HIGHWAY RESEARCH BOARD

Bulletin No.23

COMPACTION OF SOIL

TWO PAPERS

PRESENTED AT THE TWENTY-EIGHTH ANNUAL MEETING

1948

HIGHWAY RESEARCH BOARD

DIVISION OF ENGINEERING AND INDUSTRIAL RESEARCH

NATIONAL RESEARCH COUNCIL

WASHINGTON 25, D. C. NOVEMBER, 1949

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FACTORS INFLUENCING COMPACTION OF SOILS

W. J. Turnbull[1], S. J. Johnson[2], and A. A. Maxwell[3]

INTRODUCTION

The effect of moisture content upon density in compaction of soils as developed by Proctor has been widely recognized and studied in considerable detail. The moisture content is of fundamental importance in soil compaction and is the most important single variable involved. However, the influence of characteristics of the compacting equipment and certain properties of the soil being compacted have not received adequate investigation or attention in literature. It is desired to discuss these characteristics briefly and to point out what they are, in order that a more complete understanding of field compaction of soils may be had. This is timely, since these considerations affect the design of compacting equipment, and manufacturers are now displaying a great deal of interest in this in an effort to reduce the number of types of rollers being used.

Obviously, one of the first variables encountered in compaction work on any given soil is the type of equipment. In general, equipment commonly used for current work is either the sheepsfoot roller or rubber-tired wheel loads, with the former being the most common. Vibration rollers are still in the experimental stage and while they possess definite potentialities they have not demonstrated as yet any pronounced advantage over other types of rollers for large-scale compaction jobs. Factors affecting compaction with sheepsfoot and rubber-tired rollers are somewhat similar but will be discussed separately because there are some differences. A comparison of the merits of sheepsfoot rollers versus rubber-tired compactors is beyond the scope of this paper. Sheepsfoot rollers and rubber-tired rollers as used for compaction in lift construction will be discussed first and will be followed by a few remarks on subgrade compaction; that is, compacting from the surface only.

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SHEEPSFOOT ROLLERS

General

There are widely divergent views on the design and proper use of sheepsfoot rollers. This fact is evidenced by the great variety of rollers being manufactured and the even greater number of specifications regarding their use. Some standardization of both rollers and specifications has been suggested many times.

Many variables enter into the process of compaction by a sheepsfoot roller. The roller weight, areas and shape of feet, foot spacing, and drum diameter, are a few of the more obvious variables connected with the roller itself. To these must be added the variables introduced by the soils which include the type of soil, water content, initial density, and perhaps others. In addition to these, the compaction obtained is also affected by the thickness of lift and number of passes of the roller. The fact that compaction by sheepsfoot rollers is influenced by so great a number of variables is one reason for so many different opinions on this subject.

It would appear, considering how extensively sheepsfoot rollers are used, that a clear-cut picture could be obtained of just what roller should be used on any given soil to obtain adequate compaction. This is difficult, if not impossible, to do. During the last three years the authors have had occasion to examine data from numerous projects. In the great majority of cases, little or no information could be obtained that would assist in the evaluation of the variables affecting compaction. The difficulty lies in the number of variables and the interrelationship of these variables. It was found that the effect of any one variable could not be isolated in data generally available from construction projects and from many test sections. Well-planned and carefully controlled test sections are required to isolate the effect of a single variable. Answers to some questions can be found in existing data. Some questions cannot be answered now, but at least, if this fact is recognized, steps can be taken to fill in the gaps in our data.

Contact Pressure

The weight of roller and nominal contact pressure are, of course, directly related for any given roller. The effect of contact pressure is of great importance, for after all it is the effective intensity of loading which produces compaction in soils. Effective intensity of loading is something that is difficult to compute and it may have little resemblance to the nominal contact pressure computed by dividing the total roller weight by the total area of one row of feet. The contact pressure should be as large as possible but cannot be increased indefinitely, since the bearing capacity of a given soil limits the effective contact pressure. Thus, regardless of the actual weight of the sheepsfoot roller, the maximum unit pressure exerted by the feet on the soil cannot exceed a certain maximum value which is a function of the bearing capacity of the soil. This maximum value is obviously dependent on the type of soil; the moisture content and density and other factors. If loads are applied which exceed the bearing capacity of the soil, the roller will sink into the soil until a sufficient number of feet are in contact with the soil to reduce the maximum contact pressure to the bearing capacity of the soil for the existing conditions. In some instances the roller will sink into the ground until even the drum is carrying a substantial load. It follows, therefore, that there is an upper limit to the contact pressure which can be used and that this upper limit will vary with different soils.

The preceding thoughts can be illustrated in several ways. One such illustration is furnished by the walking out of a sheepsfoot roller during normal operation. When the first pass is made on a freshly-placed lift the soil is rather loose, the bearing capacity is therefore low, and the penetration of the feet is relatively great. Because of the low bearing capacity, the feet will penetrate until a sufficient number come in contact with the soil so that the total reaction of all feet in contact plus any load carried by the drum, if it is in contact with the soil, is equal to the weight of the roller. Figure 1 shows that if the four feet of a single row of the roller shown penetrate their full length, a total of 28 feet will be in contact with the soil. However, not all of these feet are carrying a load when the roller is in motion as will be discussed later. For this condition the pressures on the feet are certainly less than the nominal contact pressures which are computed by assuming that only the feet in one row are in contact. As additional passes are made, the density, and consequently the bearing capacity of the soil, increases and the penetration of the feet decreases. The increase of bearing capacity permits the feet to walk out as the number of passes increases. "Walking out" as used herein does not mean that the roller walks out completely as though it were operating on a pavement; instead it means that it walks out so that the feet are penetrating say only from 25 to 50 percent of their length.

In some soils the density can be increased, by a sufficient number of passes, to a point such that the bearing capacity of the soil is great enough to support the roller with only one row of feet in contact with the soil. In this case the roller has walked out completely and the unit foot pressures may actually be equal to the nominal foot pressures computed for the roller. Actually, this con-

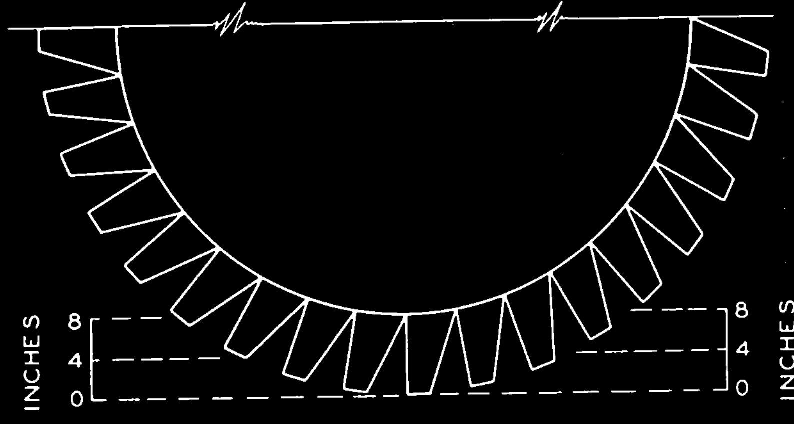


Figure 1. Variation of Number of Feet in Contact with Depth of Penetration.

dition is rarely, if ever, obtained in practice, for in the case of the roller shown in figure 1 a penetration of only 1/2 in. will bring three rows of feet in contact with the soil.

Since many engineers are accustomed to think of loads in terms of tons per square foot instead of pounds per square inch, it may be appropriate at this time to point out that contact pressures of 250, 500 and 1000 psi. are equal, respectively, to contact pressures of 18, 36, and 72 tons per square foot. When the loads on the feet are expressed in this way it can be seen that modern, heavily-loaded rollers impose tremendous loadings on the soil. It is apparent that these loadings can exceed the bearing capacity of many soils. For soils developing most or all of their strength through friction, the bearing capacity decreases with a decrease in size of loaded area, so that a relatively small variation in size of foot represents a substantial variation in bearing capacity.

Another illustration of the effect of the bearing capacity upon compaction is furnished by the following experience. In compacting a subgrade consisting of a lean clay and clayey silt, of low bearing strength, it was found that 50 passes of a roller loaded to about 600 psi. nominal contact pressure did not give the desired density, but when the roller was unloaded to about 400 psi. from 14 to 20 additional passes gave more than the required density. Evidently the heavier-loaded roller was continuously shearing the soil, but the lighter weight permitted effective compaction so that the effective contact pressure was greater than when the roller was loaded to a greater nominal unit weight. It is entirely possible that even better results would have been obtained if, instead of reducing the total roller weight, the area of the feet had been increased to the point where the bearing capacity of the soil would not have been exceeded. By using the heavier roller with larger feet the area of soil being compacted by each pass of the roller would have been increased so that the same compaction might have been achieved with fewer passes.

Another illustration of the decisive effect of bearing capacity upon compaction was furnished by one compaction study[4] with which the authors were associated. In this study it was found that for a silty clay and a clay sand, which had low to medium bearing strengths, a variation in nominal roller contact pressures had practically no effect upon the densities obtained for the number of passes used and under the test conditions existing. In these tests

[4] "Field Compaction Tests" by W. J. Turnbull and Gayle McFadden, paper IX-b-15, Vol. 5, Proc. of 2nd Int. Conf. on Soil Mechanics and Foundation Engineering, June 1948.

a field water content-density curve was actually developed eliminating the possibility that the water content was the unfavorable factor. The reason that the same densities were obtained with various nominal pressures is due to the fact that the bearing capacity of the soil was exceeded in all cases so that actually the nominal pressures were not obtained but instead the effective pressures were practically the same in all cases and equal to the bearing capacity of the soil.

The contact pressure of the feet is, therefore, an important factor in the performance of a sheepsfoot roller. It is readily apparent that adjusting the end area of the feet is a convenient means of varying the contact pressure of the sheepsfoot roller to suit the type of soil being compacted. It is believed that foot areas up to 12 or 16 sq. in. and even up to 25 sq. in. or more offer a profitable source of investigation, since by increasing the contact area of the contact pressure is decreased to a value approaching the bearing capacity of the soil but the total weight causing compaction is not changed. It is highly desirable that the total weight of the roller be as great as possible but that the contact area be adjusted to the bearing capacity of the soil.

When a sheepsfoot roller is operating efficiently it tends to walk out with an increasing number of passes. There are instances in which this did not happen when large heavy rollers having high nominal foot pressures were used. In these cases satisfactory results were obtained despite the failure to walk out. This is not difficult to explain, since the roller penetrated until an equivalent drum-roller effect was obtained which was in itself heavy enough to cause good compaction. However, compaction under these conditions is very inefficient as compared to that when the roller walks out.

Length of foot

The basic requirement for the length of foot is that it be at least as long as the thickness of lift being compacted. The length of foot does have considerable effect upon roller construction and operation. Experience shows that as the foot length is increased careful attention must be given to the design of the foot so that it can resist the larger stresses, especially in turning the roller. Another effect of foot length is in determining the length of drum required to maintain the stability of the roller. As the length of foot is increased the roller becomes increasingly more difficult to tow. Consequently, the longer the feet the longer must the drum be and the larger diameter must it have. Experience with two heavy sheepsfoot rollers of different design, each with 18-in. legs and capable of exerting upwards of 1000 psi. nominal pressure, demonstrated that great difficulty existed in turning the roller when towing with one of the common larger crawler-type tractors. Longer feet may have a place in the compaction of thicker lifts but there are little or no data available on this interesting possibility.

Thickness of lift

Thickness of lift is of relatively great importance. Some engineers and contractors consider thickness of lift to be a factor which should receive more consideration because of substantial benefits which may result from the use of thicker lifts. Many contractors are in favor of 12-in. lifts and this poses a challenge for the engineer which he should not ignore. It means that, if a satisfactory means of compaction can be found for these thicker lifts, important savings will result. Definite recommendations cannot be presented at this time but it is hoped they can be in the future and that this possibility will be considered by those concerned with compaction of soils.

Shape of foot

The feet of sheepsfoot rollers are manufactured in many shapes. This is true both for the face of the foot and for the foot shank. There may be some advantage to a particular shaped foot or foot shank with respect to ease of cleaning, rate of wear, etc., but these factors are beyond the scope of this paper.

It is desired to point out the lack of data by which the efficiency of different shaped feet in compacting soil can be compared. It is true that data are available from projects on which various shaped feet were used but the effect of the shape of the foot cannot be isolated because other factors such as roller weight, pressure intensity and type of soil were not constant.

Spacing of feet

In comparing sheepsfoot rollers, the effect of the number of feet on the drum is often ignored. The usual method of expressing this difference is drum area per tamping foot. A somewhat better method of computing or comparing foot spacing is to express the spacing of the feet as percent coverage; that is, computing the ratio of the total foot area to the area of an imaginary drum with a diameter equal to the distance between the extremities of diametrically opposed feet on the actual drum. When this is done it is seen that a variation in the number of feet results in a very considerable difference in the actual ground contacted by the roller. It is apparent if the preceding computations are made that the foot contact area is small compared to the total ground area covered by the roller. For the roller shown in figure 1 the percent coverage is only 5.2.

Distribution of roller weight

It is pertinent in discussing the loads exerted by sheepsfoot rollers on the soil to consider the distribution of the total roller weight among the feet penetrating the soil. When more than one row of feet is in contact with the soil, the pressures on the feet are not known. There will be no pressure on the feet to the rear of the axle when the roller is in motion, as those feet are being withdrawn from the soil. This, of course, neglects any rebound of the soil under a foot as the load is removed. Also, the row of feet just coming in contact with the soil will carry little or no load, as the surface soil is generally quite loose and the bearing capacity is extremely low. The roller is, in effect, always going "uphill" and it is likely that the feet forward of the axle carry a component of the horizontal force required to pull the roller. However, it is probable that the load will be carried on at least three or four rows of feet when one row of feet is penetrating the full length, and the actual foot pressures may be roughly one-third or one-quarter of the nominal pressures.

Effect of passes

The number of passes has a considerable effect on the soil density obtained and has received a moderate amount of attention. It is very often found that the relationship between density and number of passes is a straight line when the density is plotted to an arithmetic scale and the number of passes to a logarithmic scale as shown on figure 2. It is interesting that this relationship is generally obtained both for compaction in laboratory molds and for field compaction provided the water content is not very much wet of optimum in each case. It is apparent that a point of diminishing return is reached at which a large number of passes must be made to achieve a relatively small increase in density. The number of passes of a roller required to develop a certain density depends, among other factors, on the percent coverage as defined in a previous paragraph. The percent coverage for one pass of the roller shown on figure 1 is 5.2. Obviously, the total area of soil actually contacted by the feet increases with the number of passes and, assuming that the feet never contact the same area twice, the increase in coverage will be in direct proportion to the number of passes. This, of course, is the ideal case and does not necessarily occur in practice. Whatever the exact relationship may be, an increase in parcent coverage is obtained by an increase in the number of passes. If a certain number of passes is required to obtain a given density it can also be said that a certain percent coverage is required to obtain this density. If the percent coverage obtained by one pass of a roller is increased by increasing the foot

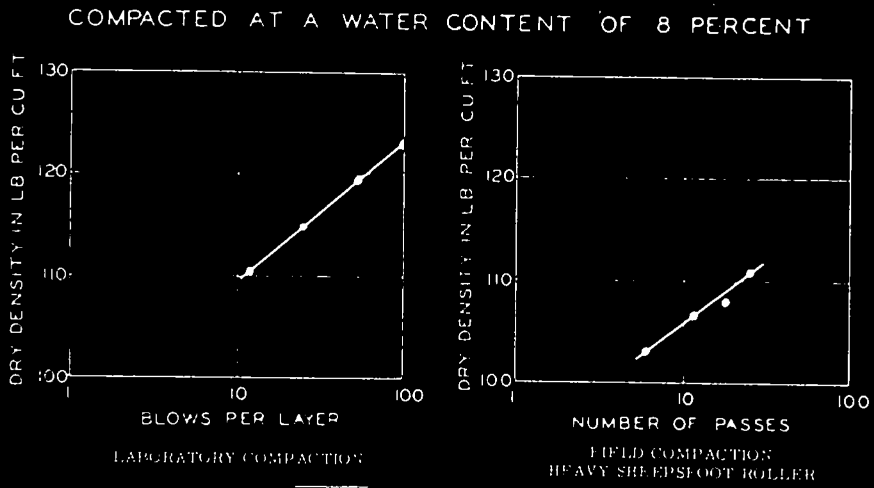


Figure 2. Relationship of Compactive Effort vs Dry Density.

area, it is apparent that the total coverage required will be obtained with a smaller number of passes. In the latter case the weight of the roller would, of course, have to be increased so that the same contact pressure will be maintained.

The above thought brings out an interesting possibility. For example, if the percent coverage of the roller shown on figure 1 were increased twofold (by doubling the foot area) from 5.2 to 10.4, and the same contact pressure maintained, would the same densities be obtained in one-half the number of passes? The percent coverage per pass can also be increased by increasing the number of feet, but this method has practical limitations due to the difficulty of proper cleaning. It is believed that the possibility of obtaining adequate densities with fewer passes by the use of rollers having a higher percent coverage per pass is well worth investigation.

In the preceding paragraph it was pointed out that the percent contact coverage of a sheepsfoot roller was quite small. A roller with, say, a percent coverage of 5 would require 20 passes to contact 100 percent of the ground area assuming the feet did not strike twice in the same place. It is, however, well established that adequate densities are usually obtained with a considerably smaller number of passes than 20. This fact is undoubtedly due to the spread of pressure with increasing depth below the end of the feet. Thus, on a plane parallel to the ground surface and several inches below the end of the foot, the area of soil subjected to pressure is much greater than the foot area, and consequently the percent coverage is correspondingly greater. The unit pressure at this depth is, of course, smaller than that obtained on the face of the foot. Thus the effective compacting pressure of a sheepsfoot roller is probably materially less than the nominal contact pressure. It is believed therefore that the above reasoning explains why a sheepsfoot roller with relatively small contact coverage per pass will produce densities comparable to rubber-tired rollers at about the same number of passes even though the latter has 100 percent contact per pass.

Rolling radius

In studying the behavior of sheepsfoot rollers, an attempt was made to analyze the motion of the feet as they penetrated and then withdrew from the soil. If the roller were operating on concrete it would be expected that the rolling radius would be the distance from the axis of the roller to the end of the feet, and if the roller penetrated the soil the rolling radius would be less.

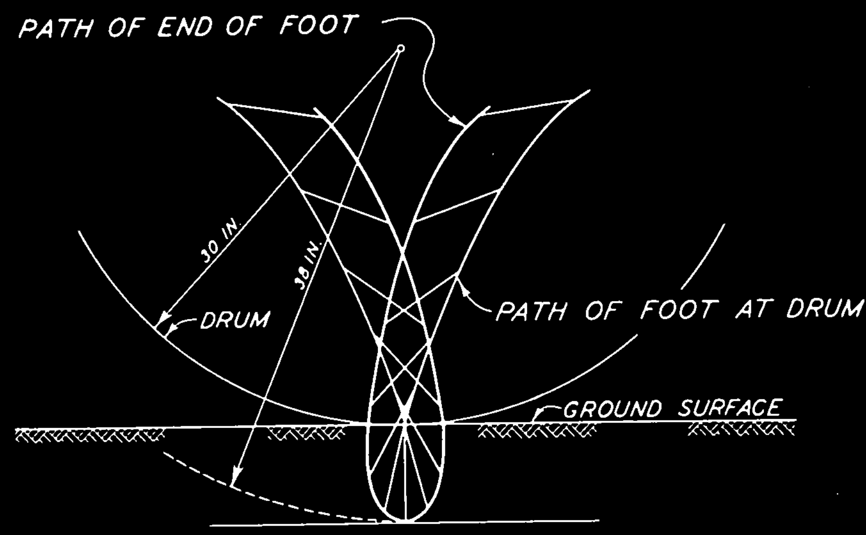


Figure 3. Locus of One Foot of a Typical Sheepsfoot Roller.

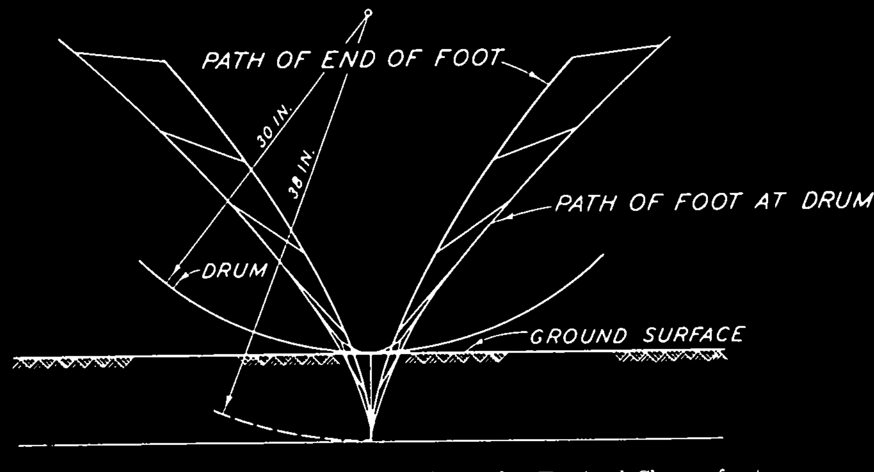


Figure 4. Locus of One Foot of a Typical Sheepsfoot Roller. (Rolling radius 38 inches)

Figures 3 and 4 show the path followed by the end of a foot for the condition when the rolling radius was equal to the distances indicated. The rolling radius was determined in the field in two instances and in both cases was more than the drum radius plus the foot length, and showed a tendency to increase with an increased number of passes. This indicates that the roller was sliding forward slightly. Such sliding may be caused by the braking action of the cleaners, resistance of the soil to withdrawal of the feet, or to other possible factors. This feature of roller behavior is cited primarily to illustrate roller action. The rolling radius is important in the case of towing a roller and in its maneuverability. It is known, for example, that a small-diameter roller pulls much harder and is harder to turn than a larger diameter roller of the same weight.

Field Optimum water content

Attention is invited to two well-known characteristics of laboratory compaction:

(1) For a given compactive effort, a water content-density curve is developed having a point of maximum density. The water content at this density is, of course, the well-known optimum water content.

(2) As the compactive effort is increased the optimum water content decreases.

Data are available from carefully constructed field test fills which substantiate the previously determined[5] but sometimes neglected fact that a water content-density curve having a point of maximum density is also obtained by field compaction. The water content at this maximum density might be termed "field optimum water content."

In spite of the fact that sufficient, reliable test data are not available to really establish a complete family of curves for compaction by various field compaction efforts, there is little doubt that field optimum water content decreases with increasing compactive effort in a manner similar to that occurring in laboratory compaction procedures.

Summary

The preceding factors which have been discussed are believed to be the principal ones affecting compaction of soils by sheepsfoot rollers. The possible effect of these variables should always be borne in mind when comparing compaction by different sheepsfoot rollers, and it is believed that these variables indicate, in accordance with actual results in the field, that it is not reasonable to expect one roller to be satisfactory for all soils and soil conditions. There is a decided tendency on the part of manufacturers to ask for a uniform specification for sheepsfoot rollers. Evidently the effect of the factors mentioned above must be considered and in such roller specifications provision must be made so that the important ones can be modified on a job to suit soil conditions. For example, it is desirable to use the heaviest roller available, but the roller must not impose heavier unit loads than the soil can carry; otherwise it will not perform any better than a lighter roller and will be more difficult to tow. It should, therefore, be possible for the engineer to require an adjustment in contact pressures when using a given roller, if it is apparent that the bearing capacity of the soil is being exceeded. Only if this is tried and the roller is found to be still too heavy should the total weight of the roller be decreased.

It is urged, therefore, that all pertinent factors be considered when proposing a standardization of roller specifications, for there are many factors entering into compaction which are still only partially understood. In addition, it is suggested that engineers be alert to observe the behavior of the roller and adjust the contact pressure to observed soil conditions. It is believed that first priority should be given to varying the area of the feet rather than the total weight of the roller.

RUBBER-TIRED ROLLERS

General

The variables present in compaction of soils in lifts with rubber-tired rollers include the area of contact, contact pressure, number of coverages, and thickness of lift. There are obviously several differences in compaction of soils by rubber-tired and sheepsfoot rollers. When a rubber-tired roller compacts a given area, every square inch of that area has been in contact with the tires, whereas when a sheepsfoot roller passes over an area only a small portion of the ground surface is contacted by a foot. The weight of the rubber-tired roller is, of course, equal to the

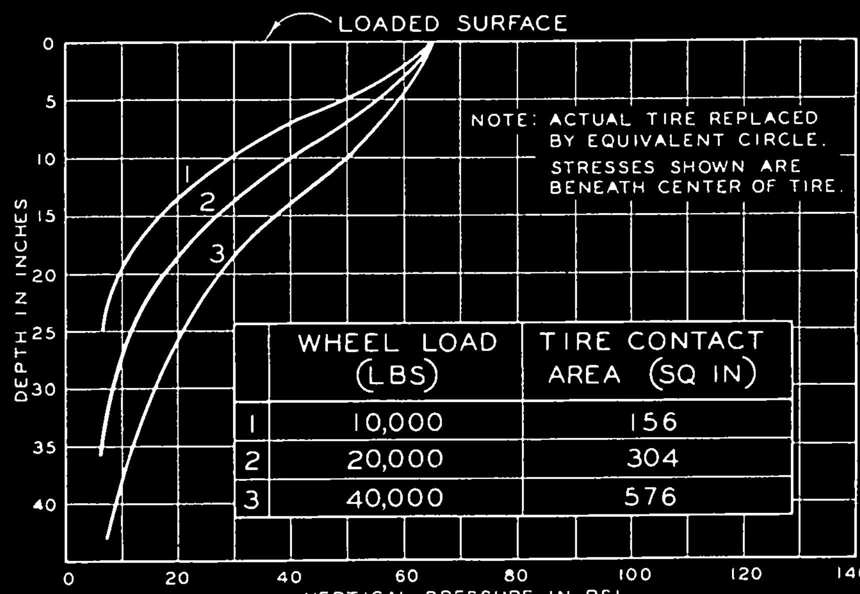
[5] R. R. Proctor, "On the Design and Construction of Rolled Filled Dams," Engineering News Record, 7 Sept. 1933.
F. H. P. Williams, Notes RN 896 and RN 963, Dept. of Scientific and Industrial Research, Road Research Laboratory, London.

product of contact area and contact pressure, and is not therefore considered an independent variable.

Contact Pressure

An increase of the contact area means an increase of the total weight of a roller if the inflation pressure, and hence the contact pressure, of the tires is unchanged. Consequently, if the total weight increases there will be an increase in the area being compacted but the intensity of loading is constant. Because the contact pressure is constant, it is apparent that the density may not be affected by an increase in total weight of the roller when compacting in lifts. An exception to the above occurs when compacting cohesionless soils, for in this case, even though the contact pressure may be constant, the confining effect of a larger area becomes important in giving better compaction.

Generally then with 6-in. compacted lifts, as are commonly used, any given area of soil will be affected principally by the contact pressure immediately on it and is little affected by the areal extent of the load. This may be seen by figure 5, which shows, for illustrative purposes, pressure distribution based on Boussinesq's equation, for various sizes of rubber-tired loads, indicating that for the relatively shallow depths to consider in ordinary lift construction (about 6 in.), the pressure imposed on the soil being compacted is practically independent of the area of the load. Thus, if various weights of rollers are used, each having the same contact pressure, it may be reasoned that very similar compaction should be obtained, and indeed this has been borne out in actual tests[6]. In certain of these tests rubber-tired compactors varying in total load per tire from 10,000 to 40,000 pounds but having the same contact pressure gave practically identical results for compaction in 6-in. lifts for both a clayey sand and a lean silty clay. This is regarded as rather conclusive proof that the density obtained in 6-in. lift construction is a function of the tire contact pressure, rather than total load. Consequently, the contact pressure is believed to be the most important single factor influencing compaction in ordinary lift construction by rubber-tired



	WHEEL LOAD (LBS)	TIRE CONTACT AREA (SQ IN)
1	10,000	156
2	20,000	304
3	40,000	576

Figure 5. Pressure Distribution Beneath Wheel Load (Contact pressure of 65 psi.)

[6]Loc cit.

equipment. The total weight of roller is of importance in the economics of the operation but is of secondary importance in influencing the results obtained.

Just as in the case of sheepsfoot rollers, the contact pressure can not exceed the bearing capacity of the soil. This becomes of greatest importance if compacting substantially wet of optimum and when high pressures are being used. In the writer's experience, high pressures are more critical in cohesionless soils than in those having some cohesion. In one instance the tires of a compactor inflated to a pressure of 100 psi. penetrated into a sandy soil to the extent that a D-8 tractor could not pull it. However, precompaction with the same roller and the tires inflated to 60 psi. permitted later compaction with the higher inflation pressure and good results were obtained.

It is considered desirable that the tire pressure be as large as the bearing capacity of the soil will permit. In addition the tire size should be as large as possible, especially if compacting thicker lifts than usual and on cohesionless soils.

Coverages and lift thickness

The effect of number of coverages of rubber-tired rollers on soil density is of importance and has a relationship similar to that given for sheepsfoot rollers. The effect of thickness of lift is particularly pronounced, however; a deficiency in contact pressure can never be fully overcome by a thinner lift, and decreasing the thickness of lift is an expedient to be used only when adequate contact pressure cannot be attained.

Distribution of tire load

At this time the importance of variations in contact pressure over the contact area cannot be evaluated but it is interesting that such variations do occur. This has been proved by direct pressure measurements as well as by indirect means. It is customary in compaction studies to measure the contact area and to obtain an average contact pressure by dividing the wheel load by the contact area. The average contact pressure so computed is generally somewhat different than the inflation pressure. In several cases where the inflation pressure was about 55 psi., the contact pressure computed from the total load and tire print area was about 65 psi., indicating that the tire sidewalls were carrying part of the load and that a uniform load distribution did not exist. In contrast, on some higher pressure larger-size tires where the inflation pressure was about 100 psi., the average computed contact pressure was but 87 psi., again demonstrating an unequal pressure distribution. Pressure cells placed beneath these tires have shown an unequal pressure distribution with a pressure on each side of the denter line of the imprint area of the tires higher than that either at the center line or edge

Summary

It is believed that the variation of the bearing capacity of different soils must be recognized, and that it is desirable to vary the rubber-tired roller to suit the soil and its bearing capacity when being compacted. In selecting a roller for a specific job of compaction, two important considerations exist, one the contact pressure as limited by the bearing capacity of the soil, and the other that of selecting the heaviest roller and largest tire size commensurate with practical and economical operation. In the case of cohesionless soils these two considerations are closely interrelated. It is apparent that the tire size greatly affects the bearing capacity in soils deriving an important part of their strength by friction, since the larger the loaded area the larger the bearing capacity. Thus, to get effective compaction in lift construction, a high contact pressure may be required, but in order not to exceed the bearing capacity for this pressure a large tire, and therefore a heavy roller, must be used. Regardless of the type of soil the most important factor governing the results obtained is the contact pressure, and this should be as large as conditions permit.

SUBGRADE COMPACTION

Subgrade compaction by rubber-tired and sheepsfoot rollers is mentioned briefly and some of the factors involved are pointed out. In subgrade compaction, soil which is a considerable distance below the sheepsfoot or rubber-tired roller must be compacted. Consequently, the total load becomes a very important consideration, since only by having a sufficiently high load can efficient compacting pressures in the soil be realized at substantial depths.

The writers have found[7] that very heavy sheepsfoot rollers having long legs have given good subgrade compaction and have achieved excellent results when the water content of the soil was favorable. It is particularly important to emphasize that the water content of the soil must be favorable if deep compaction is to be obtained. If the soil is too wet it cannot be compacted, and any attempt to do so will only result in a build-up in pore pressures with a possible decrease in shear strength. Sheepsfoot rollers of high nominal presure intensity (upwards of 1000 psi.) and with 18-in. feet have been found to give substantial increases in density up to depths of 5 feet. However, they leave the surface (12 to 18 in.) in a loosened condition and do not exhibit any tendency to walk out in the usual sense. Rubber-tired rollers of medium weight can be used satisfactorily for compacting the upper 12 to 18 in. after the sheepsfoot roller finishes its deep compaction. Stage rolling of this type appears to offer definite possibilities for subgrade compaction and may be applicable to lift construction as well. It is possible that thicker lifts could be used in this way on lift construction for roads, airfields and dams.

Experience has indicated that very heavy and large rubber-tired rollers, with contact pressures upward of 65 psi. may give substantial increases in density of subgrades up to depths of 5 feet, provided that the water content is favorable to compaction and that the ground will support the roller. The rubber-tired roller has the advantage that a loose layer is not left at the surface.

[7] "Subgrade Compaction Tests with Heavy Rollers" by S. J. Johnson and A. A. Maxwell, paper IX-b-10, Vol. 5, Proc. of 2nd Int. Conf. on Soil Mechanics and Foundation Engineering, June 1948.

COMPACTION OF SOIL AND BASE MATERIAL ON THE BALTIMORE FRIENDSHIP INTERNATIONAL AIRPORT

Henry B. McDonald, Nathan L. Smith, Jr., and B. Everett Beavin, Sr.[1]

PRELIMINARY INVESTIGATIONS

The site, located in Anne Arundel County, Maryland, containing approximately 3,300 acres or 5 square miles, is bounded on the west by the Pennsylvania Railroad, on the east by the Hammonds Ferry Road, on the north by the Stony Run Road, and on the south by the Glen Burnie-Dorsey Road. The land is gently rolling, typical of the Coastal Plain of Maryland as it approaches the Piedmont Plateau. It is drained by three major streams: Cabin Branch, Sawmill Branch, and Stony Run. Ground elevation varies from about 80 to 195 ft. above sea level. Except for a few isolated areas west and north of the site, all land within 2 miles of the boundaries lies at an elevation lower than the general level of the airport runways.

The Coastal Plain of Maryland consists of plains, hills, and terraces largely of sand and gravel and is underlain by a succession of eastward dipping sheets of clays and sands lying on a sloping floor of older rocks. Where this floor of rock rises to the surface a few miles west of the site, the Piedmont Plateau begins. Most of the site is of Patapsco formation, which is comprised of some clay, many local sand bodies, and gravel deposits. The higher parts of the site are comprised of a terrace sand-gravel of the Sunderland formation. There are many lenses of a white silty clay. These lenses vary from a few square yards to many acres in extent and from an inch or less to 6 ft. in istration System Class A-3 (USED Types GP, GW, SP and SW and CAA Types E-1, E-2, E-3, and E-4). These sands and gravels extend to considerable depth. In some parts, mixtures of poorly graded sand, silt, and clay of both the friable and plastic types are found. These are mainly of PRA Class A-2 (USED Types SP and SF and CAA Types E-3, E-4, and E-5) and borderline Class A-2-4 (USED Type SF and CAA Types E-4 and E-5) soils.

The PRA Class A-2 soils occur largely in cut areas and provide an ample supply of material suitable for embankment construction. Much of the A-2 material was satisfactory for sub-base construction.

The clean sands and gravels classified as A-3 are ideal for pavement subbase or aggregate for sand-asphalt construction. They are generally rapid-draining and are not subject to frost heaving.

The white silty clay classified as PRA Class A-4 (USED Type CL and CAA Type E-6) is unstable when wet and is subject to frost heaving. The Liquid Limit is 30 to 32, the Plasticity Index, 10 to 12.

The soil information previously given, which generally indicates the extent of knowledge at the beginning of the rough grading operation, was obtained from existing geological and agricultural soil surveys and by analyzing samples of soils taken from over 400 borings at locations scattered over the area, supplemented by samples secured from existing railroad and highway cuts and by aerial photography. The following table shows the approximate sieve analyses of the various materials.

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TABLE 1

APPROXIMATE SIEVE ANALYSES OF SOILS

FRIENDSHIP INTERNATIONAL AIRPORT

Screen Size	Sand-Gravels*	Sands*	Silty-Clays*
1-1/2-in.	100	100	100
1-in.	95-100	100	100
1/2-in.	83-100	100	100
No. 4	68-90	97-100	100
No. 10	48-85	92-100	98-100
No. 20	26-78	84-100	96-100
No. 40	12-60	30-98	94-100
No. 60	4-36	12-60	85-100
No. 140	3-20	3-22	70-98
No. 200	2-18	2-18	65-97

*Percentage Passing.

During this period, Messrs O. J. Porter, Thomas A. Middlebrooks, B.K. Houk, and C. A. Hogentogler, Jr., advised the engineers on all problems relating to soil mechanics. From the information then available, tentative decisions were made as to pavement thickness and compaction methods.

ROUGH GRADING

The rough grading for the airport was begun on May 1, 1947. The project included 7,000,000 cu. yd. of excavation and was characterized by a very fast construction schedule, the contractor moving upward of 50,000 cu. yd. per day during the major part of the construction season. This part of the work brought the subgrade to 15 in. below finished grade.

Due to the unstable conditions in the construction industry and the prevailing excessive prices for excavation, it was decided to write the specifications in such a fashion that the bidder might know exactly how much compaction would be required and to provide for additional payment if the engineers should decide additional compaction was necessary. The specifications required embankments to be formed in layers of not more than 8 in. in loose depth and that they be compacted with heavy sheepsfoot tamper type rollers, having not less than 500 lb. per sq. in. pressure under the tamping feet. Four passes over each layer were to be performed at the contract unit price. The contract unit price did not include the addition of water, it being the opinion of the engineers that moisture adjustment would not be required. The economy of relieving the contractor of the gamble as to the amount of compaction required was reflected in his bid price of 25 cents per cu. yd. for excavation and 1-8/10 cents per cu. yd. for compaction. The previous trend of similar work had been in excess of 40 cents per cu. yd. for excavation and compaction.

At the beginning of the operation, the contractor doubted the efficacy of the heavy sheepsfoot rollers in compacting the sandy soils. Therefore, an experiment was carried out using a light sheepsfoot roller, a heavily loaded Tournapull, and a heavy sheepsfoot roller. It was found that the most satisfactory results could be obtained with the latter. Compacting in 8-in. layers, the light sheepsfoot roller gave average densities of 93 percent, the Tournapull averaged 86 percent, and the heavy sheepsfoot roller averaged 99 percent (all at 2-ft. depth).

The heavy sheepsfoot roller never "rode out", but left the surface in a rather loose condition. However, at a depth of 18 in. and more, the sand was found to be of fairly high density. Knowing that several feet of the top of all fills were to be compacted with a heavy rubber-tired roller, it was decided to make all density tests, during the rough grading, at a depth of 2 ft.; and very consistent results were obtained. The Modified Proctor Test was used, adjusted for percentage of gravel contained in the samples. The densities at 2-ft. depth ranged from 95 to 107 percent, with an average of 99 percent of laboratory maximum. Tests made at depths of 12 in. averaged 89 percent and at 18 in. averaged 93 percent. The efficiency of sheepsfoot rollers, in sands of the type encountered, was well demonstrated.

The fast construction schedule undoubtedly was of benefit in obtaining the high densities because the material from the cuts was not exposed long enough to dry out before being conveyed to the fills and compacted in place. At no time was it necessary to add moisture to obtain proper compaction, although the contractor sprinkled his haul loads frequently to keep down dust and to permit faster operation of earth-moving equipment. Typical material in the cut areas averaged 88 percent of laboratory maximum density, and weighed from 100 to 130 lb. per cu. ft. (dry). Actual measurements of shrinkage showed that 1 cu. yd. of excavated material made only .77 cu. yd. of fill which provides a rough check on the relationship between densities in place and densities in the completed fills.

A great deal of exploration was done with earth augers to detect lenses of the white silty clay; and most of the large ones were located during the rough grading operation. Any of this material found within 5 ft. 3 in. of finished grade, that is, within 4 ft. of subgrade, and beneath the pavement and shoulder areas (150 ft. each side of center line on runways and 85 ft. on taxiways) was removed and replaced with selected sandy material. In many cases, additional cuts or borings were made through the remaining clay to the sandy soil below in order to reduce the size of the impervious lenses and decrease the later possibility of a perched water table. This silty material was used mainly in embankments beyond the pavement lines or it was wasted. If the clay was thoroughly dispersed through the sand, it was found to make satisfactory fill material; and it was used, in a few instances in areas to be paved but not within less than 6 ft of subgrade. Approximately 250,000 cu. yd. of this material were removed during the rough grading operation.

Approximately 165,000 cu. yd. of sand-gravel (A-3 material) were stockpiled near the northwest end of the northwest-southeast runway. Many smaller deposits were so intimately mingled with the white silty clay (A-4) that they could not practicably be separated therefrom. The stockpiled material later was used as aggregate for the two 3-1/2 in. sand-asphalt base courses of the flexible pavement.

PNEUMATIC COMPACTION ROLLER

During the preliminary investigation period, it had been decided that subsoil conditions were favorable to very heavy compaction and comparatively thin pavement. In order that confirmatory tests might be carried out to enable final design of pavement and to avoid delay to the paving operation, the Department of Aviation, in July, 1947, purchased a Porter heavy pneumatic compaction roller. The roller ready for use, but without ballast, weighs approximately 40 tons. One hundred sixty tons of cast iron ballast were furnished, giving a range in gross weight from 40 to 200 tons.

The roller consists of two articulated load boxes, each 20 ft. long, 7 ft. 4 in. wide, and 6 ft. high. Each box is supported by two wheels on a single axle. The wheels are fitted with 30 x 33 pneumatic tires. The two units are tied together by two bars on trunnion assemblies which allow the two units to oscillate. The tires are 60-ply nylon cords with an accredited manufacturer's capacity rating of 100,000 lb. each at an operating pressure of 120 to 150 psi. A towing tongue is provided and is equipped with standard hitch for attaching the roller to a crawler type tractor.

TEST PROGRAM

After delivery and acceptance of the pneumatic compaction roller (hereinafter referred to as the "supercompactor"), a program of tests was carried out for the purpose of deciding the number of passes most likely to be necessary for proper compaction during the subgrade and sub-base preparation phase immediately to precede paving.

The Corps of Engineers was interested in this test program and made available the services of several men who rendered invaluable assistance in making the necessary tests.

Unfortunately, the weather was very bad with rain, snow, and alternately freezing and thawing temperatures. These conditions were not conducive to accurate results Since it was planned to let a contract for compaction and paving early in the spring of 1948, there was no alternative but to proceed and to make allowances for the weather conditions

The test section was laid out with unrolled areas between strips. After fine grading, levels were taken at 10-ft. intervals longitudinally and transversely. In addition, a number of 6-in. square metal plates were buried at 6- and 12-in. depths along the center line of each strip, located accurately horizontally and vertically.

Four test strips were compacted with 4, 8, 16, and 28 coverages (two passes being required for one complete coverage).

After rolling, test pits were dug in rolled and unrolled areas; and triplicate field density and CBR tests were made at 1-ft. levels, to a maximum depth of 6 ft. These results varied widely due to weather and variegated soil types, but generally indicated marked improvement in strength

The metal plates furnished valuable information concerning movement of soils under compaction. As expected, the greatest movements were in the plates buried 6 in. deep. Movements were greatest in cut areas overlying clay lenses. Longitudinal movements ranged from .04 to 1.16 ft, lateral movements from 0.1 to 0.46 ft. and downward movements from .01 to .65 ft. Movements in fill areas were much smaller than those in cut areas. It was found that a satisfactory increase in density was obtained in about twelve coverages, after which the rate of increase declined.

Important information was obtained from the failures of the subgrade overlying small lenses of white silty clay with a perched water table. Rolling brought the water to the surface and severe rutting occurred. Where water was not encountered, no such failure was observed. Densities of sands under clay lenses were not improved as much as at equal depths where no lenses were present.

Movement of the soil, observed during the test program, was also noted during construction. It is interesting to note that rutting of the surface occurred where rolling was carried out across the boundary of a previously compacted section. This apparent failure was attributed to the higher density and consequent greater resistance to movement of the already compacted material. In these cases, when borings showed that no unsatisfactory soil was present, the surface was smoothed in order to facilitate operation of the supercompactor and rolling was continued. After the initial four passes, rutting became less severe and finally disappeared.

An attempt was made to correlate the data into exact rules regarding supercompaction; but for several reasons, in addition to the weather, such correlation was found impracticable. These reasons are: (1) in spite of the fact that the location selected for the test apparently was of uniform consistency, about half on cut and half on fill, it was found, under detailed examination, to contain almost as wide a range of soil as does the entire airport site (sand-gravels with as much as 35 percent gravel, sands of all types, and ever-present lenses of white silty clay); and (2) CBR tests made in the field could not be correlated with those made in the laboratory on identical soil, although the laboratory test results were very consistent within themselves.

The test program did, however, fulfill its major purpose, that of obtaining sufficient data for preparing the plans and specifications for subgrade and subbase preparation and paving. It indicated that, in the absence of clay lenses, densities of 100 percent could be obtained by supercompaction to a depth of at least 3 ft.

SUBGRADE AND SUB-BASE PREPARATION

This work was begun on March 12, under Contract No. 7. Thé contractor was allowed to use the supercompactor previously purchased by the City and was required to maintain the equipment and carry adequate insurance but was charged no rental.

From the test program it had been estimated that fills would settle about 2 in. and cut areas from 4 to 6 in. under supercompaction Twelve complete coverages with the supercompactor and 8 passes with a heavy sheepsfoot roller were specified. The pavement, based on a 100,000-lb. desigh wheel loads, was determined to be 10 in. of asphalt-bound material and 5 in. of selected granular material, plus the additional thickness due to the variable amount of settlement to be experienced under supercompaction. This space also was filled with carefully selected granular material from the site; and all of the granular material was rolled with the supercompactor.

Here, again, major economies were achieved by specifying the amount of compaction and providing for payment for additional compaction, the contractor's price for subgrade preparation being only 3 cents per sq. yd.

The first step was to make four coverages on the subgrade with the supercompactor, first, to detect weak spots or as yet undiscovered lenses of white silty clay and, second, to accomplish the gross settlement before pipe and duct lines were installed and before subbase material was placed. About 50,000 cu. yd. of white clay were removed during this phase of the operation. This clay was replaced with carefully selected granular material. Utilities were installed and the trench refill compacted by mechanical tampers and by tractors and sheepsfoot rollers.

The sub-base material was placed and disced to mix it with the subgrade material, then given eight passes with the very heavy sheepsfoot roller, followed by eight additional coverages with the supercompactor. No matter how much compactive effort was applied to trenches by other means, several inches of settlement occurred under the supercompaction. This settlement of trench refill, regardless of compaction method, led to the adoption of soil-cement as a refill material alongside certain structures which were of necessity built after the completion of rolling. Local sand, often that removed in excavation for the structures, was used with the addition of three bags per cu. yd. of Portland cement mixed in a concrete mixer. This type of refill was brought to the elevation of the bottom of the asphalt-bound base.

Where sands were of uniform grain size, it was found necessary to blend other material in order to tighten up the subgrade sufficiently to permit proper supercompaction. The only nonplastic fines available were in the very poor sandy topsoil salvaged from the site. Vegetable matter was almost nil and the admixture of this soil made it possible to obtain a dense, hard surface upon which to place the first course of paving. Effective results also were obtained by blending well graded sand-gravels into the subgrade. Unfortunately, the quantity available was limited. Most effective supercompaction was obtained when the field moisture content was approximately 2 percent below laboratory optimum moisture content.

The supercompaction furnished the most reliable control of subgrade construction, every square foot of which was tested under loads approximating those to be applied under operating conditions.

The sub-base was finished by light blading, sprinkling when necessary, and then rolling with a 10-wheel, rubber-tired roller weighing about 11 tons.

The first course of sand-asphalt (3-1/2 in.) followed closely behind this treatment, in order to obviate further sprinkling and rolling and to cover the sub-base as fast as possible to permit upper course paving while waiting for the subgrade to dry out after heavy rains.

The total cost of compaction, 31 cents per sq. yd., is about the equivalent of the cost of 1 sq. yd. of flexible pavement 1 in. thick.

TABLE 2

ESTIMATED COST OF COMPACTION

Heavy sheepsfoot compaction of fills, prorated over paved area	$0.09
Four coverages of supercompactor on subgrade	0.03
Eight coverages of heavy sheepsfoot roller on sub-base	0.0625
Eight coverages of supercompactor on sub-base	0.06
Cost of supercompactor (depreciated 50 percent)	0.06
Tests and miscellaneous expense	0.0075
TOTAL	$0.31