

An Investigation of Compaction Variability for Selected Highway Projects in Indiana

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The primary objectives of this study were to determine average levels of compaction and variation in compaction associated with present-day construction of subgrades and subbases, and to establish a statistical approach to the control of compaction. Six projects were tested using conventional methods and the actual compaction data obtained was then analyzed statistically. The results were used to establish guidelines for a statistical approach to control of compaction.

•THE application of statistical quality control to highway construction has become a subject of widespread interest during the past several years with the Bureau of Public Roads taking the lead in this area. Although the term "statistical quality control" is relatively new to the vocabulary of the highway engineer, quality control is actually an old concept which has been widely used by the manufacturing industries for many years.

It should be noted that the key word is "statistical." It is necessary to recognize that present specifications imply a form of quality control in that a given number of field tests must be performed for specific units of construction and the results obtained must exceed established minimums before the material can be accepted. In most cases, the values established for the required number of tests, frequency of test and desired minimum level of quality have evolved from trial and error and at times are not related to the construction process itself.

From the standpoint of making absolutely certain that the true value of quality is obtained from the field tests it would be necessary to perform an extremely large number of tests which would obviously not be practical. The statistical approach to control is then a compromise between performing a very large number of tests and current control methods which generally involve performing only one or two tests for a relatively large quantity of construction.

The use of a statistical approach involves establishing an estimate of the number of tests required and a level of quality to be obtained from these tests. If the test statistic thus computed exceeds some established value, the construction is accepted on the basis of knowing that statistically a mistake concerning acceptance of below quality construction will only be made a small percentage of the time.

The use of a statistical approach thus involves performing control tests on random samples from the construction unit and then inferring overall quality for the entire unit, from these tests. The size of sample is determined statistically to insure that a correct decision concerning overall quality is made a majority of the time and that an erroneous decision is made a small percentage of the time (for example, five times in every one-hundred decisions). Also, the statistical approach allows for variability that is inevitably associated with the construction process by specifying that a certain number of tests exceed some established value rather than having all control tests exceed a given minimum level.

FIELD TESTING PROGRAM

There is some question whether the variability of compaction as determined by conventional testing techniques represents the true variability of the completed product or whether this is a compounded value that is a combination of several factors. The following are factors which are considered to be primary causes of the measured variability.

1. Contractor Variability involves the difficulty of the contractor to compact any material with absolute uniformity. This results from many factors not the least of which is the influence of speed of construction and economics of the situation. This factor also includes the effect of changes in soil type and changes in moisture content.

2. Testing Variability is caused by the difficulty of the inspector in the field to reproduce his test results using conventional testing methods.

3. Material Variability involves the inability of the inspector to select the correct "arbitrary" maximum density value to be applied to the soil at the location where the in-place density test is performed. This is a very important facet of the overall problem of compaction control in that the selection of the correct value is necessary to the determination of the actual percent compaction value.

4. Engineering Judgment affects the overall problem because it involves the decision of whether the average degree of compaction is good enough and whether or not the results obtained for only one or two tests performed over a large unit of construction are really indicative of the compaction of the overall area.

A field testing program was then established using the guidelines established by the Bureau of Public Roads (2) for the purpose of evaluating the preceding factors. Figure 1 shows a plan view of the typical testing program. In all, six projects were tested including three subbases and three subgrades.

For the purposes of this study, subgrade refers to the upper 6 inches of compacted earth material directly beneath the subbase. The subbase is defined as the selected granular material (6 in.) placed immediately under the concrete pavement. The current Indiana specifications (6) require that at least 100 percent compaction be achieved for both the subgrade and subbase.

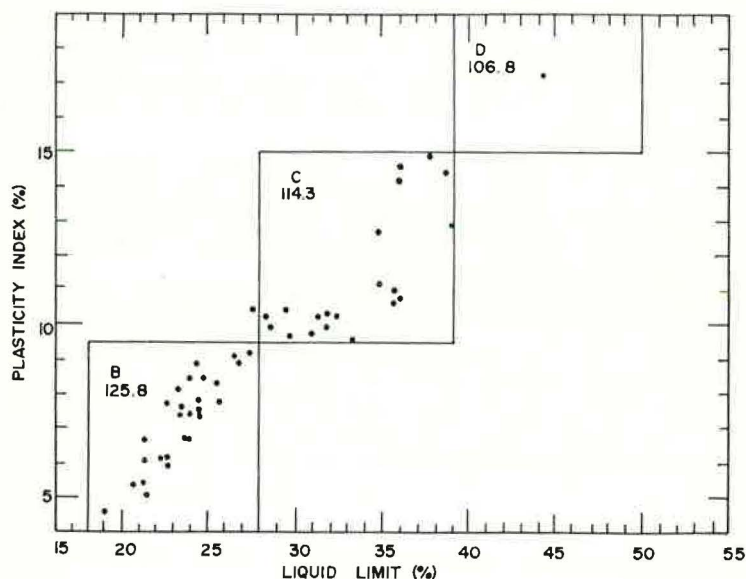


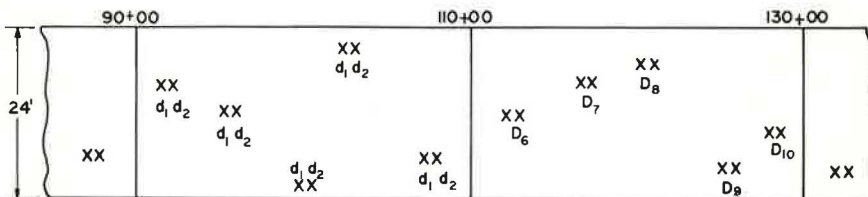
Figure 1. Plan view showing control section testing program.

The test projects were divided into ten equal size sections, designated control sections, approximately 2,000 ft long. A series of replicate control tests were performed in each section. A replicate test is defined as two density or moisture determinations performed as close to one another as is practical (approximately 6 in. apart). Density determinations were made using the Indiana Highway Commission method which utilizes the sand cone test.

Five replicate measurements were made in each control section resulting in 100 individual tests or 50 replicate tests for each project. Each of the replicate tests were identified as d_1 or d_2 with the average of these two individual measurements given the identification of D_6 , D_7 , etc. From this testing program it was possible to establish values for two variance terms using a standard analysis of variance technique. The basic ANOV used was a one-way Model II, equal number of tests per treatment approach (Table 1).

The first variance term is the within treatment variance. This variance is due to the variability in compaction between replicate tests and is determined by calculating the variance of these tests around their individual means. The second variance term is the between treatment variances (a treatment is a pair of tests performed close together). This latter value gives an indication of the variance of compaction from one location to another within a control section.

Five test values were determined for each field test location. The first of these was the in-place density of the material as determined by the conventional sand cone procedure. Other measured values were in-place moisture content as determined by a field stove drying technique, moisture content determined in a central laboratory, maximum density, optimum moisture content, and grain size distribution. In addition, the liquid and plastic limit tests were made on the samples from each test hole for the subgrades.



Each individual test hole identified as d_1 or d_2

Average of replicate tests identified as $D = \frac{d_1 + d_2}{2}$

Parameters determined for each test location

1. In-Place Density
2. In-Place Moisture Content
3. Maximum Density
4. Optimum Moisture
5. Grain Size Characteristics

Figure 2. Classification test soil groups.

TABLE 1
GENERALIZED ANOV (EQUAL NUMBER
OF TESTS PER TREATMENT) MODEL II

Source of Variation	Degrees of Freedom	EMS
Means	T-1	$\sigma_{\epsilon}^2 + r\sigma_{\tau}^2$
Error	T (R-1)	σ_{ϵ}^2

T = number of treatments

R = number of replicate tests per treatment

σ_{ϵ}^2 = within treatment variance

σ_{τ}^2 = between treatment variance

SUBGRADE RESULTS

As previously indicated, the standard sand cone test was used to determine in-place density. At the outset, it was considered advisable first to evaluate methods for determination of the density of the sand. Two techniques were studied: (a) calibrating the sand in a cylindrical steel mold with a volume of approximately 0.68 cu ft, and (b) calculating the density from the volume of the sand cone jug itself. The latter method is the one used by Indiana State Highway Commission construction personnel. Results obtained from the two methods of calibration indicated no difference between these two techniques; the first approach (steel mold) was used throughout the testing program.

Two methods for selecting the maximum dry density of the material taken from the density hole were evaluated.

The first method was based on typical Indiana moisture-density curves and the field "one point" compaction test used in conjunction with these curves. This field test followed procedures as outlined by ASTM D 698-64T, Method A, except only one point on the compaction curve is established. The Indiana typical curves are very similar to the widely published Ohio curves; a comparison of values from these two sets of curves indicated very little difference between them. The use of these curves is very straightforward and simply involves performing a simulated laboratory compaction test in the field in the form of a one point compaction test. The result of this single determination is plotted on the typical curves and the correct control curve for that material is selected. The method is similar to that described by Joslin (7).

The second technique was based on compaction tests according to ASTM D 698-64T, Method A, and classification tests and correlations between the maximum density values and the classification indices. This technique is illustrated for one of the projects in Figure 2 where plasticity index is plotted against liquid limit. The soils are grouped according to maximum density values resulting in the three groups identified as soil types B, C, and D. Similar results were obtained for the other two projects. To use this approach in the field, it would be necessary for the project engineer or inspector to perform a classification test thereby placing the material in one of the soil groups and thus establish a maximum density value. This has an obvious disadvantage: it would be necessary to run a large number of classification tests to permit correlation of these results with results of compaction tests. Also, a complete laboratory test would have to be performed by the inspector in the field.

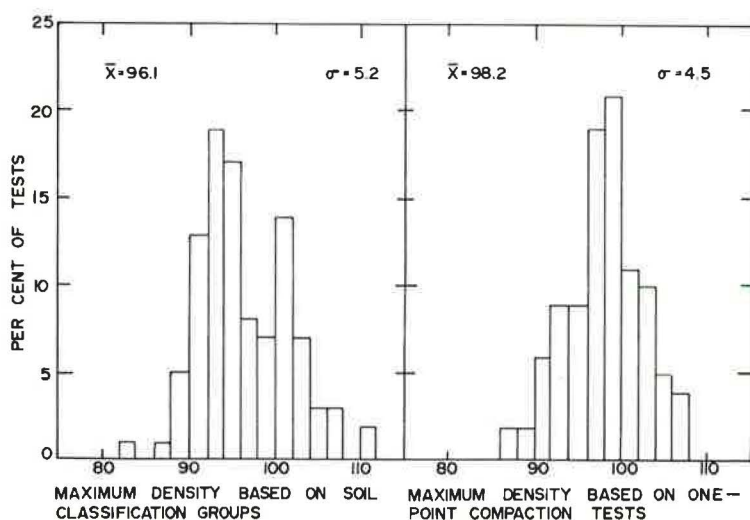


Figure 3. Comparison of subgrade percent compaction determinations.

Figure 3 shows a comparison of the two methods of selecting maximum dry density for one of the subgrade projects. For all three projects, the use of the soil classification groups resulted in a much wider spread in data with a lower average compaction level.

Therefore, the technique of performing a one point compaction test in the field and using this in conjunction with the typical moisture-density curves was considered to be the most desirable for this research. It is a relatively simple test to perform and gives a reliable basis for determination of a maximum dry density value for each density hole.

As previously indicated, moisture content in the field was determined primarily by drying the sample on a field stove. A comparison of these results with results obtained by performing a standard laboratory oven-drying test indicated excellent correlation between the methods. Over 90 percent of the tests were within ± 2 percentage points of one another. This precision was felt to be adequate for performing the one point compaction test and interpretation of a maximum density value. Field moisture content for two of the projects averaged approximately 2 percent below optimum at the time of testing; the third averaged slightly above optimum moisture content.

Figure 4 shows the variation of percent compaction for the three projects investigated. Superimposed are normal curves for the data. The Kolomogorov-Smirnov test for normality (8) was performed and it was found that the data collected for all three projects were normally distributed at the 0.05 significance level.

Data in Figure 4 represent the results of approximately 100 in-place density tests per project. The range in average percent compaction was from 96.8 percent standard AASHO for project S-2 to 100.6 percent standard AASHO for project S-1. Recalling that the specifications call for a compaction level of 100 percent, it is observed that all of these contractors achieved an average compaction level approximately equal to the specified minimum level.

The overall range in compaction ranged from approximately 80 percent to over 110 percent for the three projects, indicating the fallacy of performing a single test and assuming that it is indicative of the compaction over a large area of material. In fact, it was found by performing a large number of tests that approximately 50 percent of the tests were below the specified level of 100 percent compaction. Thus, the probability of choosing a test location resulting in a compaction level above 100 percent would be only 50 percent.

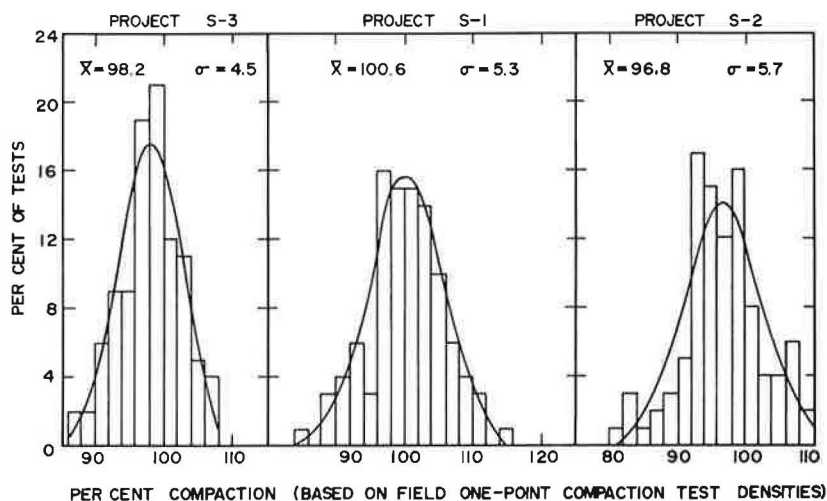


Figure 4. Variation of percent compaction for subgrades.

Standard deviation values for compaction ranged from 4.5 to 5.7, indicating the spread of the data. Obviously, project S-3 was compacted more uniformly than project S-2. Degree of uniformity of compaction is of primary importance since, insofar as acceptance is concerned, the conclusion is made that the entire control section is at a given compaction level based on the results of the tests.

It is felt that the ranges in percent compaction are much larger than desirable and that a statistical specification would account for some of this variability by requiring the performance of more tests and, therefore, permitting a better estimate of compaction. For the three projects investigated, the statement can be made that, in general, all three contractors achieved approximately the same results and that on the average they met specifications. However, uniformity of compaction varied from project to project and this fact was not revealed by the routine inspection since the inspector's tests indicated a minimum of 100 percent compaction throughout.

SUBBASE RESULTS

The methods for determining in-place density and moisture content of the subbase materials were the same as previously described for the subgrades. The technique used for selection of maximum density values for the subbase materials was based on the concept which relates maximum density as determined by ASTM D 698-64T, Method C, procedures to gradation of the material (11). Figure 5 shows this approach for one of the subbase projects. Percent of material passing the No. 4 mesh sieve is plotted against maximum dry density. The theoretical curve is based on the calculation procedure presented by Humphres (5). The control curve was developed by performing laboratory compaction tests on the materials obtained from the field and drawing a smooth curve through these data.

The No. 4 sieve was used for control since it is readily adaptable to field use. A comparison was made of field data for the No. 4 sieve with the more exact laboratory method. In the field, the material from the density hole was passed through the No. 4 sieve while in a wet condition. These samples were then wash-sieved in the laboratory and dried in an oven to determine the percent passing the No. 4 sieve. An excellent correlation between the field and laboratory values was found, indicating that the field sieve method could be used to determine accurately the percent of the material passing the No. 4 sieve. The above, however, was not true for smaller sieve sizes investigated.

After the control curves were developed, control was exercised in the field in the following manner: after the in-place density test was performed the material from the hole was passed through the No. 4 sieve. The percentage of material passing was determined. This value was then entered on the control curves chart and the corresponding

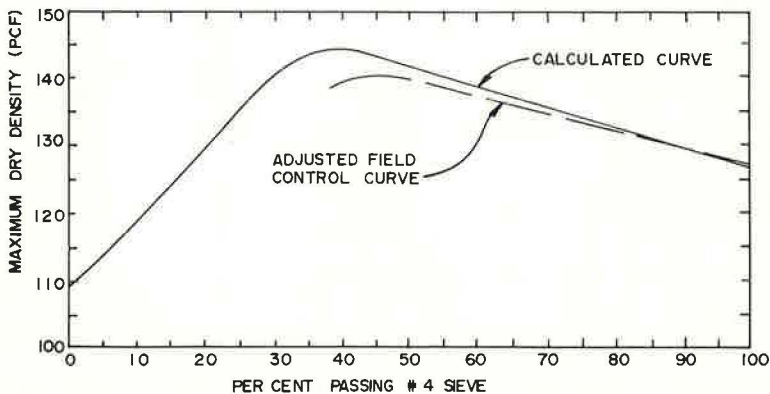


Figure 5. Subbase density control curves.

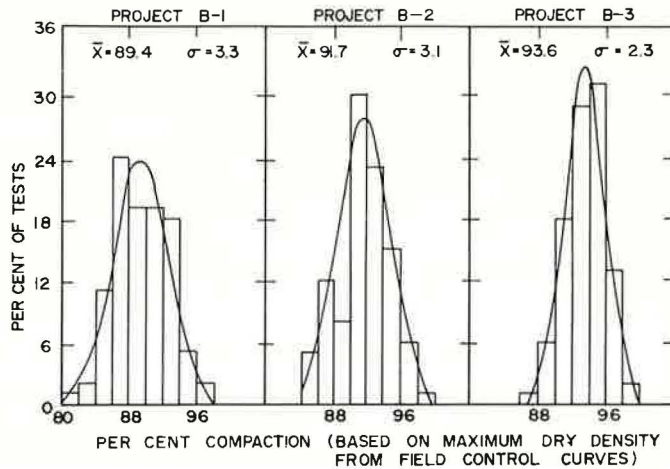


Figure 6. Variation of percent compaction for subbases.

maximum density value was determined. Figure 6 shows the variation in percent compaction for the subbases.

As with the subgrades a definite variability in compaction was noted. However, the overall variation was much smaller than for the subgrade projects as indicated by the standard deviation values (2.3 to 3.3 for the subbases compared to an average value of 5 for the subgrades).

The low average compaction level for the subbases was probably due to several causes. First, and probably most important, the maximum density values furnished to the field inspectors were determined from the laboratory tests performed on samples obtained prior to construction; these may not have been representative of the material actually removed from the sand density hole by the inspector. Second, the inability of the inspector to select the correct control value from several supplied to him certainly had an effect.

The danger of using a laboratory density value obtained from a test on material collected before construction and assumed to be relatively homogeneous is indicated by the variation in grain size characteristics determined for one of the subbase materials (Fig. 7). For the three sieve sizes, a wide range in gradation values was obtained; therefore, a laboratory maximum density value may not be indicative of the actual maximum

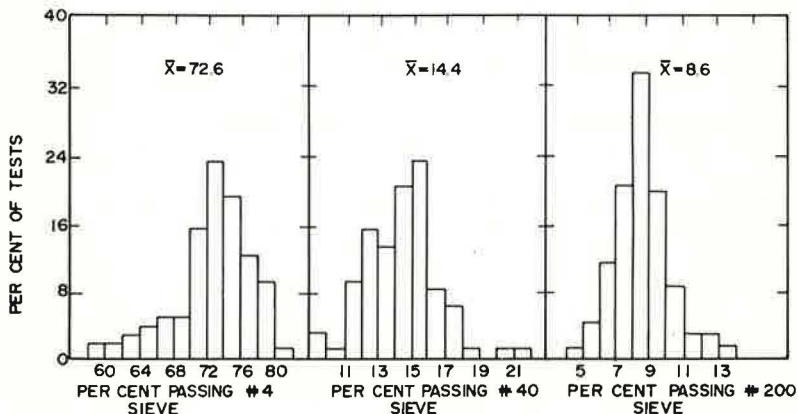


Figure 7. Variation in grain size characteristics for a typical subbase.

density due to the magnitude of variation occurring in the material. This trend in variability was observed for each of the three subbase materials. The results indicated the desirability of using control curves to determine the control value as this allows the inspector to make a decision concerning maximum density for the material from a given test spot resulting in a more realistic value.

The data for the subbases were checked for normality and results indicated that the data were normally distributed. Normality of data is important since in order to perform a statistical analysis of variance it is necessary that the data fulfill certain criteria. The first criterion is that of a normal distribution; the second is that the variances must be homogeneous from one control section to another. Both of these criteria were satisfied for all six projects involved at the 0.05 significance level.

VARIANCES INVOLVED

The next phase of the study involved the statistical applications which could be derived from the analysis of variance data. The variance terms which were of importance were the within treatment variance denoted by σ_{ϵ}^2 and between treatment variance as σ_T^2 (Table 1).

The within treatment variance represents variability caused by four factors. These are (a) technician variability, or the error associated with one man versus another performing a given test; (b) inherent inconsistencies in the tests themselves—either the sand cone or one point compaction tests which are both involved in the calculation of percent compaction; (c) soil variability within a small testing area, that is, the soil could vary in properties in these two very close locations; and (d) the compaction variability associated with the compaction process.

It was assumed that soil variability and the variation in the compaction process had less effect on causing within treatment variance than the other two factors, considering the fact that the two tests were performed extremely close together. The between treatment variance value represents variation in compaction from station to station along the project and is attributed to three main factors: (a) material variability, (b) compaction technique variability, and (c) technician variability.

To account for both of these variances and to arrive at a realistic estimate of the variance associated with this type of construction, a combination of these values was used. This overall variance is denoted by the symbol $\hat{\sigma}^2$ and is equal to the summation of $\sigma_{\epsilon}^2 + \sigma_T^2$. This estimate of variance was then used in all of the statistical tests subsequently performed.

Looking at the variances involved individually, the within treatment variance terms were much smaller for the subbases than for the subgrades. Typically this variance term for the subbases was approximately equal to 4 compared to approximately 14 for the subgrades. Several factors were felt to be the cause of this difference in within treatment variances for these two material types.

Difficulty is generally encountered when performing the in-place density tests in any type of material. In most cases, it was impossible to test the subgrade immediately after compaction was completed, and therefore, some drying out occurred in the subgrade material. This drying resulted in the material becoming relatively hard in some instances thereby increasing the difficulty in performing the in-place density tests. Also, on project S-2 the material was granular in nature and this factor compounded the difficulty in performing the in-place density test. This was probably the reason that this project had the highest within treatment variance of the six tested.

The subbases were generally tested immediately after compaction just ahead of the paving unit and were, therefore, at optimum moisture content, which somewhat simplified the actual digging of the sand cone hole. Also, if this material had been compacted to 100 percent compaction, it may have resulted in the within treatment variance values being somewhat higher. From a gradation standpoint, the subbases were relatively homogeneous in comparison to the subgrades. The factor of soil types variability was minimized for the subbases thereby resulting in a lower within treatment variance.

Another possible reason leading to the higher within treatment variances of the subgrades is that this variance term included both the errors associated with the sand cone density test and the field one point compaction test used to determine maximum density, whereas the subbase testing involved only the sand cone test error. This fact could result in a larger variance term for the subgrades due to more chance for operator error.

It was noted in examining the data that the within treatment variance terms appeared to decrease as the testing program continued. It appeared that as the technicians performed more and more tests they became more polished in their testing techniques, leading to a reduction in the replicate testing variance values. The importance in this observation lies in the fact that as the within treatment variance term decreases the required number of tests to insure a given level of quality also decreases emphasizing the need for training field personnel adequately.

The between treatment variance terms varied considerably from section to section within each project. However, this variation was much more pronounced for the subgrades than for the subbases, indicating that the homogeneity of the subbase material compared to the subgrades led to a condition of more uniform compaction. This factor of homogeneity was also indicated by the fact that the between treatment variances were generally much lower for the subbases than for the subgrades with representative values of 5 and 20, respectively.

Although it was possible to assign part of the variation observed to the variables of field personnel, soil variability, testing error and the construction process itself, the overall variation was considered to be random in nature. Evidence of this was shown by examining the data for projects S-3 and B-1. These projects were chosen as they represent both elements studied, and all of the tests on each project were performed by the same team of testing personnel. The ANOV data showed that both the within treatment variance terms and between treatment variance terms varied widely from section to section. For the subbase material, this indicates that variability exists even when material and operator effects are held more or less constant. For the subgrade, it must be realized that the soil itself is highly variable and can lead to compaction variations regardless of the operators.

The general conclusion concerning construction variability is that the factors discussed, and possibly others not studied, are interrelated and must be analyzed as an overall variability. The variability was in evidence on all six projects investigated indicating that it is of a universal nature.

STATISTICAL IMPLICATIONS

Having gathered data indicating the amount of variability associated with present-day construction practices using the control techniques presently specified, it was then possible to develop a type of statistical approach to quality control. With respect to setting up a statistical control program there are four main questions which must be answered: (a) What size of control section should be adopted? (b) How many tests should be performed in each of these control sections? (c) What average percent compaction should be specified in order to insure a quality product? (d) What range in variability should be allowed in the final product?

Several avenues of approach are available with respect to the problem of determining the size of control section to be used. One technique is to divide the project into sections on the basis of soil type. This has the disadvantage that it is sometimes very difficult to interpret when and where a soil type change occurs and how much relative change can be allowed before it is considered that a new soil type is actually encountered. A second is to establish the control section on the basis of a day's construction of a particular element, say subbase or subgrade. However, if a constant number of tests per day is specified the number of tests per unit of construction will obviously vary depending on the rate of construction. A third is to establish a fixed area or volume of material and to use this as the control section, as was done in this study. The last method allows for equal control of the material from section to section along the project, thereby providing more uniformity.

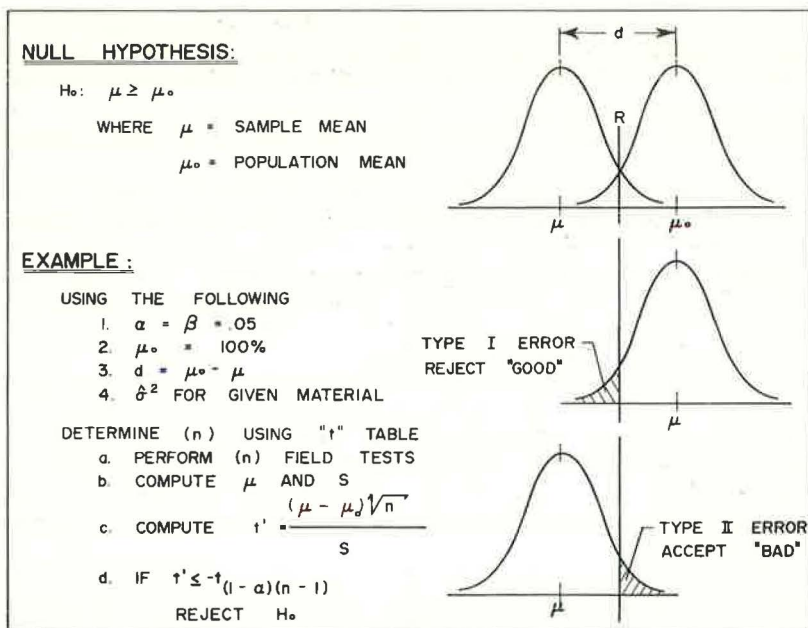


Figure 8. Hypothesis test for means.

Since it is not possible to determine the true mean of percent compaction for a given area (an infinite number of tests would be required) it becomes necessary to choose a random sample from this population and to base the decision of quality of compaction on the statistics obtained from this sample. To accomplish this, a hypothesis testing approach (Fig. 8) was used. The null hypothesis, or the hypothesis which it would be desirable to accept, occurs when μ is equal to or greater than μ_0 , where μ is the average percent compaction for a random sample and μ_0 is the true population mean. If the null hypothesis is accepted, then the true level of compaction for the control section is assumed to have a mean equal to or greater than μ_0 . That is, if n random tests are performed on a sample and the resulting test statistic for this sample exceeds the specified rejection level then the null hypothesis is accepted.

To develop such a hypothesis test, it is first necessary to establish the critical detection level. The detection level is the value which determines the range of acceptable compaction depending on the values assigned to the remaining parameters. Two other parameters which must be established are those of the type I and type II errors which will be allowed (Fig. 8). The type I error represents the probability of rejecting good construction. The type II error represents the probability of accepting poor construction.

It is difficult to establish values for these two error terms in that the contractor obviously would want the type I error to be very low and the highway department would want the type II error to be very low. On this basis, arbitrary values of 0.05 were assigned to each of these, indicating that the probability of making either a type I error or type II error will be 5 percent.

It is also necessary to establish an estimate of variance to determine the number of tests to be performed per control section. This was done by adding the within treatment variance and between treatment variance terms. The variance terms computed for the subgrades are indicative of compaction with a mean of approximately 100 percent. Having calculated or estimated values for d , $\hat{\sigma}^2$, α and β , it is possible to determine the number of tests to be performed in a section.

As an example, assume n tests as determined using these established values were performed in a control section and the mean and sample standard deviation for this

TABLE 2
NUMBER OF TESTS REQUIRED PER CONTROL SECTION

Control Section	Type of Material			
	Subgrade		Subbase	
	$\hat{\sigma}$	n	$\hat{\sigma}$	n
1	4.50	7	2.21	6
2	3.60	5	3.05	8
3	7.09	13	1.54	5
4	2.36	5	2.79	8
5	6.21	11	2.14	5
6	6.51	12	1.38	5
7	5.96	10	2.14	5
8	6.60	12	2.29	6
9	5.64	9	2.26	6
10	5.84	10	1.59	5
Entire project	5.76	9	2.28	6

sample were computed. In order to test the hypothesis of $\mu \geq \mu_0$ a statistical t-test using the t-statistic as the basis for acceptance would be used. This value can be computed for the sample using the following relationship.

$$t = \frac{(\mu - \mu_0) \sqrt{n}}{s} \quad (1)$$

where

- μ = sample mean,
- s = sample standard deviation,
- μ_0 = specified population mean, and
- n = number of tests.

This computed value of t is next compared to a tabular t -value which is dependent on the significance level and the number of tests. Therefore, the null hypothesis is rejected if $t \leq -t_{(1-\alpha)}(n-1)$.

A large variation in the value of n for a given set of parameters from section to section within a project was observed (Table 2). The values of n ranged from approximately 5 to 13 for the subgrade and from 5 to 8 for the subbase. This again indicated that the estimate of variance term was more consistent for the subbases from one section to another than for the subgrades. Taking the entire project as one long control section the values of n were 9 and 6 for the subgrade and subbase respectively. To account for this wide range in n values it was assumed that the most realistic approach would be to use an average value for each subgrade and subbase project (Table 3).

For a detection level of 95 and α and β of 0.05, the average values of n ranged from 12 to 16 for the subgrades and 5 to 7 for the subbases, indicating that a great deal more tests would be required for subgrades than for subbases to insure the same level of compaction.

By changing the detection value, it was possible to change the number of tests required. For detection levels of 96 percent and 93 percent for subbases and subgrades respectively, approximately the same number of tests are required for each element (Table 3). This would be desirable from the standpoint that the inspector would be required to perform the same number of tests for all compaction control sections regardless of the material type.

It is obvious from the preceding that many different values for the number of required tests could be established by varying $\hat{\sigma}^2$, α , β or d and that the actual size of control section is not a definite value. Although most of the control sections used in this project were 2000 ft in length the control sections for one project were in fact 3000 ft long. This variable length did not have an effect on the required number of tests as the variance terms remained approximately constant. This leaves open to conjecture the question of what optimum size control section should be used.

Also, the questions concerning the mean value of compaction to be specified and what variation from this mean is acceptable must be answered. Data from this project did not provide answers to these questions although they

TABLE 3
AVERAGE NUMBER OF TESTS REQUIRED PER PROJECT
($\alpha = \beta = 0.05$)

Subgrades	Subbases
(a) Detection Level: 95 percent	
S-1; $n = 15$	B-1; $n = 7$
S-2; $n = 16$	B-2; $n = 7$
S-3; $n = 12$	B-3; $n = 5$
(b) Detection Level: Subbases, 96 percent; Subgrades, 93 percent	
S-1; $n = 9$	B-1; $n = 9$
S-2; $n = 9$	B-2; $n = 9$
S-3; $n = 7$	B-3; $n = 6$

gave an indication of the magnitude of variation that occurs when the mean compaction level is as indicated by the projects studied during this investigation.

If it could be assumed that the standard deviations found for these data also applied when the means are different, it could then be stated that if it were required that only a few test values could be below 100 percent compaction, it would be necessary to specify a mean equal to 100 percent plus 2 standard deviations. Based on the fact that the data were normally distributed, this would result in only 2.5 percent of the data being below 100 percent compaction if this higher mean were achieved.

CONCLUSIONS

The overall conclusion was that a great deal of compaction variability exists using current control techniques. Unfortunately, present-day control techniques do not allow for variation and, in fact, do not recognize its existence. Before a statistical quality control specification can be developed, decisions must be made concerning several points: (a) optimum size of control section, (b) average compaction level to be achieved, (c) tolerable variation from the average, (d) level of types I and II errors which can be allowed, and (e) number of tests to be performed per control section.

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