between replicates and calculation of the correlation coefficient associated with the third pressure replicate versus the sample mean of the Chace tests. Results of this phase of the investigation will be discussed in a later section.

The test results were also used to illustrate techniques and procedures that may be employed in a quality control program. Control

limits are illustrated along with the use of tolerance limits, 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. A tabulation of the raw data collected in the field is presented in Appendix A. Appendix B contains data plots of sample means while Appendix C contains the basic statistical computations.

Field Observations

Dual-drum pavers were used on Sites 1 and 3 while 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 with all other operations being essentially the same.

Each method of paving had its own characteristics of control with respect to frequency of adjustment. Quite often with the dual-drum pavers the water valve was adjusted and readjusted to allow more or less water into each batch. This yielded many batches that were alternately wet or dry. This variability in water content per batch was due also to the use of dry and wet batches of aggregate.

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 cubic yards 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.

On the sites studied there seemed to be a lack of dependable automatic air entraining agent dispensers. The one used on the central mix plant was timed to squirt agent into the mixing water as the water was fed into the drum. As a consequence, the time setting on the agent dispenser could not be set for longer than the time setting on the water dispenser. This limited the amount of agent that could be introduced into the mix and did prove to be a problem for the contractor until the agent was added manually. A new, different automatic dispenser was ordered to replace the old one but the team was not on the site long enough to check its effectiveness.

On the dual-drum pavers there was no way of determining readily when the supply of air entraining agent was exhausted. There was always a possibility of the mixer running out of agent with the concrete operations continuing since it was not obvious whether there was any agent left or not. (As a possible remedy, some sort of meter should be fixed to check the level of agent in the tank). Since at all sites air entrained cement was being used, there was little danger of having zero air content.

It was noticed that the less the paving operation is changed, the more constant the concrete product is. This was quite 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 has the best grouping of data and distribution of results.

Air Content by Pressure Meter

The analysis of variance, hereafter referred to as the ANOV, for the air content measured by pressure meter is presented in Table 26 (see Appendix C). The sources of variation as determined by the factorial model are: site-to-site variation, sample-within-site variation and the error term. Table 1 presents a summary of the statistical analysis results based upon a factorial design model.

A standard test for significance, the F-test, indicates that at the 0.05 α -level (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 α -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 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 26 (see Appendix C) is $(\sigma_e^2 + 3\sigma_{\text{sample}}^2 + 150 \sigma_{\text{site}}^2)$ for the site to site component; $(\sigma_e^2 + 3\sigma_{\text{sample}}^2)$ for the sample-within-site component and σ_e^2 for the error term.

The error term (σ_e^2) is observed to be small in comparison to the sample-within-site term ($\sigma_e^2 + 3\sigma_s^2$) leading to the conclusion that sample-within-site variation is significant or that sample means are different. σ_s^2 term is large compared to the σ_{site}^2 term and when a significance test is performed: $(\sigma_e^2 + 3\sigma_s^2 + 150 \sigma_{site}^2) / (\sigma_e^2 + 3\sigma_s^2)$ the site-to-site component is determined not significant. If the distribution of sample means was smaller (i.e. σ_s^2 smaller) and σ_s^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 over-shadows the spread among site means.

The distribution of air content for all sites measured by the pressure meter is shown in Figure 6. Values tabulated are sample means. The overall mean air content is 4.40 percent. The distribution over all sites approximates a normal distribution. Figures 7, 8 and 9 show the distributions for each individual site. Sites 1 and 3 show some tendency towards normality but for Site 2 the distribution is 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.

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

TABLE 1

SUMMARY OF RESULTS FROM STATISTICAL ANALYSES - FACTORIAL MODEL

AIR CONTENT BY PRESSURE METER-PERCENT

LOCATION	VALUES OF AIR CONTENT		
	Mean	Minimum	Sample Mean Maximum
Site 1	4.48	3.03	5.70
Site 2	4.21	2.63	5.93
Site 3	4.51	3.26	5.36
All Sites	4.40	2.63	5.93

Standard Deviation (All Sites)

1) Site	0.10
2) Sample Mean*	0.16
3) Sample Within Site	0.69

Error Term (All Sites) 0.079

95% Confidence Limits

1) Site	+ 0.20 - 0.20
2) Sample Means	+ 0.32 - 0.32

* Consists of variation due to variance among determinations but not among samples.

Plots of the sample means for each site are presented in Figures 37, 38 and 39 (see Appendix B).

As mentioned previously, it was observed that assignable causes in several instances added to the measured variation and hence a one-way ANOV was performed on each test method for each site separately. A summary of the results are presented in Table 2.

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

Note the differences in the Mean Square terms (MS) and the standard deviations from site to site.

TABLE 2
ONE-WAY ANOV
AIR CONTENT BY PRESSURE METER

SITE 1

	ss	df	MS	F	EMS
Between samples	55.5895	49	1.1345	8.1774	$\sigma_{\epsilon}^2 + 3\sigma_s^2$
Within samples	13.8733	100	0.1387		σ_{ϵ}^2

$$\sigma_{s_1} = \sqrt{\frac{1.1345 - 0.1387}{3}} = 0.5761$$

SITE 2

	ss	df	MS	F	EMS
Between samples	125.8621	49	2.5686	46.0325	$\sigma_{\epsilon}^2 + 3\sigma_s^2$
Within samples	5.5800	100	0.0558		σ_{ϵ}^2

$$\sigma_{s_2} = \sqrt{\frac{2.5686 - 0.0558}{3}} = 0.9152$$

SITE 3

	ss	df	MS	F	EMS
Between samples	39.7686	49	0.8116	19.3546	$\sigma_{\epsilon}^2 + 3\sigma_s^2$
Within samples	4.1933	100	0.0419		σ_{ϵ}^2

$$\sigma_{s_3} = \sqrt{\frac{0.8116 - 0.0419}{3}} = 0.5065$$

FIG. 6 HISTOGRAM FOR THE DISTRIBUTION OF AIR CONTENT MEASURED BY PRESSURE METER, ALL SITES.

FIG. 7 HISTOGRAM FOR THE DISTRIBUTION OF AIR CONTENT MEASURED
 BY THE PRESSURE METER, SITE I

AIR CONTENT BY PRESSURE JON 2

MIN = 2.633329

MAX =

5.933330

 2.6 3.0 3.4 3.8 4.2 4.6 5.0 5.4 5.8 6.2 6.6 7.0 7.4 7.8 8.2 8.6 9.0
 3.2 3.6 4.0 4.4 4.8 5.2 5.6 6.0 6.4 6.8 7.2 7.6 8.0 8.4 8.8 9.2 9.6
 TOP LEFT HA40 SCALE IS 50.0

 FIG. 8 HISTOGRAM FOR THE DISTRIBUTION OF AIR CONTENT MEASURED
 BY THE PRESSURE METER, SITE 2

MIN = 3.3 3.7 4.1 4.5 4.9 5.3 5.7 6.1 6.5 6.9 7.3 7.7 8.1 8.5 8.9 9.3 9.7

5.566670

TOP LEFT HAD SCALE IS 50.0

MEAN AIR CONTENT, percent

FIG. 9 HISTOGRAM FOR THE DISTRIBUTION OF AIR CONTENT MEASURED BY THE PRESSURE METER, SITE 3

Air Content by Chace Meter

The ANOV for air content by Chace meter is presented in Table 27 (see Appendix C). The statistical sources of variation are the same as those associated with the pressure meter. A summary of results from the statistical analyses is presented in Table 3. It should be noted that 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 percent for purposes of handling the computation and for comparison to 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. It may be noted that the standard deviation for the Chace meter sample means is twice that of the pressure meter. Again it is pointed out that air contents by Chace meter are determined to the nearest one-half percent in the field and that 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 presented in Figure 10. 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

TABLE 3

SUMMARY OF RESULTS FROM STATISTICAL ANALYSES - FACTORIAL MODEL

AIR CONTENT BY CHACE METER

LOCATION	VALUES OF AIR CONTENT		
	Mean	Minimum	Sample Mean Maximum
Site 1	4.32	2.47	7.30
Site 2	3.92	2.53	5.63
Site 3	5.05	3.96	5.96
All Sites	4.43	2.47	7.30

Standard Deviation (All Sites)

1) Site	0.11
2) Sample Mean*	0.32
3) Sample Within Site	0.69
Error Term (All Sites)	0.30

95% Confidence Limits

1) Site	± 0.21
2) Sample Means	± 0.62

* Consists of variation due to variance among determinations but not among samples.

for each site or if one were to locate the means of each site on Figure 10, they would fall at each peak. This does not happen in the case of pressure meter results as Figure 6 clearly shows. The pressure meter distribution is nearer to a normal distribution. The distribution for Chace is more disperse, thus showing its higher variability as indicated by the higher standard deviation calculated for sample means.

From Table 3 the site to site standard deviation is 0.3%. Confidence limits placed on the site mean indicate that there is a confidence of 95% that the true mean lies between $\bar{X}_{\text{site}} + 0.2\%$ and $\bar{X}_{\text{site}} - 0.2\%$. Also, the 95% confidence limits on a sample mean is $\bar{X}_{\text{sample}} \pm 0.6\%$. This last figure is interesting when it is compared to the pressure meter results. In the analysis of the pressure meter data 95% confidence limits were determined to be $\bar{X}_{\text{sample}} \pm 0.3\%$ (Table 1). This, once again indicates the pressure air content test to be statistically more reliable than the Chace test.

Data plots for the Chace meter for each site are presented in Figure 40, 41 and 42 (see Appendix B). If one were to compare 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. The pressure air content data plot Figure 38 also substantiates this. Site 2 was a central mix project and this operation had difficulties with its air dispenser which resulted in the distribution shown in Figure 8. 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, and the results are summarized in Table 4. Again observable differences

TABLE 4
ONE-WAY ANOV
AIR CONTENT BY CHACE METER

SITE 1

	ss	df	MS	F	EMS
Between samples	127.8546	49	2.6093	5.4648	$\sigma_{\epsilon}^2 + 3\sigma_s^2$
Within samples	47.7467	100	0.4775		σ_{ϵ}^2

$$\sigma_{s_1} = \sqrt{\frac{2.6093 - 0.4775}{3}} = 0.6430$$

SITE 2

	ss	df	MS	F	EMS
Between samples	99.0519	49	2.0215	8.9801	$\sigma_{\epsilon}^2 + 3\sigma_s^2$
Within samples	23.5600	100	0.2356		σ_{ϵ}^2

$$\sigma_{s_2} = \sqrt{\frac{2.0215 - 0.2356}{3}} = 0.7716$$

SITE 3

	ss	df	MS	F	EMS
Between samples	29.6149	49	0.6044	3.0805	$\sigma_{\epsilon}^2 + 3\sigma_s^2$
Within samples	19.6200	100	0.1962		σ_{ϵ}^2

$$\sigma_{s_3} = \sqrt{\frac{0.6044 - 0.1962}{3}} = 0.3689$$

AIR CONTENT BY CHACE METER ENTIRE PROJECT

MIN = 2.496659

MAX =

7.300000

2.5 2.9 3.3 3.7 4.1 4.5 4.9 5.3 5.7 6.1 6.5 6.9 7.3 7.7 8.1 8.5 8.9
2.7 3.1 3.5 3.9 4.3 4.7 5.1 5.5 5.9 6.3 6.7 7.1 7.5 7.9 8.3 8.7

TOP LEFT HAND SCALE IS 50.0

FIG. 10 HISTOGRAM FOR THE DISTRIBUTION OF AIR CONTENT MEASURED
BY CHACE METER, ALL SITES

occur in the MS and standard deviation terms from site to site. As in the pressure method analysis, the within Sample Means 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 presented in Table 28 (see Appendix C). 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 5 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 α -level the site-to-site variation is not significant but the sample-within-site variation is. This is what would be expected in light of the 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. In the light of this, one would expect Site 2, the central mix project, to show the least variation in slump. A look at Figures 43, 44 and 45 (Appendix B) bears out this presumption. 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 presented in Figure 11. The values therein plotted 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, three inches. Figures 12, 13 and 14 show the distribution of slump for each individual site. There is a slight tendency for each site to approximate a normal

TABLE 5

SUMMARY OF RESULTS FROM STATISTICAL ANALYSIS - FACTORIAL MODEL

SLUMP

LOCATION	VALUES OF AIR CONTENT		
	Sample Mean		
	Mean	Minimum	Maximum
Site 1	3.00	0.58	7.25
Site 2	3.09	1.33	5.67
Site 3	3.03	0.75	7.25
All Sites	3.04	0.58	7.25

Standard Deviation (All Sites)

1) Site 0.14

2) Sample Mean* 0.21

3) Sample Within Site 0.98

Error Term (All Sites) 0.14

95% Confidence Limits (All Sites)

1) Site $\pm$ 0.28

2) Sample Means $\pm$ 0.42

* Consists of variation due to variance among determinations but not among samples.

TABLE 6
ONE-WAY ANOV
SLUMP

SITE 1

	ss	df	MS	F	EMS
Between samples	196.9337	49	4.0191	17.7638	$\sigma_{\epsilon}^2 + 3\sigma_s^2$
Within samples	22.6250	100	0.2262		σ_{ϵ}^2

$$\sigma_{s_1} = \sqrt{\frac{4.0191 - 0.2262}{3}} = 1.1243$$

SITE 2

	ss	df	MS	F	EMS
Between samples	89.2187	49	1.8208	16.0658	$\sigma_{\epsilon}^2 + 3\sigma_s^2$
Within samples	11.3333	100	0.1133		σ_{ϵ}^2

$$\sigma_{s_2} = \sqrt{\frac{1.8208 - 0.1133}{3}} = 0.7545$$

SITE 3

	ss	df	MS	F	EMS
Between samples	154.0871	49	3.1446	44.6575	$\sigma_{\epsilon}^2 + 3\sigma_s^2$
Within samples	7.0417	100	0.0704		σ_{ϵ}^2

$$\sigma_{s_3} = \sqrt{\frac{3.1446 - 0.0704}{3}} = 1.0123$$

FIG. II HISTOGRAM FOR THE DISTRIBUTION OF SLUMP, ALL SITES.

FIG. 12 HISTOGRAM FOR THE DISTRIBUTION OF SLUMP, SITE 1

FIG. 13 HISTOGRAM FOR THE DISTRIBUTION OF SLUMP, SITE 2

FIG. 14 HISTOGRAM FOR THE DISTRIBUTION OF SLUMP, SITE 3

distribution which becomes more pronounced when all three sites are lumped in Figure 11. The histogram for Site 2 is tighter than those for Sites 1 and 3 which substantiates what was said above concerning the central mix plant.

The 95% confidence limits on the site mean are $\pm 0.3\%$ while 95% confidence limits on the sample mean are $\pm 0.4\%$. Also, in Table 3 the minimum and maximum values are presented thus showing the extreme limits encountered. Site 2 had the smallest range in slump values, i.e., it exhibited both the highest minimum and lowest maximum slump.

Plots of sample means for slump are presented in Figures 43, 44 and 45 (see Appendix B).

As in the previous analyses, a one-way ANOV was performed on the slump data for each site and a summary of these results are presented in Table 6. Note that 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 presented in Figure 15. 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.

A summary of the results from the statistical analysis is presented in Table 7. From Table 29 (see Appendix C), 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 7) is 1.15 lbs. indicating that a unit weight determination can have an error of 1.15 lbs. due to chance alone. The 95% confidence limits on the sample mean are ± 1.2 lbs. (i.e. 95% confident that the true mean lies between $\bar{X}_{\text{sample}} \pm 1.2$ lbs.). 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.

The data plots for the unit weight are presented in Figures 46, 47 and 48 (see Appendix B).

As in the analysis of the other three test methods, a one-way ANOV was performed on the unit weight data and a summary of the results are tabulated in Table 8. Site 2 exhibits a greater variability than do Sites 1 and 2. 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.

TABLE 7
SUMMARY OF RESULTS FROM STATISTICAL ANALYSIS - FACTORIAL MODEL
UNIT WEIGHT

LOCATION	VALUES OF AIR CONTENT		
	Mean	Minimum	Maximum
Site 1	148.21	145.35	150.17
Site 2	150.35	148.11	152.86
Site 3	147.16	144.71	148.81
All Sites	148.57	144.71	152.86

Standard Deviation (All Sites)

1) Site	0.15
2) Sample Mean*	0.62
3) Sample Within Site	0.89
Error Term (All Sites)	1.15

95% Confidence Limits (All Sites)

1) Site	± 0.30
2) Sample Means	± 1.21

* Consists of variation due to variance among determinations but not among samples.

TABLE 8
ONE-WAY ANOV

SITE 1

	ss	df	MS	F	EMS
Between samples	171.2493	49	3.4949	2.1266	$\sigma_{\epsilon}^2 + 3\sigma_s^2$
Within samples	164.3397	100	1.6434		σ_{ϵ}^2

$$\sigma_{s_1} = \sqrt{\frac{3.4949 - 1.6434}{3}} = 0.7856$$

SITE 2

	ss	df	MS	F	EMS
Between samples	228.5569	49	4.6644	3.4560	$\sigma_{\epsilon}^2 + 3\sigma_s^2$
Within samples	136.9645	100	1.3496		σ_{ϵ}^2

$$\sigma_{s_2} = \sqrt{\frac{4.6644 - 1.3496}{3}} = 1.1993$$

SITE 3

	ss	df	MS	F	EMS
Between samples	118.8767	49	2.4261	5.4680	$\sigma_{\epsilon}^2 + 3\sigma_s^2$
Within samples	44.3683	100	0.4437		σ_{ϵ}^2

$$\sigma_{s_3} = \sqrt{\frac{2.4261 - 0.4437}{3}} = 0.8129$$

FIG. 15 HISTOGRAM FOR THE DISTRIBUTION OF UNIT WEIGHT, ALL SITES.

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 9 presents a summary of this work. 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 this 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. It should also be noted that the horizontal and vertical scales of the scatter diagrams are different. This difference in scales should be considered when observing the scatter diagram.

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 coefficients 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. Figures 16 to 21 are scatter diagrams overall sites for the correlation portion of the investigation. Also, included are scatter diagram for pressure

TABLE 9
TABULATION OF CORRELATION COEFFICIENTS
AND SIGNIFICANCE TESTS

All Sites

<u>Variables</u>	<u>r</u>	<u>t₁₄₈</u>	<u>t_{α=0.001}</u>	<u>Significance</u>
Pressure v. Chace	0.6060	9.2675	3.29	Highly Significant
Pressure v. Slump	0.3368	4.3516	3.29	Significant
Pressure v. Unit Wt.	-0.5491	8.6351	3.29	Highly Significant
Chace v. Slump	0.1296	1.5900	3.29	Not Significant
Chace v. Unit Wt.	-0.6445	10.2540	3.29	Highly Significant
Slump v. Unit Wt.	-0.1856	2.2977	3.29	Not Significant

Pressure v. Chace by Sites

<u>Site</u>	<u>r</u>	<u>t₁₄₈</u>	<u>t_{α=0.001}</u>	<u>Significance</u>
1	0.5130	4.1405	3.51	Significant
2	0.7288	7.3744	3.51	Highly Significant
3	0.7247	7.2861	3.51	Highly Significant

Interpretation of Correlation Coefficients¹

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

¹Hughes, C. S., Enrick, N. L. and Dillard, J. H., "Applications of Some Statistical Techniques to Experiment in Highway Engineering", Virginia Council of Highway Investigations and Research in Cooperation with the U.S. Bureau of Public Roads, February 1964.

vs. Chace for each site. Table 10 shows the confidence limits placed on the correlation coefficients.

TABLE 10
CONFIDENCE LIMITS ON CORRELATION COEFFICIENTS, ALL SITES

	<u>r</u>	<u>Limits</u>
Pressure vs. Chace	0.6060	0.49 to 0.70
Pressure vs. Slump	0.3368	0.22 to 0.51
Pressure vs. Unit Weight	-0.5491	-0.65 to -0.42
Chace vs. Slump	0.1296	-0.04 to 0.29
Chace vs. Unit Weight	-0.6445	-0.74 to -0.52
Slump vs. Unit Weight	-0.1656	-0.33 to -0.015

FIG. 16 SCATTER DIAGRAM FOR AIR CONTENT BY PRESSURE METER VERSUS AIR CONTENT BY CHACE METER, ALL SITES.

FIG. 17 SCATTER DIAGRAM FOR AIR CONTENT BY PRESSURE METER VERSUS SLUMP, ALL SITES

FIG.18 SCATTER DIAGRAM FOR AIR CONTENT BY PRESSURE METER VERSUS UNIT WEIGHT, ALL SITES

FIG 21 SCATTER DIAGRAM FOR SLUMP VERSUS UNIT WEIGHT, ALL SITES

FIG. 22 SCATTER DIAGRAM FOR AIR CONTENT BY PRESSURE METER VERSUS AIR CONTENT BY CHACE METER, SITE 1

FIG. 23 SCATTER DIAGRAM FOR AIR CONTENT BY PRESSURE METER VERSUS AIR CONTENT BY CHACE METER, SITE 2

AIR CONTENT BY CHACE METER, percent

FIG. 24 SCATTER DIAGRAM FOR AIR CONTENT BY PRESSURE METER VERSUS AIR CONTENT BY CHACE METER, SITE 3

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 11 presents a summary of this analysis. The differences between replicate 1 and replicate 2 is significant at the 0.05 α -level for all three sites. This is also true for the difference between replicate 1 and replicate 3. Replicate 2 and replicate 3 difference 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.

As a consequence of this finding, correlation analyses of the third pressure reading versus the mean of the Chace meter was 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. The correlation coefficients for each site and over all three sites are shown in Table 12. A comparison of these coefficients with those of the mean pressure versus the mean Chace show that a general trend to a lower coefficient for the case of third pressure versus 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.

TABLE 11
SUMMARY OF ANALYSIS OF DIFFERENCES
BETWEEN REPLICATE OBSERVATIONS

SITE	OBSERVATION DIFFERENCE= $\bar{d}$	$\bar{d}$	S	$t = \frac{\bar{d}}{S}$	t_{α}	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	$X_1 - X_2$	0.203	0.03436	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

TABLE 12
TABULATION OF CORRELATION COEFFICIENTS, r
THIRD PRESSURE VERSUS $\bar{X}$ CHACE

<u>Site</u>	<u>r</u>
1	0.3776
2	0.7125
3	0.7015
All Sites	0.5677

QUALITY CONTROL APPLICATIONS

It is important to understand that a quality control system depends upon 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 this data in some manner. There are two approaches to this problem. One approach is to rely on past data, data collected by examining records of construction, etc. The other approach sets out to obtain the data required via a preliminary testing program.

There are several problems associated with using past data. One of the most obvious is 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 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, or past 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.

It should be noted at this point that 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 preceding section entitled Analysis of Data, the measures of central tendency and components of variability have been presented. The problem is to now apply these results to establish a realistic quality control program that may be implemented and used in the field.

The data plots in Appendix B show the fluctuation of the sample means. The variability of the product, 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.

For purposes of illustration, 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 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 effects 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 $\bar{X}$ -charts, R-chart and the σ -chart. All three have one thing in common which is the 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 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 falling outside the limits so set 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, it may be noted that 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 upon specification limits and the known standard deviation).

To illustrate one use of control limits, moving means have been computed for the data and the plots are shown in the following pages. The moving means are averages of three sample means. The means of Samples 1, 2 and 3 are averaged and this is the first "moving mean." Then sample means 2, 3 and 4 are averaged and this is the second moving mean. This is continued for sample means 3, 4 and 5, etc., and a plot of the "moving mean" is obtained.

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- σ 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% of the data could fall outside the control limits due to chance variation alone. If the limits were based on a 0.05 α -level, then 95% of the data would fall within the limits in the long run and 5% 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 process has gone "out of control."

Assuming a $\sigma_{\bar{X}}$ of 0.60 for air content by pressure method, 3- σ control limits are: $\bar{\bar{X}} \pm 1.732 (0.52)$ or $\bar{\bar{X}} \pm 0.90$. Applying these limits to the data plots of Appendix B (Figures 37, 38 and 39) it may be noted that for Site 1 about 15% of the sample means are outside control limits hence one would conclude that some adjustments should be made. On Site 2 approximately 40% of data are outside the limits. The job is in poor

control, action should be taken. By contrast Site 3 exhibits the best control, only 4% of the data falling outside the limits. If the moving average concept is used (see Figures 25, 26 and 27) 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.

The control limits determined from the assumed values of the components of variation are shown on the overlay sheets for the data plots. The 3- σ limits are in blue while the 95% limits are not shown. These limits are to be considered illustrative only since the variables of operator and equipment have not been evaluated.

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 towards 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 4-7% and the variance is known, then a range of means may be used. If the variation on a site is known and 3- σ limits determined to be $5.5\% \pm 0.90\%$, then the average air content can be $5.5\% \pm 0.60\%$ for

a process in control and the material will meet the specified 4-7% 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%, the standard deviation may then be less than or equal to 0.5% for 3- σ limits and the product will pass the 4-7% 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.

FIG. 25 DATA PLOT OF MOVING MEANS FOR AIR CONTENT MEASURED BY PRESSURE METER, SITE I

JOB NO. 1

FIG. 26 DATA PLOT OF MOVING MEANS FOR AIR CONTENT MEASURED BY PRESSURE METER, SITE 2

JOB NO. 2

FIG. 27 DATA PLOT OF MOVING MEANS FOR AIR CONTENT MEASURED BY PRESSURE METER, SITE 3

JOB NO. 3

AIR CONTENT BY CHACE METER, percent

SAMPLE NUMBEP

JOB NO. 1

FIG. 28 DATA PLOT OF MOVING MEANS FOR AIR CONTENT MEASURED BY CHACE METER, SITE I

FIG. 29 DATA PLOT OF MOVING MEANS FOR AIR CONTENT MEASURED BY CHACE METER, SITE 2

JCR NO. 2 FIG. 30 DATA PLOT OF MOVING MEANS FOR AIR CONTENT MEASURED BY CHACE METER, SITE 3

FIG. 32 DATA PLOT OF MOVING MEANS FOR SLUMP, SITE 2

JOB NO. 2

SAMPLE NUMBER

FIG. 33 DATA PLOT OF MOVING MEANS FOR SLUMP
SITE 3

JOB NO. 2

UNIT WEIGHT, lbs. per cu. ft.

SAMPLE NUMBER

NUMBER OF SAMPLE MEANS.

JOB NO. 1

FIG. 34 DATA PLOT OF MOVING MEANS FOR UNIT WEIGHT, SITE 1

FIG. 35 DATA PLOT OF MOVING MEANS FOR UNIT WEIGHT, SITE 2

JOB NO. 3 FIG. 36 DATA PLOT OF MOVING MEANS FOR UNIT WEIGHT, SITE 3

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APPENDIX A

Tabulation of Data

Table 13
Air Content by Pressure Method, in Percent

Sample	Site 1 Observation		
	1	2	3
1	5.0	4.9	4.7
2	5.0	5.0	4.4
3	3.5	3.3	3.0
4	3.4	3.4	3.3
5	3.9	3.6	3.4
6	4.9	4.4	4.7
7	5.0	4.4	4.6
8	5.3	4.6	4.3
9	4.0	4.0	4.1
10	5.0	4.0	3.8
11	5.0	4.8	4.5
12	4.7	4.6	4.0
13	4.4	4.1	4.0
14	5.4	4.9	4.6
15	6.3	5.4	5.4
16	5.0	4.8	1.7
17	5.5	5.5	4.8
18	4.2	3.4	4.0
19	4.9	4.4	4.2
20	4.3	4.1	4.0
21	5.6	5.6	5.4
22	4.7	4.5	4.4
23	4.5	4.3	4.2
24	4.4	4.2	4.2
25	3.7	3.7	3.5
26	4.5	4.0	4.3
27	3.7	3.6	3.9
28	5.2	5.2	4.9
29	4.9	5.0	4.7
30	5.5	5.1	5.1
31	3.5	3.3	3.3
32	4.0	4.0	4.2
33	4.9	4.6	4.8
34	4.8	4.5	4.4
35	5.0	5.0	4.8
36	3.9	4.2	4.4
37	4.8	4.7	4.5
38	4.6	4.4	4.3
39	5.1	4.8	4.6
40	6.1	5.5	5.4
41	4.3	3.7	4.1
42	5.0	5.0	4.8
43	4.7	4.4	4.3
44	5.4	5.0	4.9
45	2.9	3.0	3.2
46	4.5	4.1	3.8
47	5.5	5.3	5.1
48	5.0	5.0	4.9
49	4.5	4.1	4.1
50	5.0	4.5	4.8

Table 14
Air Content by Pressure Method, in Percent

Sample	Site 2 Observation		
	1	2	3
1	2.8	2.6	2.6
2	4.1	3.8	3.7
3	4.4	4.4	4.0
4	4.6	4.3	4.2
5	4.5	4.6	5.0
6	3.7	3.9	2.8
7	4.1	4.1	4.1
8	3.0	3.2	3.2
9	3.2	3.6	3.4
10	4.2	3.2	3.6
11	3.9	3.0	2.8
12	2.9	2.8	2.6
13	2.2	2.9	3.1
14	3.4	3.5	3.9
15	4.5	4.1	4.0
16	2.8	2.8	3.0
17	3.1	3.2	2.9
18	3.1	3.3	3.0
19	5.0	4.9	4.6
20	3.6	3.9	3.6
21	4.1	3.8	3.8
22	4.4	4.4	4.6
23	4.8	4.9	4.6
24	5.0	4.5	4.5
25	5.0	4.7	4.4
26	4.5	4.2	4.5
27	4.6	4.3	4.4
28	4.5	4.2	4.2
29	5.4	5.6	5.4
30	4.5	4.6	4.4
31	3.0	3.2	3.3
32	3.7	3.7	3.7
33	3.5	3.0	3.3
34	4.0	3.6	4.0
35	2.9	2.9	2.8
36	3.8	3.8	3.6
37	5.4	4.8	4.9
38	6.1	5.8	5.9
39	5.6	5.5	5.5
40	5.0	4.8	4.6
41	6.1	6.0	5.7
42	5.3	5.2	5.4
43	4.8	4.6	4.2
44	5.9	5.6	5.7
45	5.3	5.2	5.3
46	5.1	5.2	5.0
47	4.4	4.3	4.1
48	4.3	4.0	4.0
49	5.9	5.6	5.1
50	5.8	5.9	5.4

Table 15
Air Content by Pressure Method, in Percent

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Sample	Site 3		
	Observation		
	1	2	3
1	4.6	4.4	4.3
2	4.5	4.1	3.8
3	3.6	4.0	3.9
4	3.8	4.1	4.0
5	4.8	4.6	4.7
6	4.9	4.6	4.3
7	4.9	4.6	4.5
8	4.8	4.5	4.6
9	4.2	3.9	4.1
10	4.1	3.8	3.6
11	4.1	3.9	3.8
12	4.5	4.2	4.4
13	4.4	4.1	4.2
14	4.7	5.1	4.7
15	4.9	4.8	4.8
16	5.5	5.1	5.2
17	4.7	4.4	4.3
18	5.3	4.8	5.0
19	4.2	4.2	4.3
20	4.2	4.1	4.4
21	4.2	3.8	4.1
22	5.2	4.8	5.1
23	5.0	5.8	4.8
24	5.3	5.3	5.0
25	5.4	5.3	5.4
26	4.3	4.1	4.0
27	3.6	3.5	3.7
28	5.3	5.3	5.2
29	5.2	4.7	4.9
30	4.8	4.9	4.8
31	5.3	5.1	4.9
32	5.4	4.8	4.9
33	4.8	4.7	4.6
34	4.5	4.1	4.1
35	3.6	3.7	3.6
36	4.4	4.2	4.1
37	4.9	4.6	4.6
38	5.1	5.1	5.0
39	4.3	4.0	3.9
40	4.5	4.2	4.2
41	4.8	4.5	4.5
42	3.1	3.4	3.5
43	3.4	3.1	3.3
44	5.4	5.1	5.0
45	5.3	5.1	4.8
46	4.9	4.4	4.4
47	4.7	4.2	4.2
48	5.0	5.0	4.6
49	5.7	4.8	4.7
50	4.6	4.4	4.3

Table 16
Air Content by Chace Air Meter, in Percent

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Sample	Site 1 Observation		
	1	2	3
1	5.1	4.2	5.6
2	5.1	7.4	6.0
3	5.6	4.2	3.3
4	3.3	5.6	3.3
5	3.7	2.8	3.3
6	4.7	4.7	3.7
7	4.2	4.7	4.7
8	5.6	3.7	4.7
9	6.5	4.7	5.6
10	5.1	6.5	4.7
11	3.7	6.5	3.7
12	4.7	3.7	4.2
13	4.7	6.5	6.0
14	3.7	3.7	4.2
15	7.4	8.4	6.1
16	4.2	4.2	3.7
17	6.5	7.4	4.7
18	5.6	4.7	6.5
19	3.7	2.8	3.3
20	2.3	2.3	2.8
21	4.7	5.6	6.5
22	2.8	4.7	4.2
23	4.7	3.7	4.2
24	3.7	3.7	3.7
25	2.8	2.8	3.7
26	3.7	5.1	3.3
27	2.8	2.8	3.3
28	4.7	4.2	5.1
29	4.2	4.7	4.2
30	4.2	4.2	4.2
31	2.8	3.7	2.8
32	2.8	3.7	3.3
33	4.7	4.7	4.7
34	4.7	4.2	4.2
35	4.7	4.7	4.7
36	4.2	3.3	3.7
37	4.2	3.7	4.2
38	4.2	4.2	4.7
39	4.2	4.2	4.2
40	3.7	4.2	3.7
41	2.8	2.8	3.3
42	4.7	3.7	4.7
43	5.2	3.7	3.3
44	4.7	4.7	4.2
45	3.3	2.8	3.3
46	3.8	3.8	3.3
47	4.7	4.7	5.1
48	3.7	4.7	5.1
49	3.7	4.7	3.7
50	4.7	3.7	3.7

Sample	Site 2 Observation		
	1	2	3
1	2.7	2.7	2.2
2	4.0	3.6	3.1
3	5.3	4.0	3.6
4	4.5	4.0	3.6
5	4.5	4.0	4.5
6	3.6	2.7	4.0
7	4.0	4.0	3.6
8	3.1	2.7	2.7
9	3.1	2.7	3.1
10	3.6	3.6	3.6
11	3.1	4.0	2.7
12	3.6	3.1	2.7
13	3.6	4.5	4.0
14	3.6	3.6	4.5
15	4.5	3.6	3.6
16	3.6	3.6	3.1
17	3.6	3.6	4.0
18	3.1	3.1	3.6
19	5.3	5.3	4.9
20	4.5	4.0	4.0
21	4.0	4.0	3.6
22	5.8	5.3	4.5
23	5.3	6.7	4.9
24	4.9	4.5	4.5
25	5.3	4.5	4.5
26	2.7	5.8	4.0
27	4.0	4.0	3.6
28	3.1	3.6	4.0
29	5.8	6.2	4.5
30	4.0	4.9	4.5
31	2.7	2.7	3.1
32	2.2	3.1	2.7
33	2.2	2.7	2.7
34	2.2	3.1	2.7
35	2.7	3.1	2.7
36	3.1	3.1	3.1
37	3.6	3.6	4.0
38	4.5	4.5	4.5
39	4.9	4.9	4.5
40	5.3	5.3	4.9
41	5.3	5.8	4.5
42	4.0	5.3	4.5
43	3.6	3.1	3.1
44	4.5	4.5	4.5
45	4.0	3.6	3.6
46	3.6	4.0	4.0
47	3.6	3.6	3.1
48	3.6	4.0	4.0
49	5.3	6.2	4.5
50	4.0	4.5	4.5

Table 18
Air Content by Chase Air Meter, in Percent

Sample	Site 3 Observation		
	1	2	3
1	5.5	5.0	5.0
2	4.6	5.0	5.5
3	4.6	6.4	4.6
4	4.6	5.0	5.0
5	5.6	5.0	5.6
6	5.5	5.1	4.6
7	5.5	5.5	5.1
8	5.5	5.1	5.5
9	5.5	5.5	6.0
10	4.1	5.1	4.6
11	5.1	4.6	5.1
12	5.1	5.5	4.1
13	4.6	4.6	4.1
14	5.1	5.1	5.5
15	5.1	5.5	5.5
16	5.5	6.4	5.1
17	5.1	4.6	5.5
18	6.0	5.5	5.5
19	4.6	5.5	4.1
20	4.6	5.5	4.6
21	4.6	4.6	4.6
22	5.1	5.1	4.6
23	4.6	5.1	5.5
24	4.6	5.1	5.5
25	5.5	5.5	5.1
26	4.6	4.6	4.6
27	3.7	4.1	4.1
28	5.1	6.0	5.5
29	5.1	5.5	5.1
30	5.1	5.5	5.5
31	5.5	6.0	6.4
32	5.1	5.5	5.5
33	4.6	4.6	6.0
34	5.1	5.5	5.5
35	3.7	4.6	4.6
36	4.6	4.6	5.5
37	4.6	4.1	4.6
38	5.5	5.5	5.5
39	4.1	4.6	4.6
40	4.6	5.5	4.6
41	5.5	5.0	5.5
42	3.7	4.1	4.1
43	4.1	5.0	3.7
44	6.0	5.5	5.5
45	5.5	6.0	5.0
46	5.0	4.6	6.4
47	5.0	5.0	5.0
48	4.6	5.0	4.1
49	5.5	4.6	5.5
50	5.0	5.5	4.6

Table 19
Slump, in inches

Sample	Site 1 Observation		
	1	2	3
1	3.50	3.00	2.25
2	3.75	3.50	2.75
3	2.25	2.00	2.00
4	2.25	3.00	2.25
5	2.00	1.50	1.50
6	5.50	3.50	2.50
7	2.25	2.25	2.25
8	4.75	4.50	3.75
9	2.50	2.25	2.25
10	4.00	4.00	3.50
11	6.00	3.75	4.25
12	4.00	4.25	3.50
13	1.50	1.50	1.00
14	2.50	2.75	2.25
15	3.00	3.50	3.00
16	3.00	3.00	2.75
17	3.75	3.50	1.50
18	1.00	1.00	0.50
19	3.25	3.00	2.25
20	3.00	2.75	2.50
21	2.75	2.50	2.50
22	3.00	3.00	3.00
23	3.00	3.00	2.75
24	3.00	3.00	3.00
25	0.50	0.75	0.50
26	2.50	2.00	2.25
27	2.75	2.75	2.50
28	3.75	4.25	4.00
29	3.50	3.25	3.75
30	5.00	5.25	4.50
31	1.75	2.00	1.50
32	1.75	1.75	0.75
33	4.50	4.25	4.00
34	3.00	3.00	3.00
35	4.00	5.50	3.75
36	2.50	2.75	2.25
37	2.75	3.25	2.75
38	7.75	6.50	7.50
39	3.75	3.25	3.00
40	2.50	2.50	2.25
41	2.50	2.75	2.25
42	4.25	4.50	4.25
43	3.00	3.00	3.50
44	2.50	3.00	3.00
45	1.00	1.00	1.00
46	2.00	2.25	2.00
47	4.75	3.75	3.50
48	4.00	4.00	3.50
49	3.00	3.50	2.00
50	3.50	3.50	3.75

Table 20
Slump, in inches

Sample	Site 2 Observation		
	1	2	3
1	3.00	2.75	2.50
2	4.00	2.75	3.25
3	3.25	4.00	4.00
4	3.50	3.75	3.75
5	5.50	5.25	4.25
6	2.50	2.50	2.25
7	2.50	2.75	2.50
8	3.50	3.25	3.75
9	2.25	2.25	2.00
10	3.25	3.00	2.75
11	2.00	2.25	2.00
12	2.00	2.25	2.00
13	1.00	1.75	1.25
14	2.75	3.00	3.25
15	3.50	3.50	3.50
16	3.50	3.50	3.00
17	2.75	3.00	3.00
18	2.75	2.00	2.00
19	3.50	3.50	3.75
20	3.00	3.00	3.00
21	2.25	2.00	2.00
22	4.50	3.50	3.25
23	2.75	3.00	2.25
24	2.25	2.25	2.50
25	2.50	2.00	2.50
26	2.25	2.50	2.50
27	2.75	3.00	2.75
28	3.00	2.50	1.75
29	2.50	3.00	2.50
30	3.00	3.00	2.75
31	4.00	2.75	3.00
32	5.50	6.00	5.50
33	3.75	3.75	3.25
34	4.50	4.50	4.50
35	2.75	4.00	2.75
36	3.75	3.50	3.50
37	3.50	2.75	2.75
38	3.50	3.50	3.25
39	2.75	3.75	2.50
40	2.75	3.25	3.25
41	3.50	3.50	3.00
42	2.25	3.00	2.50
43	2.50	2.25	2.25
44	4.50	5.00	4.50
45	3.50	3.00	3.00
46	3.50	3.50	3.25
47	3.00	2.75	3.25
48	3.50	3.00	3.00
49	3.25	3.75	3.25
50	3.50	3.75	3.50

Table 21
Slump, in inches

Sample	Site 3 Observation		
	1	2	3
1	3.50	3.50	3.50
2	2.25	2.50	2.50
3	1.50	1.50	1.75
4	2.25	2.25	2.00
5	2.25	2.25	2.25
6	2.50	2.75	2.75
7	4.50	4.25	4.50
8	2.75	2.50	2.50
9	3.75	3.50	3.25
10	2.75	2.50	2.75
11	1.75	2.00	1.50
12	4.25	4.75	4.50
13	3.50	3.50	3.50
14	3.50	4.50	3.50
15	4.50	4.75	4.25
16	7.00	7.25	7.50
17	3.50	3.75	3.25
18	3.75	3.50	3.75
19	2.75	2.75	2.50
20	3.50	3.75	4.25
21	3.50	3.50	3.75
22	3.25	3.25	3.25
23	2.50	2.75	2.75
24	2.75	2.75	2.50
25	3.75	4.00	3.75
26	1.25	1.25	1.50
27	1.00	0.50	0.75
28	2.25	3.00	3.00
29	2.25	2.25	2.25
30	3.00	3.50	3.75
31	4.25	3.50	3.25
32	2.75	2.25	2.25
33	1.50	1.75	1.00
34	2.25	2.50	2.75
35	2.50	2.75	2.00
36	3.50	4.00	3.50
37	2.50	2.25	2.50
38	2.50	3.00	2.75
39	2.50	2.00	2.25
40	3.25	3.50	3.50
41	3.50	3.75	4.50
42	2.75	3.50	3.50
43	2.75	2.50	2.75
44	3.00	3.00	2.75
45	3.75	3.75	3.50
46	2.50	2.00	2.25
47	2.50	2.75	2.50
48	3.25	3.50	3.75
49	3.75	3.50	3.75
50	2.50	3.50	3.50

Table 22
Unit Weight, in lbs./cu.ft.

Sample	Site 1		
	Observation		
	1	2	3
1	147.22	147.80	147.10
2	147.08	147.40	148.20
3	148.60	148.80	148.16
4	149.60	149.60	148.00
5	149.20	149.34	148.70
6	146.64	147.16	147.80
7	147.00	147.60	147.86
8	147.80	147.90	149.00
9	149.70	151.20	149.60
10	148.16	148.98	148.66
11	146.90	148.74	149.30
12	147.70	149.60	144.80
13	150.16	149.94	147.30
14	148.20	148.16	148.32
15	145.00	147.24	144.90
16	147.52	148.56	145.50
17	148.06	149.00	143.20
18	149.90	149.10	141.40
19	148.14	148.16	149.30
20	147.40	147.90	149.60
21	147.40	148.30	149.50
22	147.56	148.20	148.56
23	148.90	149.96	149.74
24	148.30	149.00	149.34
25	149.92	149.30	146.26
26	149.50	150.24	149.18
27	150.38	150.48	149.56
28	146.90	146.80	147.24
29	147.70	147.88	148.40
30	144.52	145.16	146.36
31	150.88	149.42	149.76
32	150.42	150.56	149.36
33	147.22	148.72	148.74
34	147.80	148.84	148.96
35	147.96	148.32	148.90
36	149.22	149.32	149.26
37	148.78	149.12	149.54
38	147.34	148.44	148.44
39	148.72	148.74	148.68
40	147.90	148.58	148.18
41	148.52	148.66	148.60
42	147.12	147.02	148.28
43	147.38	148.74	149.42
44	146.28	146.76	146.80
45	149.78	148.56	142.26
46	148.50	148.74	149.78
47	146.64	147.34	147.60
48	147.26	147.94	149.36
49	148.16	149.46	149.76
50	147.10	147.10	147.46

Table 23
Unit Weight, in lbs./cu.ft.

Sample	Site 2 Observation		
	1	2	3
1	153.24	152.98	150.48
2	150.28	151.72	152.38
3	150.18	150.78	152.08
4	149.28	151.38	151.88
5	148.08	149.48	150.68
6	150.68	152.78	146.78
7	149.78	150.68	152.70
8	150.30	152.88	152.60
9	151.70	153.18	153.70
10	151.90	151.98	152.68
11	151.64	152.30	152.16
12	152.64	152.56	152.88
13	152.20	151.80	146.06
14	151.28	151.08	152.68
15	149.62	151.66	152.68
16	150.44	151.96	152.42
17	150.08	151.72	151.40
18	151.78	150.98	149.34
19	147.28	149.88	150.64
20	150.10	150.80	151.28
21	150.58	150.40	151.34
22	148.92	149.74	151.08
23	149.44	150.68	151.20
24	149.44	150.74	150.94
25	147.96	149.14	148.48
26	149.32	150.38	151.58
27	148.04	150.70	150.88
28	148.44	150.30	149.52
29	148.68	149.26	150.72
30	149.56	149.40	150.08
31	151.66	153.38	152.76
32	149.52	150.04	151.40
33	150.92	150.60	152.46
34	149.70	149.50	150.72
35	151.00	151.36	152.30
36	148.68	149.58	149.98
37	147.48	149.24	148.92
38	148.38	147.76	148.98
39	147.18	148.28	148.86
40	149.88	150.04	151.06
41	147.68	148.96	149.42
42	148.82	151.16	150.56
43	149.54	150.70	150.82
44	149.28	150.36	151.12
45	149.30	150.04	149.90
46	147.48	148.86	148.84
47	148.82	149.14	149.78
48	149.44	149.68	150.90
49	147.46	148.64	148.80
50	147.24	148.84	149.48

Table 24
Unit Weight, in lbs./cu.ft.

Sample	Site 3 Observation		
	1	2	3
1			
1	146.20	146.92	147.46
2	146.80	147.02	147.50
3	148.42	148.14	149.52
4	147.04	146.94	148.10
5	147.10	146.16	148.26
6	147.54	148.70	148.68
7	145.68	146.16	146.58
8	147.36	147.52	148.34
9	147.04	147.06	148.42
10	147.40	147.14	147.22
11	147.36	147.28	148.66
12	147.40	147.16	147.46
13	145.42	146.12	147.58
14	145.76	146.10	146.26
15	145.18	145.20	146.54
16	144.34	145.86	145.90
17.	146.16	146.98	148.04
18	146.66	146.72	146.50
19	146.90	147.78	148.06
20	146.54	147.52	147.68
21	147.70	147.82	148.52
22	145.84	146.50	147.72
23	147.04	147.10	148.12
24	146.82	146.36	147.24
25	143.92	144.66	145.54
26	147.42	148.24	147.88
27	149.08	148.02	148.88
28	145.12	146.78	146.56
29	147.12	147.50	147.80
30	145.92	147.16	148.72
31	145.46	146.62	145.64
32	146.76	146.08	147.88
33	145.88	145.82	145.92
34	146.56	146.16	147.20
35	148.62	148.42	149.08
36	145.60	146.82	148.18
37	148.06	147.74	149.50
38	146.76	146.60	147.56
39	147.12	147.92	148.28
40	146.90	147.16	148.02
41	146.26	146.92	147.14
42	148.26	148.22	148.84
43	148.10	148.86	149.48
44	146.22	147.46	147.36
45	147.04	147.12	146.86
46	148.20	148.26	149.06
47	146.76	147.78	147.12
48	147.12	147.16	147.16
49	146.04	146.48	147.22
50	146.68	146.34	147.00

APPENDIX B ✓

Data Plots

A
I
R
P

SAMPLE NUMBER

FIG. 37 DATA PLOT FOR AIR CONTENT MEASURED BY PRESSURE METER, SITE 1

STIMULI CONTROL LIMITS

3-a

$\bar{x} =$

FIG. 37 DATA PLOT FOR AIR CONTENT MEASURED BY PRESSURE METER, SITE I

FIG. 38 DATA PLOT FOR AIR CONTENT MEASURED BY PRESSURE METER, SITE 2

3-a CONTROL LIMITS

ix

A
I
R
P

JOB NO. 2
FIG. 38 DATA PLOT FOR AIR CONTENT MEASURED BY
PRESSURE METER, SITE 2

SAMPLE NUMBER

JOB NO. 3

FIG. 39 DATA PLOT FOR AIR CONTENT MEASURED BY

PRESSURE METER, SITE 3

3-a CONTROL LIMITS

Xi

FIG. 39 DATA PLOT FOR AIR CONTENT MEASURED BY PRESSURE METER, SITE 3

JOB NO. 3

SAMPLE NUMBER

JOB NO. 1

FIG. 40 DATA PLOT FOR AIR CONTENT MEASURED BY
CHACE METER, SITE I

FIG. 41 DATA PLOT FOR AIR CONTENT MEASURED BY
CHACE METER, SITE 2

SAMPLE NUMBER

JOB NO. 3

FIG. 42 DATA PLOT FOR AIR CONTENT MEASURED BY CHACE METER, SITE 3

SAMPLE NUMBER

JOB NO. 1

FIG. 43 DATA PLOT FOR SLUMP, SITE 1

FIG. 44 DATA PLOT FOR SLUMP. SITE 2

FIG. 45 DATA PLOT FOR SLUMP, SITE 3

NUMBER OF SAMPLE MEANS

FIG. 46 DATA PLOT FOR UNIT WEIGHT, SITE I

FIG. 47 DATA PLOT FOR UNIT WEIGHT, SITE 2

APPENDIX C
Statistical Calculations

FIG. 48 DATA PLOT FOR UNIT WEIGHT, SITE 3

Table 25

MARGINAL MEANS

	Site 1	Site 2	Site 3	Overall
Pressure	4.47733	4.20733	4.50733	4.39733
Chace	4.31800	3.92133	5.04933	4.42955
Slump	2.99500	3.09167	3.03500	3.04056
Unit Wt.	148.21266	150.34786	147.15680	148.57238

Table 26

Analysis of Variance - Factorial Model

Air Content by Pressure Test

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

 $\alpha = 0.05$ $F_{2,147} = 3.07* > 2.72 \quad \therefore \text{site not significant}$ $F_{147,300} = 1.30 < 19.09 \quad \therefore \text{sample within site significant}$

$$\sigma_s^2 = \frac{1.50490 - 0.07882}{3} = \frac{1.42608}{3} = 0.47536$$

Table 27

Analysis of Variance - Factorial Model

Air Content by Chace Test

Source of Variation	df	SS	MS	EMS	F
Site	2	98.22882	49.11441	$\sigma_{\epsilon}^2 + 3\sigma_s + 150 \sigma_{\text{site}}^2$	28.14
Sample within Site	147	256.52075	1.74504	$\sigma_{\epsilon}^2 + 3\sigma_s$	5.76
Error	300	90.92658	0.30309	σ_{ϵ}^2	

 $\alpha = 0.05$ $F_{2,147} = 3.07 < 28.14 \therefore \text{Site is significant}$ $F_{147,300} = 1.30 < 5.76 \therefore \text{Sample within site is significant}$

$$\sigma_s^2 = \frac{1.74504 - 0.30309}{3} = \frac{1.44195}{3} = 0.48065$$

Table 28

Analysis of Variance - Factorial Model

Slump

Source of Variation	df	SS	MS	EMS	F
Site	2	0.70778	0.35389	$\sigma_{\epsilon}^2 + 3\sigma_s + 150\sigma_{\text{site}}^2$	0.12
Sample within Site	147	440.23903	2.99482	$\sigma_{\epsilon}^2 + 3\sigma_s$	21.91
Error	300	40.99997	0.13667	σ_{ϵ}^2	

$$\alpha = 0.05$$

$$F_{2,147} = 3.07 > 0.12 \quad \therefore \text{Site not significant}$$

$$F_{147,300} = 1.30 < 21.91 \quad \therefore \text{Sample within site is significant}$$

$$\sigma_s^2 = \frac{2.99482 - 0.13667}{3} = \frac{2.85815}{3} = 0.95272$$

Analysis of Variance - Factorial Model

Unit Weight

Source of Variation	df	SS	MS	EMS	F
Site	2	792.84192	396.42096	$\sigma_{\epsilon}^2 + 3\sigma_s + 150\sigma_{\text{site}}^2$	112.35
Sample within Site	147	518.68643	3.52848	$\sigma_{\epsilon}^2 + 3\sigma_s$	3.08
Error	300	343.67211	1.14557	σ_{ϵ}^2	

 $\alpha = 0.05$ $F_{2,147} = 3.07 < 112.35$ Site is significant $F_{147,300} = 1.30 < 3.08$ Sample within site is significant

$$\sigma_s^2 = \frac{3.52848 - 1.14557}{3} = \frac{2.38291}{3} = 0.79430$$

Calculations of the Standard Deviation of Site Means

$$\text{Pressure Meter:} \quad \frac{S}{\bar{X}}_{\text{site}} = \sqrt{\frac{1.50490}{150}} = 0.1000$$

$$\text{Chace Meter:} \quad \frac{S}{\bar{X}}_{\text{site}} = \sqrt{\frac{1.74504}{150}} = 0.1077$$

$$\text{Slump:} \quad \frac{S}{\bar{X}}_{\text{site}} = \sqrt{\frac{2.99482}{150}} = 0.14145$$

$$\text{Unit Weight:} \quad \frac{S}{\bar{X}}_{\text{site}} = \sqrt{\frac{3.25848}{150}} = 0.1533$$

95% Confidence Limits on Site Mean
(df = 147, $\alpha = 0.05$)

$$\text{Pressure Meter:} \quad \pm 1.98 (0.1000) = \pm 0.198$$

$$\text{Chace Meter:} \quad \pm 1.98 (0.1077) = \pm 0.213$$

$$\text{Slump:} \quad \pm 1.98 (0.14145) = \pm 0.280$$

$$\text{Unit Weight:} \quad \pm 1.98 (0.1533) = \pm 0.304$$

Calculation of Standard Deviation of Sample Means

$$\text{Pressure Meter:} \quad \frac{S}{\bar{X}}_{\text{sample}} = \sqrt{\frac{0.07882}{3}} = 0.16208$$

$$\text{Chace Meter:} \quad \frac{S}{\bar{X}}_{\text{sample}} = \sqrt{\frac{0.30309}{3}} = 0.31785$$

$$\text{Slump:} \quad \frac{S}{\bar{X}}_{\text{sample}} = \sqrt{\frac{0.13667}{3}} = 0.21345$$

$$\text{Unit Weight:} \quad \frac{S}{\bar{X}}_{\text{sample}} = \sqrt{\frac{1.14557}{3}} = 0.61795$$

95% Confidence Limits on Sample Mean
(df = 300, $\alpha = 0.05$)

$$\text{Pressure Meter:} \quad \pm 1.96 (0.16208) = \pm 0.318$$

$$\text{Chace Meter:} \quad \pm 1.96 (0.31785) = \pm 0.623$$

$$\text{Slump:} \quad \pm 1.96 (0.21345) = \pm 0.418$$

$$\text{Unit Weight:} \quad \pm 1.96 (0.61795) = \pm 1.211$$

Calculations for 3- σ Control Limits

$$\text{Control Limits} = \bar{\bar{X}} \pm \frac{3}{\sqrt{n}} \sqrt{\frac{\sigma_e^2}{3} + \sigma_s^2} \quad (\sigma_e^2 \text{ and } \sigma_s^2 \text{ from Factorial Analysis})$$

Air Content by Pressure Meter:

$$\bar{\bar{X}} \pm \frac{3}{\sqrt{3}} \sqrt{0.02627 + 0.47536} = \bar{\bar{X}} \pm 1.23$$

Air Content by Chace Meter:

$$\bar{\bar{X}} \pm \frac{3}{\sqrt{3}} \sqrt{0.10103 + 0.48065} = \bar{\bar{X}} \pm 1.32$$

Slump:

$$\bar{\bar{X}} \pm \frac{3}{\sqrt{3}} \sqrt{0.04556 + 0.95272} = \bar{\bar{X}} \pm 1.73$$

Unit Weight:

$$\bar{\bar{X}} \pm \frac{3}{\sqrt{3}} \sqrt{0.38186 + 0.79430} = \bar{\bar{X}} \pm 1.89$$

Calculation of 3- σ Control Limits from Assumed Values of σ_{ϵ}^2 and σ_s^2 based on One-Way ANOV's.

Air Content by Pressure Meter:

$$\text{assumed } \sigma_{\epsilon}^2 = 0.06$$

$$\text{assumed } \sigma_s^2 = 0.25$$

$$\bar{\bar{X}} \pm \frac{3}{\sqrt{3}} \sqrt{\frac{0.06}{3} + 0.25} = \bar{\bar{X}} \pm 0.90$$

Air Content by Chace Meter:

$$\text{assumed } \sigma_{\epsilon}^2 = 0.21$$

$$\text{assumed } \sigma_s^2 = 0.35$$

$$\bar{\bar{X}} \pm \frac{3}{\sqrt{3}} \sqrt{\frac{0.21}{3} + 0.35} = \bar{\bar{X}} \pm 1.12$$

Slump:

$$\text{assumed } \sigma_{\epsilon}^2 = 0.09$$

$$\text{assumed } \sigma_s^2 = 0.60$$

$$\bar{\bar{X}} \pm \frac{3}{\sqrt{3}} \sqrt{\frac{0.09}{3} + 0.60} = \bar{\bar{X}} \pm 1.37$$

Unit Weight:

$$\text{assumed } \sigma_{\epsilon}^2 = 0.45$$

$$\text{assumed } \sigma_s^2 = 0.62$$

$$\bar{\bar{X}} \pm \frac{3}{\sqrt{3}} \sqrt{\frac{0.45}{3} + 0.62} = \bar{\bar{X}} \pm 1.52$$

Tests for Significance of Correlation Coefficients (All Sites)

$$n = 150, \alpha = 0.001, t_{\alpha} = 3.29, t_{n-2} = \frac{r}{\sqrt{1-r^2}} \sqrt{n-2}$$

$$\text{Pressure vs. Chace: } t_{148} = \frac{0.6060}{\sqrt{1 - (0.6060)^2}} \sqrt{148} = 9.2675$$

$$\text{Pressure vs. Slump: } t_{148} = \frac{0.3368}{\sqrt{1 - (0.3368)^2}} \sqrt{148} = 4.3516$$

$$\text{Pressure vs. Unit Weight: } t_{148} = \frac{0.5491}{\sqrt{1 - (0.5491)^2}} \sqrt{148} = 8.6351$$

$$\text{Chace vs. Slump: } t_{148} = \frac{0.1296}{\sqrt{1 - (0.1296)^2}} \sqrt{148} = 1.5900$$

$$\text{Chace vs. Unit Weight: } t_{148} = \frac{0.6445}{\sqrt{1 - (0.6445)^2}} \sqrt{148} = 10.254$$

$$\text{Slump vs. Unit Weight: } t_{148} = \frac{0.1856}{\sqrt{1 - (0.1856)^2}} \sqrt{148} = 2.2977$$

TESTS FOR SIGNIFICANCE OF CORRELATION COEFFICIENTS

PRESSURE V. CHACE METER PER SITE

SITE 1

$$\left. \begin{array}{l} n = 50 - 2 = 48 \\ \alpha = 0.001 \end{array} \right\} t_{\alpha} = 3.51$$

$$r = 0.5130$$

$$t_{n-2} = t_{50-2} = t_{48} = \frac{r}{\sqrt{1-r^2}} \sqrt{n-2}$$

$$= \frac{0.5130}{\sqrt{1 - (.5130)^2}} \sqrt{50-2}$$

$$t_{48} = \frac{(0.5130) (6.9282)}{0.8584} = 4.1405 > 3.51$$

Significant

SITE 2

$$r = 0.7288$$

$$t_{48} = \frac{0.7288}{\sqrt{1 - (0.7288)^2}} \sqrt{48}$$

$$= \frac{0.7288 (6.9282)}{0.6847} = 7.3744 > 3.51$$

Significant

SITE 3

$$r = 0.7247$$

$$t_{48} = \frac{0.7247}{\sqrt{1 - (0.7247)^2}} \sqrt{48}$$

$$= \frac{0.7247 (6.9282)}{0.6891} = 7.2861 > 3.51$$

Significant

TABLE 30

ANALYSIS OF DIFFERENCES BETWEEN REPLICATE OBSERVATIONS

SITE	OBSERVATION DIFFERENCE=d	$\sum d_{ij}$	$\bar{d}_{ij} = \frac{1}{50} \sum d_{ij}$	$\sum d_{ij}^2$	$50 \sum d_{ij}^2$	$\sum (d_{ij})^2$	$50 \sum d_{ij}^2 - \sum (d_{ij})^2$	$s_{ij} = \sqrt{\frac{50 \sum d_{ij}^2 - \sum (d_{ij})^2}{50 \cdot 50 \cdot 49}}$	$t_{ij} = \frac{d_{ij}}{s_{ij}}$
1	$X_1 - X_2$	12.8	0.256	6.68	334	163.24	170.16	0.0013091	0.03727
	$X_1 - X_3$	19.9	0.398	1.21	1060.5	396.01	664.49	0.0054244	0.07365
	$X_2 - X_3$	7.1	0.142	13.09	654.5	50.41	604.09	0.0049313	0.07022
2	$X_1 - X_2$	6.8	0.136	5.78	289	46.24	242.76	0.0015817	0.04452
	$X_1 - X_3$	9.5	0.190	8.05	402.5	90.25	312.25	0.0025489	0.05049
	$X_2 - X_3$	2.7	0.054	2.91	145.5	7.29	138.21	0.0011282	0.03360
3	$X_1 - X_2$	10.4	0.208	5.14	257	108.16	148.84	0.0012150	0.03486
	$X_1 - X_3$	11.6	0.232	5.90	295	134.56	160.44	0.0013097	0.03619
	$X_2 - X_3$	1.2	0.024	1.50	76	1.44	74.56	0.0006087	0.02467

	<u>Site 1</u>	<u>Site 2</u>	<u>Site 3</u>
Sample	* ₁		
	* ₂		
	* ₃		

} 3 observations per sample

50 samples for each of 3 sites

$d_{i,j} = d_{\text{site}}, \text{ difference}$

Difference notation: $d_{i,1} = *_1 - *_2$

$d_{i,2} = *_1 - *_3$

$d_{i,3} = *_2 - *_3$

$d_{i,j}$ $i = \text{site}$

$j = \text{difference}$