The Role of Judgment in Inspection and Control of Subgrades

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INTRODUCTION

There are two principal reasons for compacting highway subgrades and fills. One of these is to improve subgrade strength, thereby permitting an economical pavement design to support the required wheel loads. The other purpose is to create a fill of low compressibility, thereby minimizing settlements of the roadway. Although high strength and low compressibility are always in the pavement designer's mind, it is seldom if ever that subgrade specifications are written directly around these two properties. Customary practice is to specify a certain density or a certain percentage of an arbitrary maximum density as a means of securing adequate compaction. This is done on the assumption that the sought-for strength and compressibility characteristics will be obtained if this minimum density is achieved. The validity of this assumption is open to question.

The terms "inspection" and "control" are frequently grouped together when applied to those activities that are undertaken to insure that specifications are met on a soil compaction job. The two terms are not synonymous, of course. "Inspection" in this case tends to be associated largely with the density tests that are performed after compaction is complete to determine whether the finished product meets specifications. "Control," on the other hand, includes a variety of efforts, not limited to soil tests, that are made while compaction is in progress to help bring about its efficient and successful completion. Adequate performance of inspection, in the limited sense just mentioned, requires mainly a knowledge and command of field testing techniques. The performance of control duties, on the other hand, requires not only a knowledge of field and laboratory testing techniques but also a capacity

1 Presented as part of a "Symposium on Inspection and Control of Highway Construction."
for sound judgment—a product of knowledge and experience. Control represents an active rather than passive participation in the construction operation and is therefore a more challenging task.

At this point I would like to relate an incident which illustrates how judgment, good or bad, enters into compaction control. In this case, faulty judgment was a major contributing cause to the inadequate performance of an earth fill, in spite of the fact that testing had demonstrated reasonable compliance with the specifications. In 1953, an earthen dam 80-ft. high by approximately one mile long was constructed in one of the southwestern states. Material used for this dam consisted almost entirely of lean clay. The specifications for its construction were similar to those for most highway fills: fill material was to be spread in 8-in. lifts and then compacted to at least 95 per cent of Proctor maximum density. Material in the borrow pits at the time of construction was relatively dry, and by the time it was spread on the fill in hot and dry summer weather its water content was still lower. Some limited additions of water were made to the fill at the start of construction. Only a few of the initial field density tests indicated results less than the specified minimum. Encouraged by the fact that the sheepsfoot roller “walked out” of each layer and produced a hard, concrete-like surface, the inspector permitted the fill to continue with less attention to the addition of water. Four years passed before water in the reservoir approached spillway level. At about that time, longitudinal cracks began to appear at the top of the dam. These became progressively more severe, reaching several inches in width, and extending 30 ft. or more vertically into the embankment. A parallel system of cracks became noticeable in both the upstream and downstream slopes.

An investigation into the causes of this distress revealed a direct connection between the cracks and the method of compaction of the dam. Lower portions of the embankment had become saturated, a normal condition in itself, but in the process the original stiffness of this part of the embankment had been almost entirely lost. This saturated material was much more compressible than before and, under the influence of the overlying fill, permitted the entire embankment to settle. The upper portions of the embankment, as yet unaffected by water, were still quite strong but exceedingly brittle. In conforming itself to the unequal settlement, the brittle portion of the embankment was subjected to severe bending stresses and the observed tension cracks resulted. Extensive and costly grouting operations were required to restore the dam.
I allowed myself to select the foregoing example from outside the field of highway construction because an earth dam in distress is somehow more dramatic than a subgrade failure. The illustration was not irrelevant, however, because similar reliance on visual appraisal of compacted soil is not uncommon in highway work. All too frequently, hard and dry subgrades have been approved, only to fail later due to an increase in water content. As mentioned previously, soils are compacted to achieve either high strength, or low compressibility, or both. It is incumbent upon a good inspector then to have some idea how these ends are achieved by the compaction process. This requires a more-than-moderate acquaintance with soil technology extending beyond the simple field measurement of in-place density.

BASIC MOISTURE-DENSITY RELATIONSHIP

I would like to review some of the more familiar technical concepts of soil compaction, and proceed from there to some of the less familiar concepts and how these can make a contribution toward an inspector's judgments. Fig. 1 is a curve expressing the typical relationship between soil density and water content at the time of compaction.

Fig. 1. Typical moisture-density relationship for soil compaction.
If a given soil is subjected to the same amount of compaction at a range of water contents, different densities will result. If these densities are plotted against the compacting water content, as in this illustration, the plotted points group together to form a curve having the indicated familiar shape. For a relatively low water content, compaction of the given amount achieves a relatively low density. At somewhat higher water contents, a higher density results; and at still higher water contents, compaction again becomes less efficient and there is a decrease in the resulting density. This relationship between density and water content during compaction is quite general. Similar relationships are found for different degrees of compactive effort, for both laboratory and field compaction, and for soils of various types. The greatest density that can be achieved for the particular effort being supplied is marked by the peak of the curve and is commonly referred to as “maximum density.” The molding water content at which this maximum density is achieved is called the “optimum moisture;” the existence of this optimum is an important concept in compaction technology. When compaction is performed with the soil water-content less than optimum, it is referred to as compaction on the “dry side;” similarly, compaction performed when the water content is higher than optimum is referred to as compaction on the “wet side.”

EFFECT OF COMPACTION ENERGY

As stated previously, equal compactive effort was supplied to establish each of the points on the curve in Fig. 1. If this compactive effort were changed, a similar but different curve would result. As a matter of fact, it would take several such curves to express fully the moisture-density relationship for one soil. Fig. 2 shows a typical set of curves for one soil, as determined by laboratory compaction tests. The numbers attached to each of the curves indicate the number of standard hammer blows applied to soil layers of standard thickness and area. It can be seen that the maximum density and optimum moisture content cannot be expressed as unique values for a given soil. As the compactive effort increased—in this case, as the number of blows per layer became greater—the maximum density increased and the optimum moisture at which this was attained decreased.

Many different laboratory compaction procedures have been proposed to evaluate the moisture-density characteristics of a given soil. Each of these produces a different compactive effort, and therefore defines a somewhat different maximum density and optimum moisture content. The most familiar procedure is that proposed by R. R.
Fig. 2. Effect of compactive effort on moisture-density relationship.

Proctor in 1933 and subsequently adopted in almost its original form both by ASTM and by AASHO. This test employs 25 blows of a standard hammer on each of three layers in a standard-size container. Another procedure that is now almost as familiar is the so-called modified AASHO test, introduced by the U. S. Corps of Engineers almost two decades ago. This test is very similar in procedure to the standard AASHO test, but applies approximately five times the compactive effort. This is done through the use of a heavier hammer, more blows per layer, and a larger number of layers.

The variation in maximum density and optimum moisture produced by varying compactive efforts can be produced in the field as well as in the laboratory. Variations in field compactive effort are achieved by varying the number of roller passes; also by varying the area of contact with the soil and the intensity of pressure applied through that contact.

CONVENTIONAL COMPACTATION SPECIFICATION

Let us turn now to a consideration of the usual basis for compaction specifications, toward which inspection and control of compaction
must be oriented. The principal requirement for compaction of a fill or subgrade, in almost all specifications, is the attainment of a stipulated percentage of maximum density as defined by one of the standard laboratory tests. Many specifications go beyond this and include certain other control features, but nearly all rely principally on measurement of the percentage compaction. On Fig. 3 is shown a moisture-density curve for a lean clay, as determined by the standard AASHO procedure. The maximum density in this case is 111 lb per cu ft. One of the most common compaction specifications is to require 95 per cent of the maximum density defined by the AASHO test. As the diagram shows, this minimum state of compaction can be equalled or exceeded, using a field effort comparable to the laboratory test, with a molding water content ranging anywhere from 12 to 19.5 per cent. Should the contractor choose to double compactive effort in the field, the specified density could be obtained with even wider variations in water content—from 8.5 to 20 per cent, as indicated by intercepts on the dashed-line curve of this illustration. Thus, a wide range of field compactive efforts and of field water contents can be combined in achieving
95 per cent of maximum density as commonly specified. Since attainment of adequate subgrade strength is probably the objective of such specifications, it is reasonable to inquire into the strengths that may result under these variations in field procedure.

**STRENGTH OF COMPACTED COHESIVE SOILS**

Many studies have been made of the strengths of compacted soils, particularly for cohesive materials. Some of the tests employed for this purpose include the Hveem stabilometer, the triaxial shear test, and the California Bearing Ratio or CBR test. The CBR test, now widely known throughout the highway industry, was used by the Corps of Engineers in a study of the strength of compacted soils, results of which were described by Turnbull and Foster[1] in 1958. Data for the next three illustrations were taken from that report.

Shown in the first of this series of illustrations, Fig. 4, are curves of CBR versus density for a lean clay compacted at three different

![Fig. 4. Relationship between California bearing ratio and molding water content for unsoaked specimens (after Turnbull and Foster, 1958).](image-url)
water contents. Several specimens were compacted to varying densities for each of these water contents by changing the compactive effort. The water content for the intermediate curve corresponds to optimum water content by the standard AASHO procedure. Samples for the uppermost curve were compacted at a water content of 12 per cent, which is on the dry side of optimum. For a low compactive effort, the resulting density and CBR are both quite low; as the density increases to the right, due to added compactive effort, the strength increases rapidly—approaching the CBR of a fairly good base material. The intermediate curve is for a molding water content of 15 per cent, which is the standard optimum moisture. Strength is again quite low at low density; for higher densities at this same water content, the strength is again higher although the increase is not as rapid as for the 12 per cent curve. The lower curve on Fig. 4 is for 18 per cent water content, which is on the wet side of optimum. Again at a low density, the strength is low—somewhat lower than in the two companion curves. Surprisingly, as the density increases and the material becomes more compact at this water content, the strength is reduced to an even lower amount.

These, then, are the strengths that may be observed by an inspector during compaction of a cohesive soil. The visual appearance of the fill in one or more of the conditions represented by these curves inevitably becomes an influencing factor in the judgment exercised by the inspector as he endeavors to control compaction. For example, the very high strength achieved by heavy compaction on the dry side of optimum may lead an inexperienced inspector to a false sense of security. To another more experienced inspector this high strength, combined with obvious signs of unusual dryness, may constitute a warning sign. Certainly, for most subgrades, there is a potential water-content increase subsequent to compaction, and its effect must also be taken into account.

The next illustration of this series, Fig. 5, provides similar strength data for the same specimens after they were subjected to four days' soaking. It is readily apparent that the strength versus density relationships were completely altered by this exposure to moisture. In order to appreciate better the changes that are represented, Fig. 6 combines on a separate plot both the soaked and unsoaked data for each molding water content.

In the plot at the top of Fig. 6, the CBR versus density curves for both the unsoaked and soaked conditions are shown for samples prepared with 12 per cent molding water content. This pair of curves illustrates the dramatic loss of strength that occurs when a dry, compacted
cohesive soil is subjected to an increase in water content. In the center plot are compared the strength-density curves for this soil compacted close to standard optimum moisture, with and without subsequent soaking. In this case, although there is an understandable loss in strength as a result of the soaking period, there is nevertheless a consistent and appreciable increase in strength for the higher densities. The lower plot illustrates that the low strengths achieved by compaction appreciably on the wet side of optimum are only slightly reduced by subsequent soaking.

The tendency to lose strength with increased compaction of cohesive material on the wet side of optimum is another example of technical information that is necessary to the understanding and judgment of an inspector under certain situations. A case history which illustrates this concerns the compaction of a high fill in one of the western states a few years ago. This fill was to be constructed with a volcanic soil

Fig. 5. Relationship between California bearing ratio and molding water content for soaked specimens (after Turnbull and Foster, 1958).
Fig. 6. Effect of soaking on strength (after Turnbull and Foster, 1958).

having rather unusual properties. The soil was predominantly silt in character, with a very low PI and a natural water content about six per cent higher than optimum by the standard AASHO procedure. In spite of this relative wetness, the material had the appearance of being quite dry due to a light cementing of the particles. Control tests performed as the material was being placed indicated that more discing and blading of the material would be required to produce aeration and
loss of moisture in order to get proper compaction. The contractor was one of the most widely known in this type of construction in the United States; his personnel, with many years of experience in compaction of earth fills, doubted the validity of this observation on the basis of their judgment and the visual appearance of the fill. When difficulty was experienced in compacting initial lifts to the required density, the contractor employed heavier rollers and the specified density was finally achieved. However, as construction proceeded and additional lifts were placed, previous layers progressively lost strength under the additional compactive effort; this strength loss was more evident where there was concentration of equipment traffic. The resulting effect was that the top of the fill began to shove and weave so badly that additional compaction was severely hampered. Resumption of work with increased attention to reducing the molding water content cleared this problem up. This incident demonstrates that sound judgment cannot be acquired solely by witnessing the placement of thousands of yards of earth fill, but requires an adequate founding in soils technology also.

DENSITY TESTING

The previous discussion has pointed out the necessity for an inspector to utilize more than density tests in controlling subgrade compaction. But what of density tests themselves? They are still the basic tool in the inspector's kit. Unfortunately, too many engineers and inspectors consider their laboratory compaction curves as impeccable standards of comparison for evaluating field densities. Many seem to have the same faith in field density measurements themselves. This idealistic view is far from reality, for two important reasons. First, natural materials of which subgrades are made are inherently variable; thus, the laboratory data may be faultless from a technique standpoint but apply to materials significantly different from the soil samples in the field density test. Second, the test methods themselves, both in the laboratory and in the field, are not precise and therefore do not permit a precise interpretation.

To elaborate on the last of these points first, the inexactness of the standard compaction test was demonstrated in a cooperative study undertaken by ten independent laboratories in Louisiana and Texas[2]. A large sample of plastic clay was mixed and blended into a more-than-natural state of uniformity. From this sample, ten specimens were split, distributed to the various laboratories, and then subjected to the standard AASHO compaction test. Resulting maximum densities from
these tests ranged from 93.7 to 100.7 lb per cu ft. To appreciate the significance of this wide range, consider the fact that a field density of 89 lb per cu ft would be an acceptable 95 per cent of the maximum density on the lower end of this range; yet this same density would "fail" at less than 95 per cent when compared to any of the other nine tests. Compared to the laboratory test at the upper end of the density range, this field density would represent only 88 per cent of maximum.

Field densities face similar testing problems. Principal requirements for the test are (1) determination of the volume of a prepared hole in the subgrade and (2) measurement of the weight of material that was excavated from the hole. The weight measurement poses no particular problem, but determination of the volume of the hole is not so simple. Many devices for accomplishing this have been proposed and are in use today. A study described by Redus[3] in a recent Highway Research Board publication found that these methods have inherent testing errors ranging from plus or minus one per cent for the best type tested to plus or minus two to seven per cent for the least reliable tested. Since these observations were made under closely controlled conditions, it is reasonable to expect the variation for normal field testing to be even greater.

Earlier mention was made that natural variations in soils contribute to the inexactness of field evaluation of per cent compaction. According to a published discussion by W. N. Carey, Jr.[4] based on data from the AASHO test road, some 300 samples were tested from a deposit supposed to be highly uniform in character. Maximum densities determined by these tests ranged from a low of 110 lb per cu ft to as high as 126. Similar variations were found in field density measurements, duplicate tests taken side by side generally differing by two or three lb per cu ft. These variations no doubt include some testing errors of the sort previously mentioned, but the additional influence of natural variations is inescapable. Comparison of a field density test on one soil with the laboratory compaction test on a similar but slightly different soil adds to the inexactness of compaction control by the per cent maximum density approach.

In summary, this review has pointed out some of the difficulties associated with the density approach to compaction control. I have no thought, however, of urging that we abandon this control method at the present time. Actually, density testing performed and interpreted consistently by one individual or by one organization overcomes some of the objections I have mentioned, because the approach is essentially
one of comparisons. The main point, which I would like to stress, is that density testing alone is not enough. It is essential for an inspector to supplement such testing by intelligent, trained observations and by interpretations of these observations based on sound knowledge of compaction technology.

In particular, an inspector should (1) verify the adequacy of his techniques for measuring field densities and for laboratory compaction tests, (2) exercise caution in making direct comparison between field tests and laboratory standards, and, (3) compensate for the basic limitations in density control techniques by the exercise of sound technical judgment.

REFERENCES


