Current Specifications, Field Practices and Problems in Compaction for Highway Purposes

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This paper attempts to summarize the current status of highway specifications and field practices for compaction of embankments, subgrades and granular bases. The information has been obtained from the published standard specifications of the 50 states, and from an extensive interview program with state highway engineers. Construction specifications and procedures for embankments, subgrades and granular bases are summarized and followed by discussions of the problems related to the practical application of the specifications of field construction. Quality control procedures and related problems also are discussed.

•FROM July 1964 to August 1966, North Carolina State University, under the sponsorship of the U. S. Bureau of Public Roads, conducted a comprehensive review (1) of the current state of knowledge in regard to the compaction of soil and rock materials for highway purposes. As one part of this study, a compilation and evaluation of current state highway specifications and field practices for earthwork construction was undertaken. This paper presents a summary of the findings.

Primary information regarding specifications was obtained from the most recent editions of each state's standard highway specifications and special provisions for earthwork construction. To supplement this published information, a comprehensive program of personal interviews was conducted. State highway department offices were visited in 22 states, selected to provide a reasonable cross section of geographic, climatic and soil conditions. In each state, two to six individuals were interviewed, including materials engineers, construction engineers, field and laboratory soils engineers and geologists. Interviewees were questioned regarding local compaction problems and techniques for overcoming them, interpretation of specifications in practice, compaction control procedures and problems, and suggestions for improvements of specifications and practices. When time permitted, visits to construction sites or problem areas were arranged. The interviews provided considerable insight into the practical aspects of earthwork construction and the problems that are of major concern to highway engineers.

Several limitations of the interview program should be recognized. No interviews were conducted in approximately half of the states. In the states that were visited, the interview program was limited to engineers in the central office because of limitations in both time and funds. The interviewees frequently commented on the variation in practices and attitudes from one district to another within their state; thus, the opinions expressed in the central office may not be representative of the attitudes at the district level. This was generally attributed to the autonomy of the district engineers. In addition, it was apparent that some individuals discussed their problems, practices, and the enforcement of their specifications more frankly than others. Nevertheless, certain general impressions of universal problems and practices became apparent through the interview program.

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The discussion of current specifications and practices is separated into two main sections. First, field procedures and compaction requirements are presented. For each pavement component, a summary is given of the information obtained from the published specifications. The summary is followed by a discussion of the findings of the field interview program pertaining to the particular aspect of the specifications. The second major section discusses current quality control procedures. The paper concludes with a summary of major field problems.

CURRENT SPECIFICATIONS AND PRACTICES

Compaction specifications may indicate the procedure by which the compaction is to be accomplished, the required quality of the compacted materials, or some combination of procedure and required results. The specified procedure may include moisture control, lift thickness, type and size of compaction equipment, and the number of coverages of the equipment. The quality of the compacted material generally is specified in terms of dry density, which usually is expressed as a percentage of the maximum dry density achieved in a specified laboratory compaction test.

Specifications commonly are referred to as "procedural" or "end-result" specifications, depending on whether or not density requirements are specified. However, these terms may be somewhat misleading. End-result specifications usually include some procedural requirements. Lift thickness and moisture control commonly are included, and equipment type and size are sometimes indicated. However, the equipment requirements may be quite general, and the number of coverages, or required compactive effort, is omitted. On the other hand, the procedural specifications will include the number of coverages or a relatively simple visual acceptance criterion, such as the walk-out of a sheepsfoot roller.

The addition of a minimum-density requirement to a detailed procedural specification generally is considered undesirable because of the potential contractual problems. Legal problems may result if the contractor adheres closely to a detailed procedure and yet is unable to achieve the required density. However, several states are successfully combining a minimum procedural requirement with a density requirement. The concept of minimum compactive effort is introduced to insure uniformity of compaction and to reduce the number of density tests required.

A comparison of current specifications with those compiled in 1960 indicates a general trend toward greater reliance on the end-result or density requirement. Current usage for each component of the road section will be discussed in subsequent sections on embankments, subgrades, and granular bases.

Equipment

Approximately three-fourths of the states include some minimum equipment standards in their specifications. Frequently standards may be given for only one type of compaction equipment, usually smooth-wheeled or pneumatic-tired rollers, or for construction of one component of the pavement section, most commonly the base course. In addition, most state specifications include a provision that equipment must be satisfactory to or approved by the engineer. In practice, these minimum equipment standards appear to be of little practical concern to highway engineers. Most contractors are using adequate equipment with regard to both size and type suitable for each soil type encountered. Consequently, inspectors rarely are called upon to exercise their authority regarding approval of compaction equipment.

In practice, a wide variety of types of field compaction equipment is being used including smooth-wheeled, pneumatic-tired and sheepsfoot rollers, vibratory compactors, and specialized equipment that utilize combinations of compactive actions, such as the vibratory sheepsfoot roller. For cohesive soils, sheepsfoot and pneumatic-tired rollers still are most commonly used. However, for granular soils, there is an increasing utilization of vibratory compactors. This equipment apparently is providing efficient and satisfactory compaction of such materials with a minimum of problems. Advantages attributed to vibratory compaction of granular materials include the effective compaction of thicker lifts than is possible with conventional rollers and the reduction of degradation effects in crushed-limestone base course materials. However, the magnitudes of these effects remain subject to debate.

Although many states require that equipment specifically designed for compaction be at each compaction job site, in practice a considerable amount of compaction still is accomplished by hauling equipment. It is recognized that hauling operations can produce significant densification of earth fills. However, compaction solely by hauling operations is considered undesirable because uniform coverage and, as a consequence, uniform density generally are not achieved. To overcome this difficulty, some states permit compaction by hauling equipment together with supplementary rolling by compaction equipment to improve the uniformity. It should be noted that the compaction equipment must produce higher stresses in the fill than the hauling equipment if greater uniformity is to be obtained.

The heavy loads imposed by hauling equipment create a major problem in some embankment construction. In many states examples were cited of heavy hauling or paving equipment causing stability failures in compacted embankment and subgrade materials that had already satisfied compaction specifications. Almost all of the cited problems occurred in silty materials that are extremely sensitive to moisture and density conditions. The wheel loads from this equipment may produce higher stresses in the compacted soils than the stresses to be anticipated from traffic loads after the road is in service. It can be anticipated that these problem with heavy equipment will become more common in the future unless corrective measures are employed.

Embankments and Subgrades

The current trend for embankment and subgrade specifications is to minimize the procedural requirements and to place greater reliance on density requirements. For subgrades, only 4 states do not have density requirements. All four, Maryland and 3 New England states, merely specify compaction with a 10-ton roller. Several other states specify minimum equipment together with density requirements. Three other states, for some types of work, specify minimum equipment without density requirements. However, the vast majority of states rely almost entirely on density requirements for subgrades.

For embankments, all states have density control specifications. However, approximately 25 percent of the states have alternate specifications for compaction without density control that are used for certain types of construction. In these cases, the specified procedure may be the minimum number of passes of a specific piece of equipment or the use of suitable equipment for compaction to the visual satisfaction of the inspector.

In practice this kind of specification generally means using a sheepsfoot roller until it walks out or a pneumatic roller until there is no further observable densification of the soil. In some instances compaction by hauling equipment, usually followed by proof rolling, is permitted.

For embankment construction, the maximum lift thickness is specified, usually expressed in terms of the loose or uncompacted material. Almost 60 percent of the states specify the maximum uncompacted thickness as 8 in. and an additional 15 percent specify 6 or 9 in. Some allow 12-in. lifts in all materials, while others increase the allowable thickness to 12 in. for granular soils or rocks. Occasionally lift thicknesses greater than 12 in. are permitted when rock is encountered. In regions of high rock content, lift thicknesses may be increased to permit burial of large boulders near the bottom of embankments. Four states specify lift thickness requirements in terms of the compacted thickness, specifying either 6 or 8 in. as the compacted thickness.

All but 10 states specify the minimum depth of subgrade compaction. More than 60 percent of the states specify compaction to a minimum depth of 6 in. The remaining states specify depths of compaction varying from 4 to 12 in. A few states require subgrade compaction to a depth of 18 in. or greater when rock is encountered.

Lift thickness was not an area of major concern to most of the highway engineers who were interviewed.

Density Requirements for Embankments and Subgrades—The density requirements for embankments and subgrades are based predominantly on the AASHO T-99 Compaction Test or a similar test with an approximately equivalent compactive effort. For both subgrades and embankments, the most common requirement, used by almost half of the states, is 95 percent of the maximum dry density obtained in the T-99 test. For subgrades approximately 10 states use 100 percent of T-99, and only 2 use 90 percent. On the other hand, for embankments only 2 states require 100 percent and 11 require 90 percent of T-99. In all instances, the subgrade density requirements are equal to or greater than those required in embankments. In approximately 20 percent of the states the embankment requirements in the upper 1 to 6 ft of the embankment, depending on the state, are equivalent to those of the subgrade, and are less for the remaining depth of the embankment. Less than 5 states use the AASHO T-180 test for embankments and subgrades. In addition, California uses a special impact test that uses a compactive effort intermediate between the AASHO T-99 and T-180 efforts, which produces densities approximating those from the T-180 test. Several states base density requirements on a relative density concept in which the required density is specified in relationship to a maximum and a minimum density for the material. One example of this technique is the Texas compaction ratio method.

Approximately 10 states vary density requirements with soil type, magnitude of maximum dry density, and height of fill. When the requirements vary with maximum dry density, the percent of maximum density required decreases as the magnitude of the maximum dry density increases. Because the maximum dry densities usually are higher for granular soils than for cohesive soils, the required percent of maximum density usually is lower in granular soils than in cohesive soils. One of the states that varies density requirements with soil type also reduces the density requirements for granular soils. However, the other states that vary density requirements with soil type increase the percent of dry density required for granular soils. Inconsistencies among adjacent states sometimes develop. For example, both Illinois and Indiana generally require 95 percent of AASHO T-99; however, for granular soils Illinois increases its requirements to 100 percent and Indiana reduces its requirements to 90 percent. In almost every case, the variations in density requirements have resulted from judgment and experiences with local construction practices rather than from theoretical considerations. For instance, in Ohio and Indiana, the higher density requirements for cohesive soils were attributed to experiences that indicated more stability problems were encountered with cohesive soils. In Nebraska, higher density levels are being used with granular materials because they can be easily attained, whereas the same density levels cannot be achieved in cohesive soils without extremely close moisture control and much additional cost. In addition, it was felt that the cohesive soils would not maintain the high density in service. In Colorado, lower density levels are used for expansive clays.

In the interviews, most highway engineers appeared satisfied with their current density requirements and made almost no mention of a need for higher density. In fact, density requirements in Georgia have actually been reduced recently and to date satisfactory results are reported. In other states where silty soils are prevalent the feeling was expressed that higher density, and in some instances current density levels, will not be maintained in service even if they can be achieved during compaction. Experiences were cited, for example, in the loesses of Iowa and Nebraska, for which the compacted density was reported to have been reduced after exposure to environmental conditions and traffic. However, the reports generally involve observations of stability loss rather than density loss. No evidence was reported to indicate clearly whether the stability loss was caused by a loss of density or a loss of strength caused by increasing degree of saturation at constant or even increasing density. The latter explanation is strengthened by reports in the same states of instability of silty embankments immediately after moisture-density requirements have been satisfied.

As noted earlier several states require higher densities, which are usually equal to their subgrade requirements, in the upper 1 to 6 ft of an embankment. This apparently is done because the stresses produced by wheel loads are greater in the upper regions of the embankment. In some states the feeling was expressed that the density achieved in the upper parts of the embankment can be economically produced uniformly throughout the entire embankment. Because the contractor will furnish equipment that can provide the higher density levels with a reasonable number of coverages, it is reasoned that the entire embankment can easily be compacted to the same density level. Consequently, except for very high fills there appears to be very little concern for variations in density requirements as a function of position within an embankment.

In a few states, the embankment density requirements are increased throughout the entire embankment when the embankment height exceeds some predetermined elevation or when the embankment is subject to flooding. In the first case, the increased densities are used to offset the higher overburden pressures. In the second case, the higher densities are required to offset the loss in strength that will accompany saturation caused by flooding.

Although density control procedures will be discussed more fully in later sections, it should be noted that some of the lack of concern for more exact density requirements is related to the reliability of the percent compaction determinations. These computations can be no more accurate than the field density tests and the laboratory compaction test on which they are based. Problems related to testing procedures are discussed in the second part of this paper.

Moisture Control for Embankments and Subgrades—A statement regarding moisture requirements is included in the specifications for embankments in all but 2 states and for subgrade in all but 9. However, in approximately 60 percent of the states the moisture conditions for both embankment and subgrades are specified in a qualitative manner which leaves the interpretation largely to the judgment of the inspector. Qualitative statements include "to the satisfaction of the engineer," "as required by the engineer," and "as required for compaction." Quantitative statements for moisture limits relative to the optimum moisture content for the soil are specified by approximately 40 percent of the states for embankments and approximately 25 percent for subgrades. Some of these quantitative requirements merely specify "at optimum moisture content" or "as near as possible to optimum moisture content." In practice, these statements become qualitative by interpretation of the inspector. However, the majority of the states using quantitative moisture requirements specify minimum and/or maximum moisture conditions. Either the maximum or the minimum limit may be omitted in a number of states because of the predominant climatic conditions. For example, states in arid regions frequently specify lower moisture limits but not upper limits. In wet regions, the converse may be true. Occasionally moisture control requirements are waived for granular soils and rock.

The importance of maintaining proper moisture contents during compaction apparently is recognized by almost all practicing highway engineers. However, there are many differences of opinion regarding the practical procedures for, and even the feasibility of, controlling moisture. Specifications that state moisture control should be "to the satisfaction of the engineer" or "as required by the engineer" are difficult to enforce. They rely entirely on the engineer's judgment which may be questioned by the contractor. Wide variations in interpretation may exist among inspectors within a state. Indirectly construction costs may be increased because the contractor may increase his bid to allow for the uncertainties involved with this type of control. On the other hand, specifications that indicate specific moisture limits with respect to the optimum moisture content from a standard laboratory test create other problems. Inspection becomes more costly and more time consuming, and delays to the contractor may result. Because the compaction characteristics differ for various soil types, it is difficult if not impossible to specify one moisture content range that will be satisfactory to all soil types.

General practice regarding moisture control varies with state, soil type, and climatic conditions. As would be expected there is little concern for moisture control in granular soils. For cohesive soils the closest control is exercised for soil types, such as silts and swelling clays, which through experience have caused the most difficulty. The moisture-density curves for silts have sharp peaks indicating that the density is extremely sensitive to small changes in moisture content. Consequently, contractors find this material very difficult to compact unless the moisture is closely controlled. Through experience, moisture control in silts is directed toward compaction at moisture contents slightly less than the optimum moisture content as determined from the AASHO T-99 laboratory test. However, if the field compactive effort is greater than the laboratory test effort, the optimum moisture content for field compaction should be slightly less than the laboratory value. Thus, the actual field compaction may not be on the dry side of field optimum.

For swelling clays, the general practice appears to be to attempt to compact on the wet side of optimum. This is in conformance with the general awareness that the swelling potential of these soils is considerably less when they are compacted wet of optimum rather than dry of optimum. Unfortunately, the most severely swelling clays are found in the arid regions of the southwest at natural moisture contents much less than the optimum moisture content. In these regions the addition of sufficient water is sometimes impossible and always very costly. Consequently, alternate procedures for reducing swelling potential have been attempted. For example, states such as Texas and Oklahoma appear to be successfully reducing swell problems through the use of lime stabilization techniques. These techniques are beyond the scope of the present paper and will not be discussed here.

In many states not plagued by swelling soils or silty materials, the moisture control is less stringent. In practice, the wet-side control is frequently governed by the mobility of the compaction equipment; i.e., the upper moisture limit is the moisture content at which the compaction equipment begins to bog down. The dry-side control sometimes may be primarily for dust control rather than compaction requirements. The moisture range imposed by these practical considerations usually is too broad to insure satisfactory compaction.

When natural soils are too wet, disking frequently is used to improve the rate of drying through aeration. Disks sometimes are required on jobs where wet cohesive soils are anticipated. In addition, some states encourage construction practices that tend to decrease rewetting due to rainfall during construction. When rainfall is anticipated, the contractors are encouraged to blade a steep crown on the surface and to roll the surface to seal it. This practice increases runoff and frequently eliminates construction delays.

Severe moisture control problems arise in very wet climates such as the Pacific Coast of Oregon and Washington, where the natural soils are very wet and the climatic conditions hinder natural drying. Under such circumstances, it is sometimes impossible to dry cohesive soils satisfactorily, and they must be compacted at moisture contents much higher than optimum. For these conditions, Washington has reported some success with controlling the degree of saturation rather than the moisture and density. Density requirements are reduced so that the degree of saturation does not exceed approximately 87 percent for the minimum moisture contents that can be attained in the field. When this is done the design procedures must be modified to account for the lower strengths to be expected. The concept of adjusting design procedures appears to be a significant one.

To overcome extremely wet conditions, sandwich construction has been successfully utilized for embankment construction in some regions. The wet cohesive soil and coarse granular material are placed in alternate layers. This practice has been successful in regions such as New England where ample sources of granular materials are readily available. However, the procedure becomes impractical when such materials are not plentiful.

When additional water is required, the water is sometimes added in the borrow pit and sometimes on the fill. In general, better moisture control is obtained when the water is added in the borrow pit. This practice is employed both by the Corps of Engineers and the Bureau of Reclamation for earth dam construction, and it is being followed whenever practical for highway construction in many states. However, much highway construction is not well suited to borrow pit operations. Highway construction commonly involves balancing cut and fill sections for which there is no distinct borrow pit. For these conditions the water generally must be added on the fill, but more problems should be anticipated to obtain suitable moisture control and proper mixing on the fill.

Granular Bases

Procedural Requirements for Granular Bases—The size and type of compaction equipment is specified much more frequently for bases and subbases than for embankments and subgrades. Nine states rely entirely on procedural control without density requirements. An additional 22 states specify only procedures for certain classes of work and specify both procedures and density requirements for other work. Most of the minimum equipment requirements in state specifications are related to base course construction.

The greater reliance on equipment and procedural specifications for base courses probably can be attributed to a greater uniformity of base course materials. Select granular materials that satisfy specified gradation requirements are used. Consequently, a satisfactory procedure can be established on a statewide basis.

From the interview program relatively few problems were noted in base course construction. Vibratory compactors frequently are used and satisfactory results are reported. Some states reported problems with degradation of crushed limestone due to compaction, resulting in excessive amounts of fines. Research underway in Iowa appears to indicate that the degradation can be significantly reduced or eliminated through the use of properly adjusted vibratory equipment. Other problems cited were related primarily to difficulties with measuring field densities in coarse materials rather than with the quality of the compacted material.

Maximum allowable lift thicknesses are specified by almost all states. Approximately half of the states specify a maximum compacted thickness of 6 in. The majority of the remaining states specify compacted thicknesses of 3 to 5 in., several specify 8 in., and a few specify 9 to 12 in. In some states, the maximum thickness will vary within the previously indicated range depending on the total thickness and the type of base or subbase. Only 2 states specify loose thicknesses rather than compacted thickness.

Density Requirements for Granular Bases—Forty-one states use density requirements for at least some categories of base and subbase construction. Approximately 10 states base density requirements on the AASHO T-180 test, almost all of which specify 95 percent of the maximum dry density. About 17 states use the AASHO T-99 test for base materials, most specifying 100 percent compaction or greater and a few specifying 95 percent. Fourteen states base density requirements on tests other than AASHO T-99 or T-180. When the AASHO impact tests are not used to establish density requirements, a variety of alternative procedures are used. Most of these attempt to overcome difficulties inherent to application of the AASHO test procedures in coarse materials. Some states express the required density as a percent of the maximum density obtained from a laboratory vibration test. Others express the required density as the percent of a theoretically voidless mass; i.e., the dry density of the solid. For example, Kentucky specifies 84 percent and Wyoming 77 percent of the dry density of solids. Ohio determines base course density requirements on the basis of test sections constructed at each project site. Virginia is also currently trying this technique on an experimental basis.

Most highway engineers appear to feel density requirements for base courses are adequate.

Moisture Control for Granular Bases—Almost 80 percent of the states specify moisture requirements for base courses in a qualitative manner. These statements generally take the form "as required for compaction," or "as directed by the engineer." An additional 5 states specify optimum moisture content, which must be interpreted in a qualitative manner. Five states specify upper and/or lower moisture limits. Two states do not specify moisture control.

Interviews with highway engineers indicate that qualitative moisture control may work more satisfactorily for base materials than for embankments and subgrades. This may be attributed to the select quality of materials utilized for base course construction. Because of the high permeability, the water content cannot be closely controlled; however, for most coarse materials, moisture control is not critical. For dense-graded aggregates, moisture content may be critical but the proper moisture content is easily observable during construction. Consequently, both the contractor and the inspector easily agree on proper moisture conditions.

Other Factors Related to Granular Bases—The most significant factor present in base course construction that is not present in embankments or subgrade construction is the utilization of selected materials. Base course materials usually must meet certain gradation and quality requirements. When natural materials do not meet these requirements, materials are processed to alter the gradation so as to satisfy the specifications.

As a part of gradation requirements, most states specify the maximum percent of fines, usually as the percent passing the No. 100 or 200 sieve. The allowable percentages frequently vary with materials within a state and should depend on the overall gradation of the material. However, approximately 25 percent of the states explicitly require 10 percent or less material finer than the No. 200 sieve. Frequently, the plasticity of the fines also is limited. Occasionally the allowable plasticity index is raised as the percent fines decreases. For example, New York generally permits no more than 10 percent finer than the No. 200 sieve, and the plasticity index of this material must be 3 or less. However, a plasticity index as high as 5 is permitted if the percent of fines is 6 percent or less.

In several states engineers expressed concern regarding particle size degradation caused by compaction. The extent of these effects is generally conceded to be unknown, although as previsously noted research on this subject is underway at Iowa State University. Because of the possibility of degradation during compaction, gradation tests for acceptance of base course materials generally are conducted prior to compaction. This practice permits materials to be accepted that may not meet gradation requirements after compaction and unsatisfactory performance of the base course may result if the percent of fines becomes too large. To avoid such problems, degradation during compaction must be minimized or the maximum allowable percent of fines prior to compaction must be sufficiently small to allow for some increase in fines during compaction.

QUALITY CONTROL PROCEDURES

Quality control and acceptance procedures include density measurements, test rolling and visual inspection. In current practice, most compaction control is accomplished by measuring the field density and comparing it to the maximum density obtainable for this material in a specified laboratory compaction test. Because the control generally is in terms of dry density, the measurement of field moisture content also is involved, even when moisture requirements are not specified quantitatively. Consequently, this section will be concerned with current practices for obtaining field moisture and density measurements and procedures for converting these measurements to relative densities or percent compaction.

The successful implementation of any quality control procedure ultimately depends on the capabilities of the personnel who are responsible for the inspection. Many of the compaction control problems and dilemmas that will be discussed in this section are directly related to the qualifications of the inspection personnel. Consequently, prior to discussing control procedures, the general level of training and experience of earthwork inspectors will be discussed.

Inspection Personnel

The responsibility for earthwork inspection generally resides with the field construction engineer who usually holds an engineering degree and/or has many years of construction experience. However, in practice the actual inspection is performed by an earthwork inspector under the general supervision of the field engineer. Although the background of these inspectors varies considerably within a state, most frequently the inspector is a worker who has little fundamental understanding of the concepts of soil compaction. He may be a new engineering graduate on his first assignment, a college student undertaking summer employment, or a high-school graduate with brief on-the-job training in soil testing procedures. The engineers very quickly advance to more responsible field and office duties, and the better technicians advance to positions as paving and structural inspectors. Thus there is a continual problem of inexperience and of training new personnel. In addition, the wage scales for earthwork inspectors generally are relatively low. Consequently, the position of earthwork inspector is not generally held in high regard, and as a result it is difficult to find competent people to fill these positions.

All of the states visited expressed concern for the problem of obtaining and keeping competent earthwork inspectors. Most states conduct formal or informal training programs for new inspectors. Generally all training programs are oriented toward testing procedures with the trainees being instructed in the following tests: Atterberg limits, sieve analysis, standard laboratory compaction tests and field moisture-density tests. Emphasis is placed on testing techniques and acceptance criteria, and there is little effort to present fundamental concepts of soil behavior.

One of the major dilemmas of compaction control is a result of the qualifications of most earthwork inspectors. Many experienced soils engineers strongly believe that the most satisfactory construction is obtained through visual inspection and the use of engineering judgment with little or no density testing. The attitude is prevalent that much is gained by watching and checking the contractors' operations. The feeling is expressed that when the inspector is performing density tests, the contractor is operating unobserved on another part of the project. These views are undoubtedly valid and correct appraisals of desirable earthwork control when experienced inspectors are available. However, it appears today that the majority of inspectors lack both the experience and the training to make satisfactory engineering judgments that are required by these qualitative control procedures.

Density Control Procedures

Types of Field Moisture and Density Tests—Many state specifications, which include density requirements, do not specify the method by which the field density is to be measured. In many instances, the standard testing procedures are described in a separate manual. In general, no single method dominates current usage. In many states the test methods may vary from one district to another, with the local selection governed by the personal preferences of the district personnel. In some localities, strong opinions exist regarding the relative reliability of the various test methods. Opinions in different parts of the country may be diametrically opposed. The attitudes regarding the reliability of specific tests seem to be related very closely to local experience and details of local testing procedures.

The most common field density tests are destructive tests that involve digging a hole, determining the weight and moisture content of the soil removed, and determining the volume of the hole created. The two most prevalent destructive test methods are the sand-cone method and the balloon method, in which the volume of the hole is determined by refilling the hole with sand and water (in a rubber membrane) respectively. Other techniques encountered occasionally involved refilling the hole with oil, plaster, and, on an experimental basis, paraffin. Approximately the same amount of time is required to perform either the sand cone or the balloon test. The accuracy of these tests is influenced by the coarseness of the soil, with the true volume becoming more difficult to assess when large particles are involved, such as crushed stone or glacial till with rock fragments. To compensate for this, larger holes frequently are used with coarser materials. Most states that encounter such materials have developed rock correction factors with which to adjust test results. The correction procedures differ somewhat from state to state.

The major disadvantage of all destructive density tests is the length of time required to conduct the test, which severely limits the number of tests that can be performed without delays to construction. Often it is not possible to determine whether the material satisfies density requirements until additional lifts of material have been placed over the material that has been tested.

Moisture content determinations usually accompany field density measurements. Because of the time delays involved, the standard laboratory technique of drying for

24 hr in a thermostatically controlled oven generally is not acceptable in the field. Consequently, for many years the prevalent field procedure has been to dry the soils over an open flame. This method, which is still commonly used today, is relatively satisfactory for coarse materials but somewhat unreliable for fine-grained soils. Today many states are using the Speedy Moisture Tester for the field determination of moisture content of fine-grained soils. This relatively new device, which makes use of calcium carbide reaction, permits rapid field moisture determinations. The prevailing opinion regarding experience with this device indicates that it is at least as reliable as the open-flame method which has been used previously. Thus, this device appears to have made a significant contribution to speeding up conventional moisture-density determinations. However, it can accommodate only a relatively small sample and consequently is unsuitable for use with very coarse materials. As a result, states that encounter coarse materials continue to use the open-flame method of drying.

Most states are experimenting with nuclear methods for determining moisture and density. The several available hand portable units are being tested primarily, but some states also are experimenting with the Lane Wells Road Logger, a mobile unit that provides a continuous density record along the length of a fill. The chief advantage of the nuclear methods is the speed of the operation, which permits many more density measurements to be obtained. The major disadvantages are the high cost of equipment and the need for more highly trained technicians. In addition, there remains some concern for the reliability of the nuclear density measurements, although this concern appears to have decreased significantly in recent years. There has been a growing recognition that relatively large variations in density may exist within very small areas of a compacted fill. These local variations are more frequently detected with nuclear devices than with destructive tests. The recognition of these real variations in compacted materials has given impetus to the movement to develop statistical quality control procedures.

In many states, the view was expressed that nuclear methods do not afford as much time saving as is generally reported. While the time required for an individual measurement is much less than by conventional methods, calibration and repair times also must be considered. Most agencies feel that the nuclear equipment must be calibrated for each individual soil and the calibrations must be repeated or checked at least twice a day. Furthermore, perhaps because of excessively rough handling in the field, repairs are required frequently. The repairs, which are made by the manufacturer, are often time consuming and sometimes costly.

As will be discussed in the following section, some states require a standard compaction test, which is conducted in the field using the soil for which the field density has been determined as a part of the field control procedure. In these instances the actual field density determination represents only a small part of the total test time. Consequently, the introduction of nuclear methods produces only a small percent reduction of the total testing time. States that currently use this procedure are hesitant to adopt nuclear methods.

Although the Lane Wells Road Logger can provide more density measurements than the hand portable units, its extremely high cost appears to limit its potential application. Its use does not appear to be economical unless large quantities of earthwork construction were being planned in relatively small geographic areas, perhaps in a large metropolitan area or for an extremely large embankment.

Despite the many problems with nuclear devices, there is every indication that their use will become much more widespread. In the summer of 1965, only Colorado was using nuclear methods for the legal control of earthwork construction. California was beginning a project in each of its eleven districts that would use nuclear control methods. Since that time several additional states have adopted nuclear devices for legal control and it appears fairly certain that additonal states will do so in the future. However, it should be noted that the most effective use of nuclear devices involves more than merely changing the field density determination method. It will probably involve a complete revision of the density specifications to include statistical concepts and conceivably to eliminate the need for the standard laboratory compaction test. The former has already been done, for example, in California where a special specification was written for the jobs to be controlled by nuclear methods.

Field Evaluation of Standard Maximum Compacted Dry Density—In current practice, almost all density requirements are expressed as a percent of the maximum density attained by a specified compaction test procedure. Occasionally, a relative density criterion is used; i.e., the field density requirements are expressed relative to both a maximum and a minimum laboratory density. Thus, to determine the acceptability of the compacted material, the maximum dry density for the material must be established.

From the field interviews, it appears that one of the major problems in the practical interpretation of a density criterion is the proper evaluation of the dry density to which the measured field density should be compared. Typically, laboratory compaction tests are performed on representative samples of primary materials during preliminary planning and prior to construction. The moisture-density or control curves from these tests generally are available for field control. The simplest field control procedure is to compare the measured field density with the control curve that the inspector judges is most representative of the compacted material. To aid in relating control curves to field materials, a library of jar samples of materials for which the control curves were attained is sometimes kept at the job site to facilitate visual identification of materials.

However, in many instances the primary materials are mixed in the earthmoving operations, and as a result, none of the laboratory curves may be directly applicable to the material being placed on the fill. To overcome this problem, most states attempt to make a field evaluation of the maximum dry density in conjunction with field density measurements.

The most common procedures for the field evaluation for maximum dry density involve the use of a one-point field compaction test and/or the development of families of moisture-density curves. One common practice is to use the laboratory compaction test procedure to compact the field material at the placement moisture content. The moisture-density point so obtained is plotted with the family of control curves for the job, and the maximum dry density for the material is estimated by constructing a new moisture-density curve through the test point and roughly similar in shape to the available curves. Some states, Ohio, for example, have developed elaborate statewide collections of typical moisture-density curves. In the Ohio system, the penetration resistance as determined by the Proctor needle is utilized in conjunction with the field compaction test. The statewide family of moisture-density-penetration resistance control curves is then used to estimate the maximum dry density for the field material. A circular slide rule, which is supplied to all inspectors, has been developed to simplify the identification of the proper typical curve from the one-point field data.

These control practices, which require at least a one-point field compaction test in conjunction with each density field test, are time consuming and can potentially delay construction. However, they are deemed necessary in a majority of the states because of the great variations in the materials encountered in highway construction.

As has been noted for the field density test, the laboratory compaction test results also become less reliable when rock-size particles are encountered. In various states, the view was expressed that conventional field test procedures and the laboratory impact compaction test are unsuitable for soils that contain large quantities of rock. A few states, such as Kentucky, have eliminated the need to determine maximum dry density for crushed stone base materials by specifying the density requirements as a percent of the specific gravity of the solids. However, the problems of the measurement of field density remain.

Number and Location of Tests—Until quite recently most states did not specify the number of density tests to be performed or the methods for selecting the position at which the test is conducted, these decisions being left to the judgment of the engineer. During the past few years, however, minimum testing requirements in terms of tests per unit length of roadway or per cubic yard of material placed have been developed in most states. These specifications are being instituted largely at the insistence of the Bureau of Public Roads and frequently over the objections of state highway engineers. Strong opinions are expressed by many highway engineers regarding the unfavorable aspects of specifying the minimum frequency of density testing.

In many states engineers expressed the view that the majority of their compaction work was satisfactorily accomplished without difficulty and, consequently, only minimum results of inspection were necessary. On the other hand, on the relatively few jobs for which problems were encountered, much higher frequencies of testing were deemed necessary. Also, more testing frequently is conducted when a project is first initiated; after the job is running smoothly the rate of testing is frequently reduced. In other words, the states feel that the rate of testing must be related to the degree of difficulty of the particular project. One engineer expressed the view, "80 percent of our testing is done on 20 percent of our compacted materials."

Engineers fear that the minimum frequency of testing will become the standard frequency of testing for all jobs and that, as a result, unnecessary testing will be performed on the satisfactory jobs or insufficient testing will be conducted where problems exist, depending on the established frequency of testing. In most states the tendency has been to set minimum frequency requirements as low as will be accepted by the Bureau of Public Roads. When this is done the states must insure that the inspectors conduct more than the minimum number of tests when problems are encountered.

The selection of locations at which density tests will be conducted has traditionally been left to the judgment of the inspector. Sometimes he is instructed to look for weak spots, on the premise that the density requirements represent a minimum standard which all materials must meet. Also, it is argued that if the weaker-appearing spots can be shown to be acceptable, the entire fill should be satisfactory and the number of tests required can be substantially reduced. Other states instruct inspectors to look for average conditions when selecting a testing site. In this instance it is reasoned that a small weak spot in one lift will not adversely affect the behavior of the completed embankment.

In recent years, random sampling techniques have been proposed for selecting sampling locations. Random sampling is a requirement of the statistical quality control procedures that are currently being advanced for earthwork control. Many highway engineers voice strong objections to random sampling and, as a result, to statistical quality control concepts. Their primary concern is the belief that the statistical procedures will eliminate engineering judgment and increase the chances that an unsatisfactory area will be accepted as a part of the larger section because the random sampling technique did not require tests in the weak zone. They argue that engineering judgment must be maintained to avoid this possibility.

It appears that many of the objections to random sampling and statistical quality control procedures can be eliminated by consideration of the relation of engineering judgment to these procedures. First, before random sampling can be employed, the total area of the section to be considered must be defined. The size of the section is not specified, but rather is selected on the basis of engineering judgment. The section to be considered usually is selected on the basis of uniformity of soil type, moisture content, compactive effort, and other placement conditions. In uniform base course material, several thousand linear feet of material may be considered as a single section, whereas in embankment construction the section more likely may be several hundred feet long because of more frequent changes in material and placement conditions. Hence, the random sampling and the statistical analysis are then applied to the evaluation of the mean quality and the variability of a section that, by visual inspection, the inspector has judged to be uniform. The statistical procedures compensate for the local variability that will exist in even the most closely controlled construction.

The statistical procedures and random sampling are not designed to account for the possibility of a large area within the section that is significantly different from the remainder of the section. For example, in a 500-ft long lift of embankment material a 25-ft long layer of weak material could be present, perhaps as a result of water ponding in a depression during construction. This weak spot might be visually detectable by observing the deformation of this soil under the action of the compaction equipment. However, it is possible that a random-sampling technique based on consideration of the entire 500-ft layer as a uniform section would not designate tests in the weak zone. As a result the unsatisfactory material could be accepted along with the satisfactory material. This possibility illustrates the primary fear of random sampling.

However, this objection can be overcome if the engineer's judgment is properly exercised. In the situation described, proper engineering judgment would dictate dividing the 500 linear feet of embankment into two sections, one of 475 linear feet and the other containing the 25 feet of visually different material. Random sampling and statistical analysis would then be applied independently to each of the two sections, and each would be rejected or accepted separately. Thus, it appears that the proper use of random sampling and statistical control does not eliminate the role of engineering judgment but rather supplements it.

The preceding discussion refers primarily to density testing for control during construction. It should be noted that density testing also is used for documentation purposes after completion of earthwork. Random sampling and statistical quality control are more clearly applicable for this purpose, and few objections were noted to this use.

Compliance with Specifications—With the exception of several recent specifications based on statistical concepts, density requirements are considered to be mimimum standards that must be exceeded by all field test results. If an unsatisfactory test result is obtained, the material is rerolled or removed and replaced, depending on the severity of the deficiency. The material is retested for compliance with specifications. As a result, earthwork construction records will show 100 percent compliance with specifications. However, during interviews with highway engineers, it was admitted that some inspectors do not report unfavorable test results. If, in the inspectors' judgment, an embankment is satisfactory and the majority of test results are acceptable, the inspectors may simply disregard 1 or 2 unfavorable test results. Also, the inspector can affect the test results in marginal cases through his selection of sampling locations. This practice cannot be eliminated without exercising extremely close supervision over inspectors. In fact, the disregard of an occasional unsatisfactory test on the basis of engineering judgment may be a satisfactory and justifiable practice.

Statistical concepts for density requirements have been introduced in part to overcome the problem of the occasional bad test. For any statistical distribution of test results, the probability of an unfavorable test result can only be reduced by raising the mean value or reducing the standard deviation of the test results. Even for closely controlled field experiments the standard deviation can be expected to exceed 2 lb/cu ft (2). Thus, if for illustrative purposes a normal distribution is assumed, approximately 2 to 3 percent of the tests could be expected to fail if the mean value is two standard deviations greater than the minimum requirements. Therefore, for normal construction conditions, an occasional bad test could be anticipated even when the average density of the fill is 5 percent greater than the minimum requirements. The proponents of statistical specifications thus would argue that specifying an allowable percent defective is merely formalizing what is currently informally practiced as a part of engineering judgment.

It appears that the use of statistical compaction control will increase in coming years. However, the acceptance of these procedures by the states will only come with an understanding that statistical methods are a tool to aid engineering judgment and not to eliminate it.

SUMMARY

As a result of the interviews with many highway engineers and the review of current specifications, problems of common concern became apparent. The major difficulties in compaction for highway purposes, as cited by highway engineers, are summarized as follows:

1. Problem soils. The major compaction problems are encountered in construction of embankments of silty soils, swelling clays or extremely wet clays. For these materials, satisfactory placement conditions are difficult to achieve.
2. Heavy construction equipment. The wheel loads of very heavy hauling and paving equipment are overstressing and failing some embankments that would otherwise perform satisfactorily under traffic loads. This problem is most severe for silty embankments.

3. Rapid control procedures. Modern construction equipment and methods have significantly increased the rate of highway construction. As a result, conventional control testing procedures frequently cannot keep pace with construction and delays to construction may result. Most construction engineers are seeking rapid control procedures that will not slow a contractor's progress.

4. Variablility of materials. Because of the variability of natural soil deposits, the raw materials utilized for embankments and subgrades are constantly changing. As a result, most engineers feel that it is neccessary to make field evaluations of the maximum compacted dry density in conjunction with field density measurements. This procedure significantly slows the control testing.

5. Acceptance criteria for materials with high rock content. Materials that contain relatively large percentages of rock fragments frequently are readily placed to form very stable embankments or pavement components. Control and acceptance procedures for the materials commonly are based on the field density, expressed as a percent of standard impact compaction tests. For rocky materials, these tests appear to be slow and inadequate to represent the compaction characteristics of the material.

6. Inspection personnel. In every instance, highway engineers expressed concern for the quality of earthwork inspectors. Although most states have either formal or informal programs for training earthwork inspectors, experienced inspectors are difficult to find. Earthwork inspection is frequently a beginning position from which the more capable individuals quickly advance.

7. Statistical quality control. Statistical quality control procedures and related random sampling plans are causing much concern among state highway engineers. They fear that the role of engineering judgment is being subjugated to handbook statistical methods. However, the inability of the advocates of engineering judgment to provide inspectors who are capable of exercising such judgment has created a vexing dilemma to the states.

Additional problems noted by project personnel but not strongly voiced by highway engineers include the following:

1. Reliance on density criteria. Current compaction specifications are based on the concept that density is a direct indicator of strength. Experimental data from the literature, which are summarized by Langfelder and Nivargikar (3), indicate that strength is affected by many factors in addition to density. Eventually, compaction criteria must be based more directly on strength and other engineering properties of compacted materials.

2. Correlation of laboratory and field compaction. The effects of compaction method on moisture-density relations and the physical properties of compacted materials are noted by Langfelder and Nivargikar (3). There are sufficient data to indicate that the densities and physical properties of samples compacted by laboratory impact methods may differ significantly from the properties of the same material compacted by field construction equipment.

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