A Critical Review of the Density Testing Program in Washington

H. W. HUMPHRES and J. W. JASPER
Respectively, Assistant Director for Construction, and Construction Engineer—Grading, Washington State Department of Highways, Olympia

In recent years, Washington has used "end product" specifications for compaction of embankments and has carried out extensive training programs regarding control of compaction and density testing. To review the adequacy of the testing program and to determine the effectiveness of the training programs, a study of density requirements and results was initiated in 1963 and continued in 1964, requiring the review of over 23,000 field density tests.

A computer program based on statistical review of data was utilized to compute and plot curves which assisted in studying and evaluating the testing results for each project and district. A uniformity index was developed and used as a guide for comparing test results and determining what progress had been obtained in the testing program.

The paper describes the improvement throughout the state in density testing and control and summarizes the advantages of the bias testing program over other prepared procedures.

•EVER since the concept was first developed that the strength and stability of earth embankments could be improved by controlling densification through compaction and moisture control, the State of Washington has attempted to utilize this knowledge in highway construction. Early efforts were in the direction of developing construction methods and procedures that would yield adequate results as determined by controlled experiments and tests. This approach proved quite satisfactory until road-building equipment and techniques underwent radical change during and after World War II.

It was soon recognized that specifications based on methods and procedures could not take advantage of economies resulting from the development of new equipment and techniques. In 1952, the Department of Highways started a series of research projects directed at developing compaction control tests and equipment which would permit control of compaction in the field on an "end product" basis. This led to the development of the Washington Densometer, which is a rapid and accurate water-ballon test for determining densities in the field (1), and companion rapid methods for determining the maximum density required, such as a refined one-point Proctor method, and the Washington Method for Determination of Maximum Density for Granular Materials (2).

In 1957, Washington adopted end product specifications for embankments and in 1963 extended this concept to granular surfacing materials. Simply stated, embankments must be built in layers and in accordance with one of three specification methods designated as Method A, Method B, or Method C. All three methods require lift construction, uniform compaction throughout the embankment width and depth, control of moisture content to not more than 3 percent above optimum, and the addition of moisture should it be necessary for proper compaction. The difference between the three methods lies in the thickness of lifts specified, the degree and control of compaction required, and the degree of control of moisture below optimum. The use of suitable

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compaction units is required for Methods B and C, although routing of hauling units may be used to obtain partial compaction.

Method A normally is not specified for state highway work, but may be applied on county or city projects or on certain secondary state highway projects. Embankment lifts up to 2 ft in thickness may be placed, and compaction is achieved by routing the hauling equipment over the entire width of the embankment. It must be determined by inspection that the routing schedule is such that all parts of the fill receive approximately the same amount of compactive effort, including the outer edges of the fill. Drying of soil or addition of moisture may be required if necessary.

Method B is used on all state highway projects, except where other methods are specified. This method requires that the embankment be constructed in lifts not exceeding 8 in. in loose thickness, but lifts in the upper 2 ft should not exceed 4 in. in loose thickness. Ninety percent of maximum density, as determined by ASTM D 698 for fine soils or the Washington Test for granular soils, is required throughout the embankment; however, 95 percent of maximum density is required in the upper 2 ft. Control density tests must be performed to verify compliance with specifications. The contractor is required to dry soil or add moisture as necessary to insure proper, uniform compaction. The selection of compaction equipment or methods is the responsibility of the contractor; however, the use of any method or equipment which does not achieve the required density within a reasonable time may be ordered discontinued.

Method C is required when it is considered essential to the structural quality of the embankment that the entire fill be compacted to a high density, and where the expansive characteristics of the soil dictate a need for a minimum amount of moisture at the time of placement to avoid damaging differential swell after construction. This method differs from Method B in that the entire embankment must be compacted to 95 percent of maximum density, and a limit is specified for minimum moisture content in addition to the maximum. In all other respects the 2 methods are the same, and each requires a high standard of compaction control.

TRAINING PROGRAMS

Prior to 1957, the number of projects requiring Method C compaction and density control tests was relatively small; however, a limited number of personnel had been trained and were utilizing the Washington Densometer on construction projects. After 1957, with the adoption of end product specifications for all embankment construction, it became necessary to train more personnel for inspection and testing of embankment compaction. This was accomplished by placing instructions in the Construction Manual and in yearly training sessions conducted by the headquarters Construction and Materials Divisions. Because of the large increase in the number and size of contracts being constructed, and the increase in the rate of embankment construction brought about by newer equipment and critical scheduling, it soon became necessary to extend the training program to reach even more employees. The yearly construction seminars emphasized the necessity of obtaining uniformity in inspection and compaction of embankments on all projects and explained current problem areas.

In addition, all districts were required to assign an experienced person on a permanent basis as a progress sampler to provide independent checks on the quality of all materials going into the work, and to further provide on-the-job assistance and guidance to field inspectors on proper sampling and testing techniques. The progress sampler works with field personnel and has been of considerable value where circumstances require that inspectors with minimum experience and training must be used.

Another program was initiated early in 1964 wherein a team of 7 experienced employees under the supervision of the construction and materials engineers conducted an inspector training program throughout the state, covering all phases of field inspection. This program involved 5 days of instructions, with one full day devoted to the duties of an inspector on a grading project. The other 4 days included lectures and demonstrations of inspection and sampling procedures for various contract items requiring control sampling, testing and inspection. One session was held in each district, with two sessions being given in the two larger districts. Over 400 state employees attended

WASHINGTON STATE HIGHWAY COMMISSION
DEPARTMENT OF HIGHWAYS
DAILY COMPACTION TEST REPORT

Cont. No. 7622
S.SH No. 7C
Project Name Delight to Watson Road
Specified Method of Compaction (circle one) A (B) C

Date 11-25-64
Contractor N. Degerstrom
Res. Engr. D. Walker
Inspector J. Odette

Test No.	Station and Ref. to C/L	Ref. to Grade	Type of Material and Use	Moisture Percent			Percent Passing #4 Sieve	Dry Density pcf					Remarks*
				Opt.	Test	Corr.		Max.	Corr.	Std. No.	Test	% Max.	
33	88+60	-5	Tan Silt	18.9	17.6	—	100	100.6	—	60012	97.0	96.4	
	40' Rt		Emb										
34	99+50	-7	Tan Sandy	16.0	10.1	—	100	105.2	—	60013	101.0	96.0	Rd. Appr.
	100' Lt		Silt-Emb										

Optimum Moisture — Moisture content of #4 minus from Proctor curve.
Corrected Moisture — Optimum moisture corrected for oversize = Optimum Moisture Content × Percent Passing #4 Sieve.
Maximum Dry Density — Density from Proctor curve or Maximum Density for Granular Materials Curve.
Corrected Density — Proctor Maximum Dry Density corrected for oversize.
Standard Number — Laboratory or identifying number of Density Standard used, i.e., Proctor No. or Maximum Density Curve No.
Test — Moisture content or Density of field sample tested.

SUMMARY OF COMPACTION QUANTITIES

Material	Lift Thickness	Compaction Equipment Used (Type and Number of Units)	Number of Coverages Per Lift	Est. Emb. Quant. (or Backfill) Placed (cu. yd.)	Accum. Total Emb. Quant.	Number of Density Tests Taken
Tan Silt	6"	2 Sheepfoot rollers	2	5000	67,000	2
& Sandy Silt						

* If percent of maximum is below specification requirements, note corrective action taken and reference to check test.

Note: If material is gravel and is being placed as any portion of surfacing, indicate the type of surfacing in parenthesis.

Remarks:

N. G.

DISTRIBUTION:
Hdqs. Const. Engr.
District Engr.
Resident Engr.
Dist. Soils Engr.

H. F. 26.73—OS—(Rev. 1-31-64)

Figure 1. Sample of test report.

these sessions. In addition, one session was conducted in Eastern Washington and one in Western Washington for the benefit of the county and city employees. Over 100 county and city employees attended these two sessions.

During the winter of 1965-66, a similar but briefer program was conducted in each district. A list of the items to be covered was sent out by headquarters to the district engineers and the training program was conducted by construction and materials personnel from each district. During these training sessions, inspectors were instructed in the background philosophy of compaction control, the purpose and importance of proper and adequate testing, and the need for uniform inspection and specification enforcement, as well as being given technical training in the control test procedures themselves.

To make a record of tests performed, and to keep the project engineer and others informed as to compaction results, tests and other pertinent data were reported on the Daily Compaction Test Report (Fig. 1). This report provided a basis for evaluating the efficiency of the testing program and revealed areas of training that needed emphasis. For example, during the early stages of its use, retesting of failed areas after correction was seldom being performed. As a result, instructions have been refined and the situation has improved.

Although all concerned have been pleased with the improvement in quality of inspection and control resulting from the intensified training, a need has been felt for some means of measuring the degree of improvement realized. Concepts concerning the adequacy of biased sampling and testing have been set forth by proponents of the statistical approach to process control and product acceptance. To furnish answers to these questions, a study of density requirements and results was initiated in 1963 and continued in 1964, in which all density tests taken on all projects completed during these two years were reviewed. For the 2-yr period 22,300 tests were reported, of which over 7,600 covered Method B compaction.

To clarify factors influencing the data used in these studies, the following inspection criteria are descriptive of the controlling conditions expected.

1. At least one density test should be made for each 2500 cubic yards of embankment placed. Where variable soils occur, more frequent testing should be done. A higher frequency may be necessary in the early stages of construction.
2. Testing should be performed primarily in those areas that appear questionable, with periodic tests being performed in obviously well-compacted areas for confirmation.
3. Maintain a record of compactive effort being applied so that a suitable procedure for compaction can be developed early in the contract.
4. Obtain a standard density curve (ASTM D 698) for each major soil type on the project. Keep a jar sample for quick reference in the field to insure applying the proper standard to the soil being tested.
5. Where soils are being mixed, or where a new soil type is encountered, perform ASTM D 698 on the soil.
6. Report all tests.
7. When test indicates failure to meet specifications, prescribe corrective action and, after the contractor has corrected the area, retest. (Exception: if the original test was within 1 percent of required minimum, retest after correction is not required.)

From the information listed in the compaction reports, a computer program was established which gave the standard deviation, computation and plots of test results for each contract, and summarized these results for each district and for the entire state. Only the results for Method B compaction are included in this report. Figure 2 shows an example of the computer listing, summarizing the compaction results for District 1 during 1963. The left column shows the percent of maximum density and the right column shows the frequency of tests for the corresponding density; the adjacent column lists the percent of the total tests for each corresponding frequency. The listings also show the total number of tests, the mean density and standard deviation. The computer program also gave for each project the cumulative percentage of tests for the respective density, and a plot of the ogive curve for the accumulative percentages (Fig. 2-A). For density tests falling below specifications and when the area received additional compaction and was satisfactorily retested, only the results of the retests

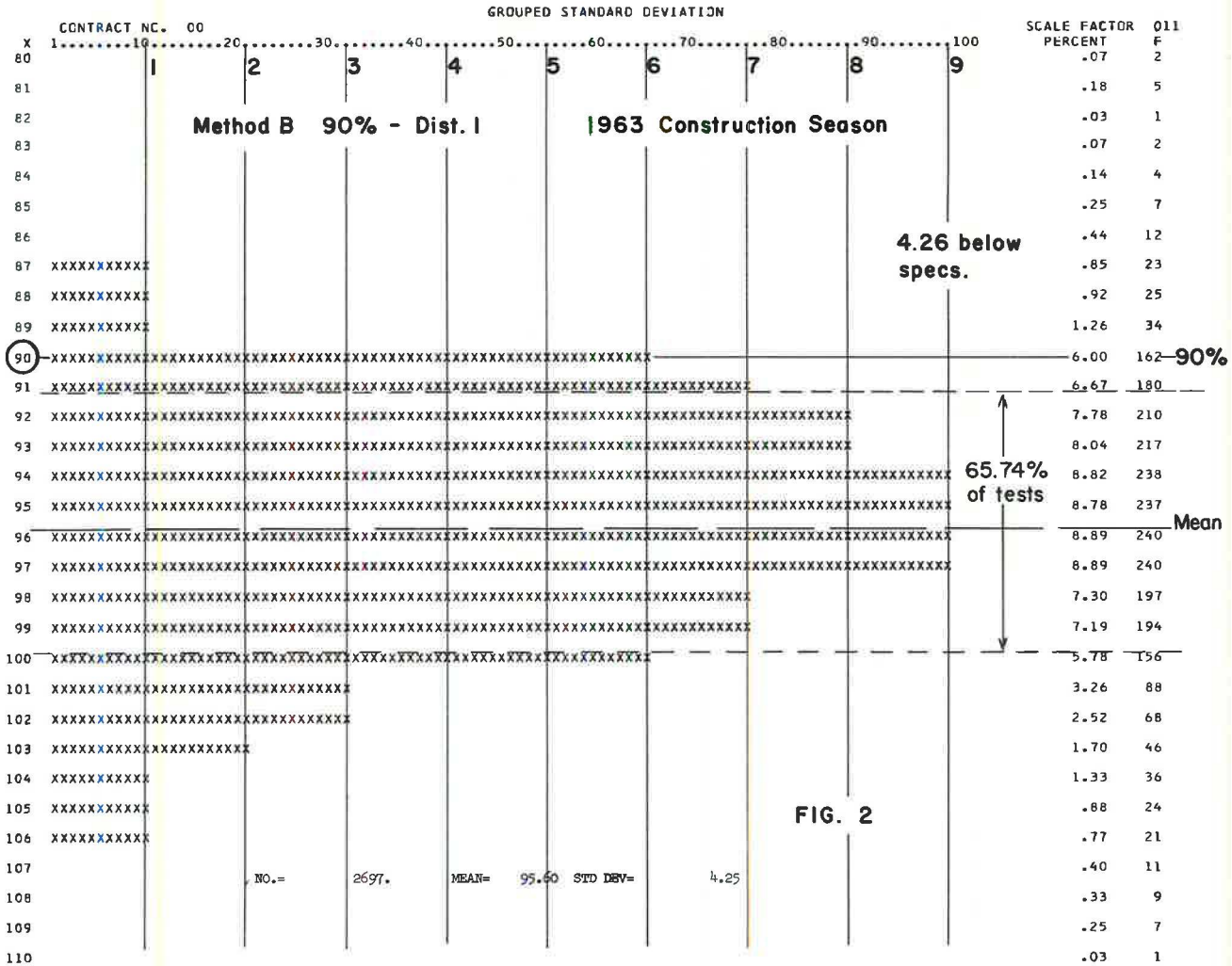

Figure 2. Results of computer program for District 1.

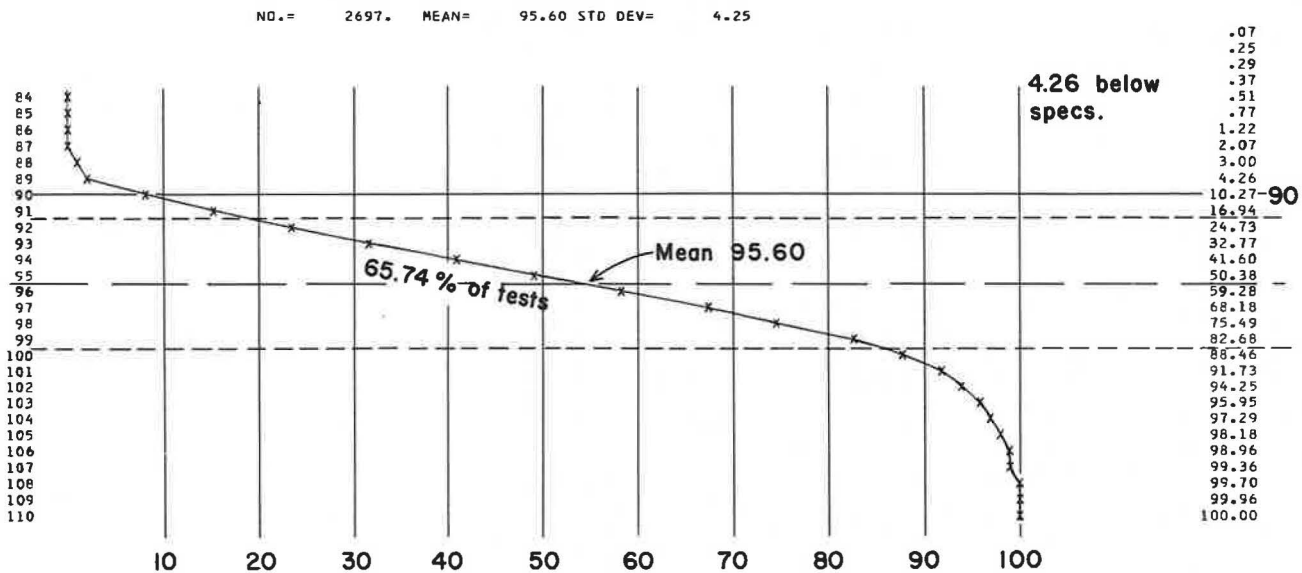

Figure 2-A. Cumulative percentage of tests for each density.

were included in the input data for the computer run. Therefore, the failing tests shown below 90 percent in Figure 2 are those tests for which corrective action was normally indicated, but due to conditions in the field retests were not performed, or if performed were not recorded as a retest.

The number of tests below specification requirements was very small, and on a statewide basis amounted to only 4.0 percent of the total tests for Method B compaction in 1963 and 2.3 percent in 1964. The number of retests performed was approximately 5 percent of the total tests taken. Figure 2 shows 4.26 percent of the tests falling below specifications. In most cases, this is representative of the condition of the embankment at the time tests were taken. Most reports indicate that corrective measures subsequently were employed without retesting, as 65.74 percent of the tests fell within the limits of one standard deviation. This indicates the uniformity of compaction and test procedures. District 1 had the lowest percentage of tests within this range. The sharp rise between 89 percent and 90 percent compaction indicates that the inspectors as a whole were maintaining a rigid control of the work. It appears that tests were taken often enough so that the inspector knew when the specifications were being met. The range of the greatest number of tests (approximately 84 percent) lies between 90 and 100 percent compaction.

About 10 percent of the tests lie above 100 percent compaction. It is possible and feasible to get a density higher than 100 percent by applying more compactive effort at a lower moisture content. Within haul roads and turning areas, compaction is likely to exceed the average density for the embankment and may very well exceed 105 percent in some instances. Out of 39 projects tabulated, 10 projects reported tests higher than 105 percent maximum density, whereas 10 projects did not have any tests over 100 percent. Over half the inspectors on the 39 projects reported densities up to 105 percent. We consider that densities up to 105 percent are valid. They represent 8.5 percent of all tests taken for the 39 projects studied. About 1.5 percent of the tests taken on these projects show densities higher than 105 percent. Although some of these may be valid, it is more likely these are the result of an inspector's error developing from misapplication of the standard density curve.

Table 1 was prepared from the computer listings and gives (for Method B compaction) the comparison of test results for 1963 and 1964. A study of the standard deviation curves and Table 1 shows that with a required density of 90 percent, the curve distribution is on the higher side. Discarding the failing tests and utilization of the retests may account for a portion of this; however, subtracting one standard deviation from the

TABLE 1

COMPARISON OF DENSITY TEST RESULTS FOR 1963 AND 1964
(Method B Compaction)

District	Mean Density		Std. Deviation		Tests Within Std. Dev. (%)		Total Number of Tests	
	1963	1964	1963	1964	1963	1964	1963	1964
State	95.75	95.77	4.34	3.27	71.04	68.44	3798	3881
1	95.60	95.68	4.25	4.18	65.74	67.57	2697	2692
2	97.93	99.16	5.90	5.45	65.83	67.80	125	59
3	95.71	97.25	4.14	4.23	73.90	66.02	249	412
4	96.13	94.67	4.21	3.53	68.44	63.22	215	87
5	96.13	93.92	4.50	4.02	74.73	71.80	182	39
6	95.75	95.11	4.34	3.24	69.40	73.81	330	592

mean density still gives a figure above the specified density in all cases except District 5. It was reported that during 1964, District 5 had only four contracts requiring a minor amount of earthwork with Method B compaction. Most of the earthwork in this District is solid rock for which density tests are not taken. On the four projects involving earth embankments, only 39 density tests were taken of which four failed and corrective action was taken without retesting.

From our own experience and observation and from HRB Bulletin 270, we know that the number of roller passes required to increase the density of the soil from 90 percent to 95 percent is small compared to the number of passes required to increase the density from 95 percent to 100 percent. Normally, Method B compaction test results are well above the 90 percent minimum requirement; however, we are concerned with the high mean densities, especially where the high mean is caused by extremely high densities brought about by excessive rolling. This is an unnecessary expense which is ultimately reflected in high bid prices. In Washington, embankment compaction is paid for by the cubic yard.

A great spread on density results may be caused by many factors, such as existing materials, weather conditions, moisture, compaction effort by the contractor, additional compaction from hauling equipment and misapplication of density standards. Our goal is to achieve uniformity in density testing and enforcement of requirements which should result in reducing extremely low and extremely high density tests. We further

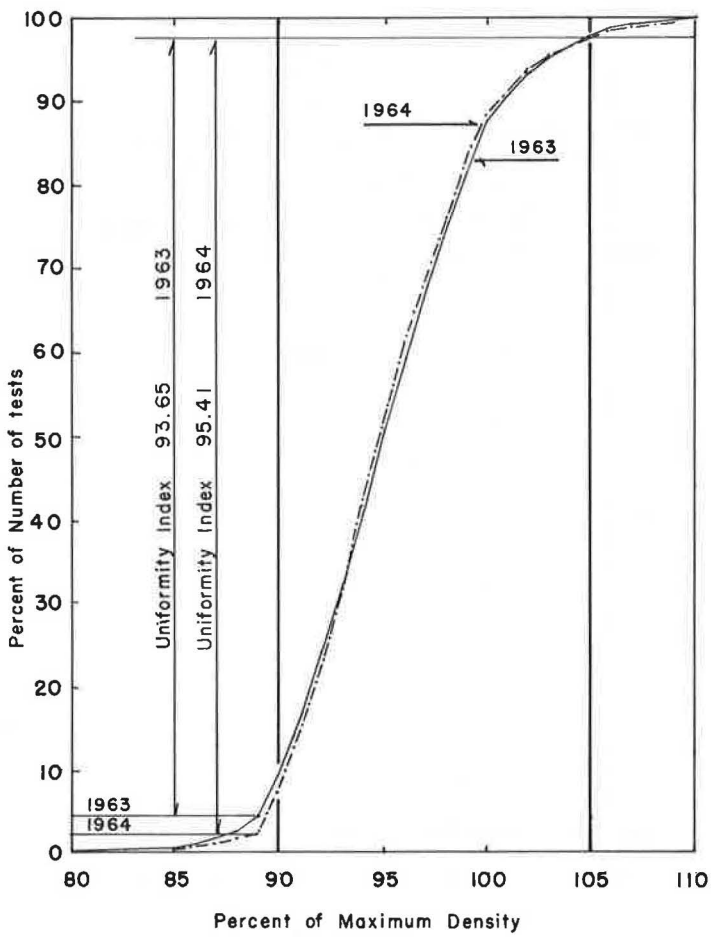

Figure 3. Uniformity index for statewide density testing for 1963 and 1964.

assume that improvement would be shown by a decrease in the mean density to a few percent above minimum requirements, a decrease in the standard deviation, and an increase in the percent of tests within one standard deviation.

It is possible to use each of these factors for comparing improvement on a project or district basis; however, since each factor is influenced by the others, overall comparisons are more difficult.

For example, on a statewide basis in 1964 the mean density stayed about the same, the standard deviation decreased, but so did the percent of tests within the standard deviation (Table 1). From our review, we know that overall improvement did occur, but the data do not clearly indicate this. In District 2 for 1964, the standard deviation decreased, but the percent within the standard deviation increased as did the mean density from the high mean of 1963. If the mean density had not increased, we could definitely say that District 2 improved during 1964. Here again, there are too many variables to contend with. After study, it became apparent some factor other than those indicated would be needed for overall comparison.

On the basis that improvement should be shown by more adequate retesting (which would result in less failing tests being used in the final accumulated data) and fewer densities above 105 percent (which would indicate less misapplication of density standards and less wasted compactive effort), it was concluded that uniformity of test results would be an appropriate indicator for comparison.

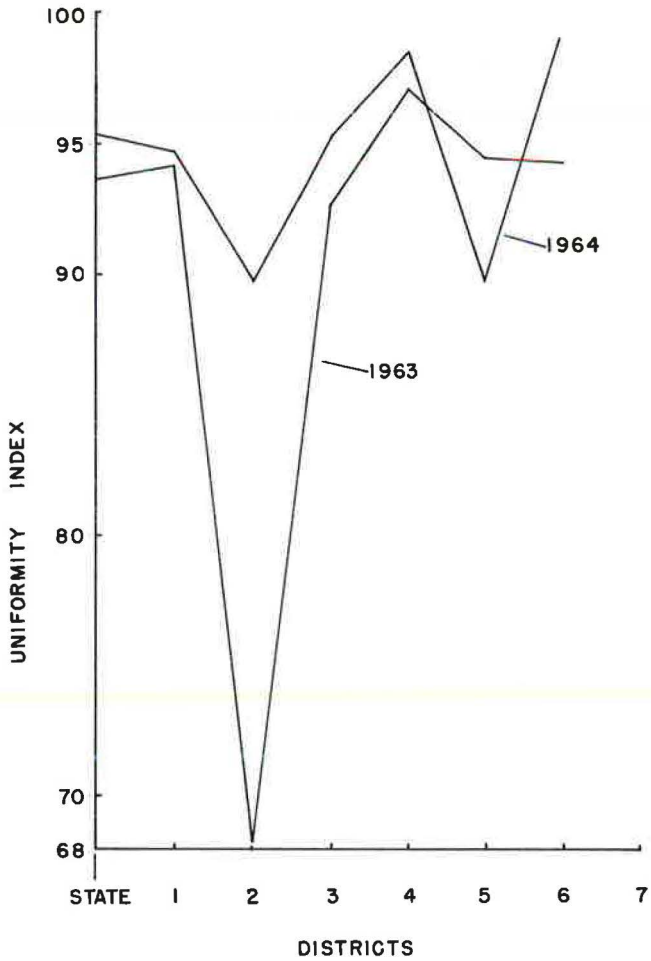

Figure 4. Plot of the uniformity index for all districts for 1963 and 1964.

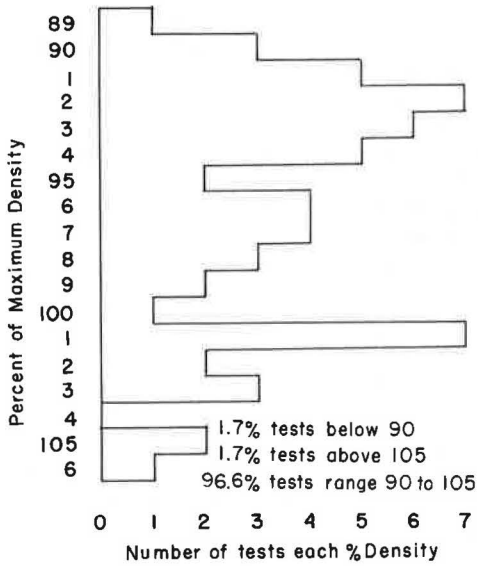

Figure 5. Apparent misapplication of maximum density curves.

From the computer results, the ogive curves were studied and it was noted that the percent of tests falling within specified limits were readily available and could be used for comparison purposes. From the test data for Method B compaction, it was determined that the lower limit for comparison purposes should be the specified requirement of 90 percent density and the upper limit of 105 percent density. A new term called "uniformity index" was coined which, for Method B compaction, is the percent of the number of tests falling within densities of 90 percent to 105 percent. The difference in the uniformity index from 1963 to 1964 (Fig. 3) represents an increase of 1.76 percent of the tests falling within the selected limits. This indicates a very definite improvement.

The uniformity index of each district and statewide for 1963 and 1964 is shown in Figure 4. Improvement is noted in all districts except District 5. As previously noted (Table 1), District 5 had a small number of tests in 1964, with a high percent of failing tests on a minor quantity of embankment. Figure 4 shows where improvement has been the greatest and where additional training is needed.

District 2 shows radical improvement from 1963 to 1964. A review of individual test reports for District 2 shows that the low uniformity index for 1963 is the result of a large number of low tests and extremely high tests. This also accounts for their high mean density and standard deviation given in Table 1 for 1963. The greater emphasis on the use of proper standards is largely responsible for the improvement.

As previously mentioned, the instructions require that a sample of the soil be retained in a sealed jar and identified with the corresponding maximum density curve (ASTM D 698) for each type of soil on the project. This is necessary in order that the proper maximum density curve be used with the corresponding field density test to calculate the percent of maximum density. If the wrong standard curve is used for a given field density test, either high or low results may be indicated and the test has no real value. Present instructions require that the standard density curve be prepared either by the district or the headquarters Materials Laboratory on preliminary samples, and be identified for each project with a standard curve number. Supplemental tests are made in the field as necessary. In some cases where visual identification is difficult, a one-point Proctor test is run for each density test. Based on our review, it appears that misapplication of standard curves is one of the major problems in the density testing program; additional emphasis will be directed toward improving this condition in the future. Figure 5 shows an apparent misapplication of standard curves where two high peaks developed within a reasonable range of densities. Between 89 percent and 100 percent density, a peak occurs at 92 percent; between 100 percent and 196 percent density, a peak occurs at 101 percent. The double peak indicates that the inspector probably used the wrong standard density curve on some tests. There are other factors which could have caused this, such as variability in moisture and compactive effort; however, they would not tend to create two distinct peaks.

SUMMARY

Although studies presented here cover only a 2-yr period, which is admittedly not long enough to form definite conclusions, it is considered that the results warrant

extension of the study program on a continuing basis. Consequently, the Office for Construction plans to continue making similar annual studies and to use the uniformity index as a guide to planning inspector training programs and evaluating the effectiveness of the density control program.

The emphasis being placed on good density control procedures and the realization on the part of inspectors that their work is being used, reviewed, and evaluated has created a pride in work and a recognition of importance that did not always exist before. The response to the training program has indicated the need to utilize the intelligence and individual abilities of inspectors and to foster this utilization by delegating responsibility as well as accountability. Without exception, where inspectors are not cognizant of the importance of their work, quality is low.

We have tentatively concluded that the present density control program is adequate and offers several advantages over other prepared procedures for the following reasons:

1. The frequency of testing appears adequate to give full assurance that specifications are being complied with when applied in accordance with present instructions; i.e., testing is concentrated on suspect areas as are revealed by reaction to hauling units and compactors.
2. The procedure results in early detection of non-specification work which permits correction immediately, thus avoiding costly waste and delays.
3. The amount of testing required and the speed with which individual tests can be made (20-30 min) causes little or no delay to production, and the contractor can proceed with reasonable confidence that he has either met specifications or has corrected deficient areas as they occur, thus avoiding the possibility of major rejections or reconstruction.
4. Early in the contract the testing program is directed toward assisting the contractor in establishing a compaction procedure which will assure compliance yet not result in costly over-compaction. This substantially increases the efficiency of the inspectors as they can concentrate on suspect areas.
5. Utilization of the progress sampler and crosscheck and review of results gives further assurance of adequate inspection.

REFERENCES

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2. Humphres, H. W. A Method for Controlling Compaction of Granular Materials. HRB Bull. 159, 1957, pp. 41-57.