Effect of Base Course Gradation on Results of Laboratory Pumping Tests

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This paper reports the results of a laboratory study to investigate the performance of a variety of base course samples with different gradations when these samples are placed over a standard subgrade soil and subjected to repetitions of load in such a way as to induce the pumping of fine soil to the base course surface and the intrusion of subgrade soil into the interstices between base course particles.

A good correlation existed between large deflections of a subgrade-base course system and either base course pumping or subgrade intrusion. Specimens with very open-graded gravel bases were subject ot intrusion of subgrade soil, and specimens with dense-graded gravel bases (excess of 3 percent by weight finer than the No. 200 mesh sieve) demonstrated pumping of fine soil sizes to the base course surface. An optimum gradational range exhibited neither base course pumping nor significant subgrade intrusion. Test specimens with coarse sand base course samples performed satisfactorily over a wider range of gradation than those with larger sized gravel bases. Test results were compared with existing filter criteria for thin base courses.

THE DESIGN of granular base courses for use under rigid highway pavements, from the standpoint of gradation, has for the most part developed from the results of numerous pavement performance surveys and several highway test sections (1, 18, 19, 29). These performance surveys have been conducted and these test sections built by the highway departments of the various states and by public and private research organizations. The results of such endeavors have been general in nature, in most cases indicating trends, and have been incorporated into the specifications for base course materials of various agencies, most often in the following forms: (a) limits on the allowable percentage of different size fractions, (b) restrictions on the quantity of material finer than the No. 200 mesh sieve or finer than 0.02 mm, (c) a maximum allowable plasticity index of the finer soil sizes and (d) general direction toward the use of either open or dense-graded materials. Often, however, specifications have necessarily been tempered by the quality of locally available materials, the economics of altering the gradation of existing natural materials and expedients of construction. The concern of engineers regarding the gradation of granular base courses has developed primarily through attempts to control the detrimental effects that often accompany frost penetration and pavement pumping. As a result, gradational requirements vary from area to area with the factors that influence these problems (differences in soil conditions, rainfall, temperature, traffic, and available materials of construction) and with the experience of local engineers.

In September 1953, the Purdue Research Foundation entered into a contract with the Arctic Construction and Frost Effects Laboratory of the Corps of Engineers, U.S. Army, to study base course requirements for rigid pavements constructed over frost-susceptible subgrades. The purpose of this study was to provide data either to substantiate or to revise existing criteria relative to required thickness and quality in areas which experience significant frost penetration.

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This investigation consisted of two phases, an extensive field and office correlative study of highway and airfield pavements (32) and a statistical laboratory study to evaluate the relative influence of various subgrade and base course factors on the pumping of rigid pavements (17).

The former included a literature search of current airfield and highway practices, field observations at selected air installations, and an edge sampling program and performance survey of rigid pavements in Indiana constructed with granular subgrade treatment. Data obtained from this study indicated that performance of rigid highway pavements built with granular bases is greatly influenced by the gradation of the base course material.

The laboratory study showed that the performance of a subgrade-base course system cannot be explained solely by a consideration of the direct effects of one selected factor as base course gradation, but is dependent to some extent on the interaction between a number of factors; such as, subgrade type and compaction, base course type and compaction, and the magnitude of the applied load. It was concluded, however, that if selection of a base course type is feasible in a given situation, one with an open textured gradation should be chosen since it would be apt to deflect less under repeated loads than a dense-textured base until the total deflection of the latter had increased to a point where structural failure of the overlying pavement could be postulated.

DEFINITION OF THE PROBLEM

In an investigation of this nature, it is important that the event being observed be defined so that test results may be viewed in the proper perspective. No attempt is made to review the literature pertaining to pavement pumping as this has been done many times by others. The following comments, however, present a concept of pumping action which may or may not be in contrast to that of others. It is important to note that these remarks apply only to pumping of rigid pavements built on granular bases. Pumping of fine-grained soils has received attention by many investigators and will not be discussed here.

Pumping action, with respect to rigid highway or airfield pavements constructed over granular base courses, is an inclusive term relating to the movement of finer soil sizes (sand, silt, and clay), which exist beneath a pavement surface. Removal of fine soil sizes results from the rather rapid movement of water carrying with it soil particles either in suspension or in motion as a result of hydrodynamic forces, the water moving under a pressure differential caused directly or indirectly by the deflection of a loaded pavement slab. This action may be minor and produce no significant pavement distress or it may result in severe pavement damage. This action may proceed for varying periods of time before surface evidences of it are discernible. The action is generally intermittent or cyclic in nature over a given period of time.

Pumping action may consist of one or all of the following:

1. The movement of particles from and about the base course surface. This aspect of pumping is erosional in nature and results from the lateral movement of free water along the base course surface as a result of displacement by a deflecting slab causing water and soil, upon occasions, to be ejected at pavement joints, cracks, and edges. The conditions necessary for this type of pumping to occur are: the existence of a void space between the pavement slab and the base course surface, the presence of a small amount of free water on the base course surface, and the existence of particles small enough to be moved. This type of pumping has been termed "blowing" by some investigators.

2. The movement of the finer soil sizes within and out of the base course. This aspect of pumping may result from the release of pore water pressures or by elutriation if deflections within the base course are great enough. Conditions necessary for this type of pumping to occur are: a high degree of saturation of the base course with the presence of free water to at least the base course surface, deflection in the base course sufficient to cause the development of adequate pore water pressures,

pore sizes in the base course of sufficient size to permit the movement of fine soil particles, and soil particles within the base course small enough to be moved. This type of pumping has been induced in laboratory tests (17).

3. The movement of subgrade soil into the interstices between base course particles. It has been postulated (17) that this might reslut from the release of pore water pressure developed in a softened subgrade soil resulting from the transmission of load through a granular base course to the subgrade surface. A distinction is made here between this aspect of pumping and the intermixing of subgrade and base course that may result from a kneading action. The latter is not considered to constitute pumping in terms of the definition given above but, rather, is related to local shearing failure of the subgrade soil at its surface of contact with the base course. The conditions considered necessary for this type of pumping to occur are: a high degree of saturation of the subgrade soil so that appreciable pore water pressures will result from small deflections of a loaded pavement, cohesive bonds in the subgrade soil which are not strong enough to resist the hydrodynamic forces of escaping pore water, a compressible subgrade soil, a base course which is many times more permeable than the subgrade, a source of available ground water, and pores in the adjacent base course material of sufficient size to permit the entrance and movement of subgrade soil particles.

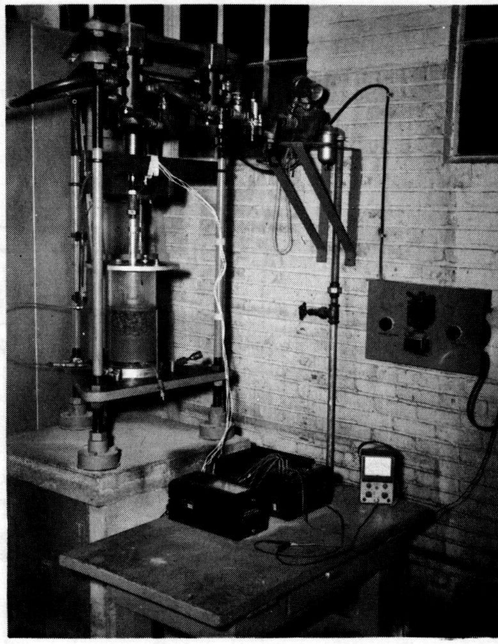

Figure 1. Repetitive loading equipment.

PURPOSE AND SCOPE

This research program investigated by means of repeated load tests, the performance of a variety of base course gradations with respect to the movement of fine soil to the base course surface and the movement of subgrade soil into the interstices between base course particles. Eight gravel base course samples, varying from extremes of open-graded to dense-graded; 7 coarse sand base course samples, similarly graded; and a series of uniform-graded samples were placed, each at a relative density of approximately 90 percent, over a standard silty-clay subgrade compacted to 90 percent of modified AASHO density, and subjected to repetitions of a 25-psi load applied at the base course surface. In each case, the load was applied through a loading piston which at all times remained in contact with the base course surface. It was possible with this type of test to induce the movement of fines through and out of the base course as well as the intrusion of subgrade soil into the interstices between base course particles by a pumping action or by mechanical manipulation or kneading at the subgrade-base course surface of contact. It was recognized that there are other aspects of base course performance for instance, permeability, which are dependent upon gradation; but these were not considered.

TEST EQUIPMENT

The loading device used for testing subgrade-base course combinations is shown in Figures 1 and 2. Essentially this piece of equipment consists of a piston mounted vertically in a loading frame and activated by compressed air. The pressure applied at the piston face could be controlled for magnitude by a regulator in the air line and

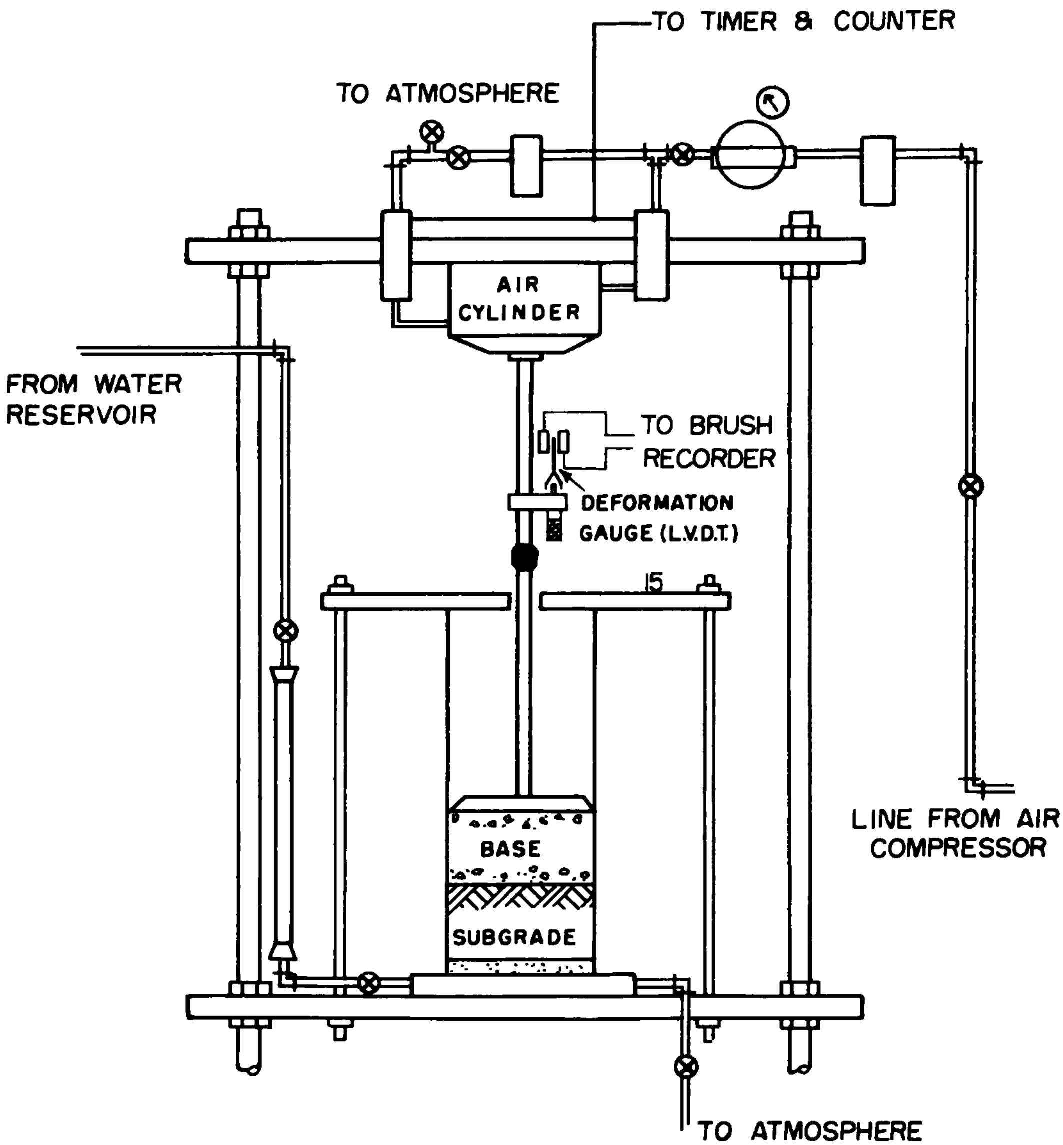

Figure 2. Schematic diagram of repetitive loading equipment.

for duration and interval by a set of inlet and exhaust valves activated electrically by a timing device (17).

Compressed air at 100- to 110-psi outlet pressure was supplied by an air compressor. From the compressor tank a 1-in. diameter galvanized pipe led through an air line filter to remove moisture and any foreign particles from the air, and thence into a pressure regulator.

From the pressure regulator the line passed through an air line lubricator and branched to enter 2 electrically-controlled valves, each of which was connected to one end of an air cylinder. This cylinder was mounted vertically to the upper platen of a loading frame and afforded a downward stroke of from 0 to 2 in. for the loading piston. A loading head attached to the loading piston applied load directly to samples of subgrade and base course placed on the lower platen beneath the air cylinder. Any desired number of loading cycles between 0 and 99,999 could be preset by means of a predetermined counter.

Adjustments were made so that only the single-acting type of movement of the loading piston was used; that is, the loading piston remained in contact with the base course surface at all times. The arrangement used to measure deflections of the subgrade base course system utilized a linear variable differential transformer with suitable recording apparatus (see Fig. 2).

MATERIALS

Subgrade Soil

The soil chosen for the molding of subgrade samples was light-brown silty clay collected in the vicinity of Lafayette, Indiana. This soil was taken from the "B" horizon of the Crosby profile which begins at a depth of about 4 in. below the ground surface and extends to a depth which may reach 50 in. The Crosby profile occupies a considerable portion of the gently undulating Tipton Till Plain of the Older Wisconsin Drift. As such, it provides the subgrade support for many miles of highway pavement in the Lafayette area. The index properties of the Crosby soil, performed on random samples of the air-dried processed soil, are as follows:

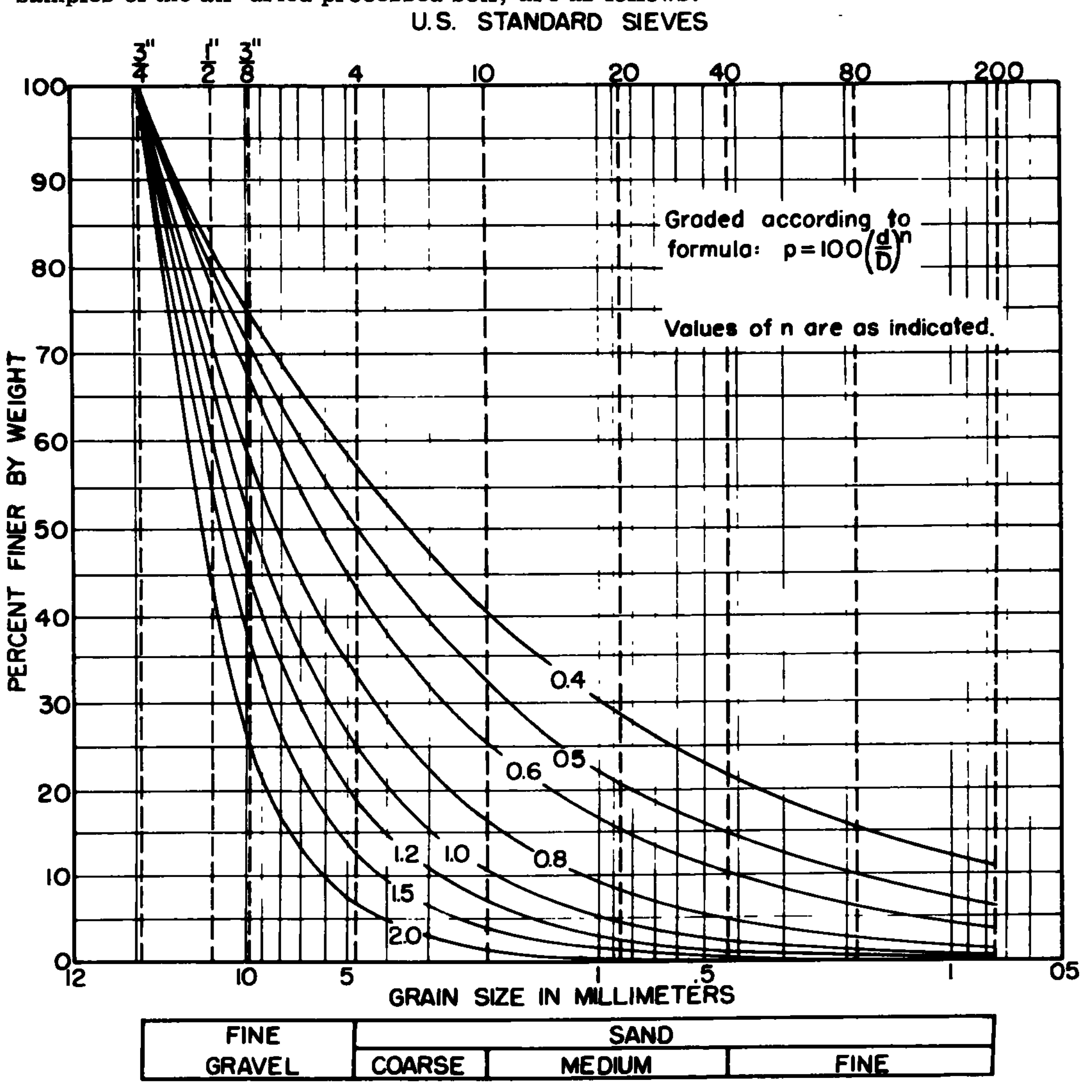

Figure 3. Base course gradations; maximum size 3/4 in.

Liquid limit =	37.2%
Plastic limit =	19.4%
Plasticity index =	17.8%
Specific gravity =	2.69
Modified AASHO maximum density =	118.8 lb/cu ft
Modified AASHO optimum moisture =	13.6%
Grain size distribution	
No. 4	100% finer
No. 200	85% finer
0.01 mm	40% finer
0.005 mm	30% finer
0.001 mm	20% finer

Base Course Materials

The material selected for use in preparing base course samples was washed glacial terrace gravel obtained commercially from a local source.

A dune sand supplied the size fraction contained between the No. 80 and No. 200 sieves and a silt of low plasticity, pedologically classed as Vigo, was used as a minus No. 200 filler. The particle shape of the individual gravel pieces ranged from subrounded to well-rounded.

For the graded materials, two maximum sizes were selected for study: ¾-in. and No. 4. A set of distribution curves was developed for each maximum aggregate size, based on Talbot and Richart's (30) mathematical expression:

$$p = 100(\frac{d}{D})^n$$

where p is the percent of material by weight which passes a given sieve having openings of width d; D is the maximum particle size of the given aggregate; and n is a variable exponent. If n equals 1.0, the curve on a linear plot will be a straight line. If n equals 0.5, the curve will be a parabola which represents the ideal grading curve for maximum density shown by Fuller and Thompson (16).

For each of the two maximum sizes, a family of curves was obtained by varying the exponent n. The gradation curves selected for study were chosen so as to be equally spaced with respect to one another and so as to cover the region between the natural limitation of uniformity and the practical limitation of minus No. 200 material (Figs. 3 and 4).

In addition uniform base course samples were prepared from 8 different sands and gravels. Using these samples, it was possible, to a considerable extent, to eliminate the problems of segregation inherent in the use of more well graded materials. The nominal grain size of base course materials used for this series of tests ranged from ¾-in. to the No. 200 mesh sieve (Fig. 7).

PROCEDURES

Compaction Studies

The procedures adopted for determining index properties and compaction characteristics of the subgrade soil were those normally used by soils engineers.

Moisture-density relationships were determined for each of the fifteen base course gradations in accordance with the Corps of Engineers' Specification CE 807.1 (13), which requires compaction in a 6-in. diameter mold by a 10-lb hammer falling 18 in. for a total of 55 blows on each of 5 layers. Considerable difficulty was encountered in developing these compaction curves particularly for the sands where the effects of bulking make moisture content very critical in the range of moisture near the optimum content. Obvious difficulties arose in attempting to screed a level surface on the compaction cylinder where particles as large as ¾-in. were involved. Since a considerable amount of aggregate breakage occurred in developing these curves, an at-

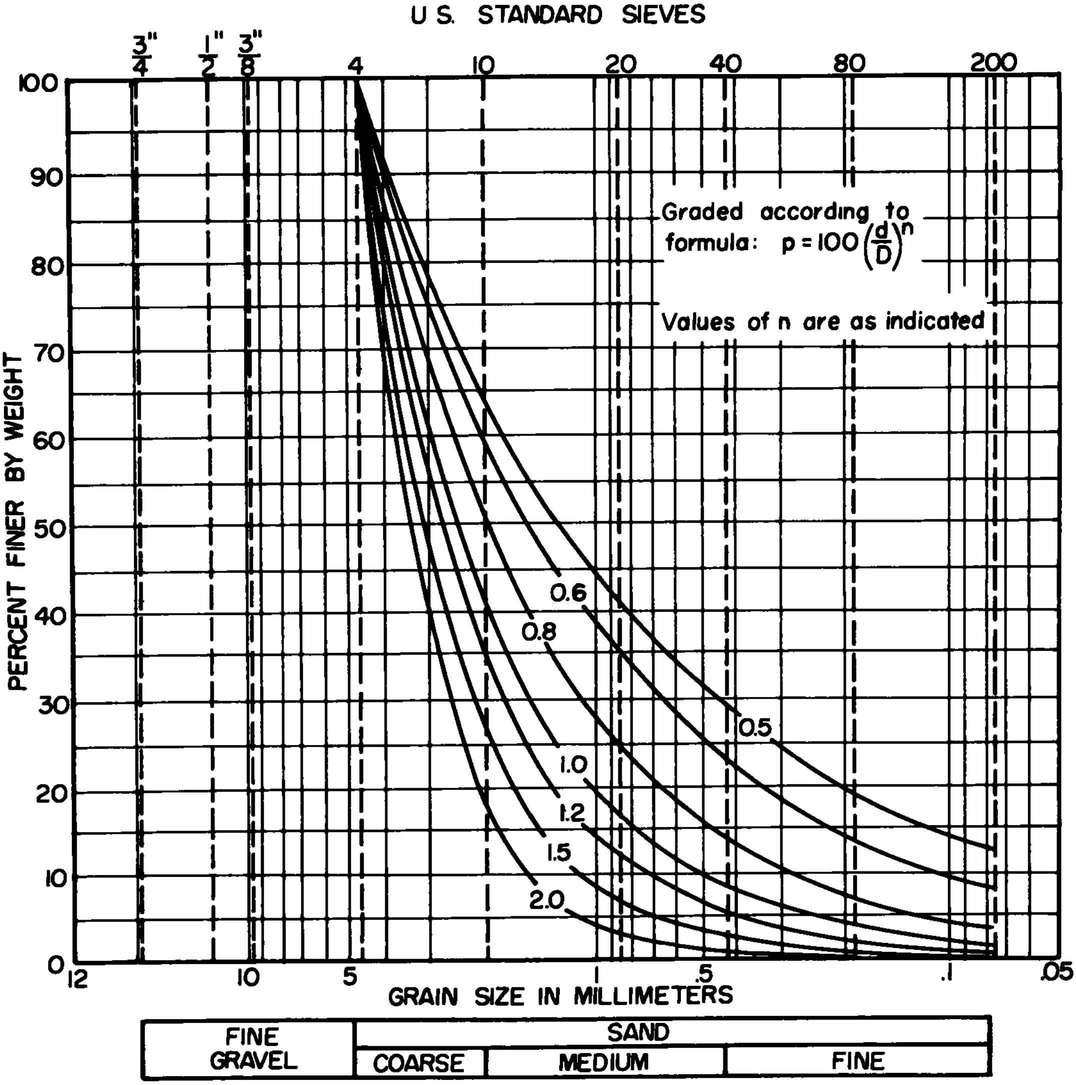

Figure 4. Base course gradations; maximum size No. 4.

tempt was also made to obtain a maximum vibrated density by vibrating a known weight of material in a lucite cylinder which was secured to the upper tray of a Gilson mechanical testing screen. The apparatus used to determine these vibrated densities is shown in Figure 5.

During the vibrating process, a surcharge weight of 80 lb was applied to the surface of the submerged sample. The sample was vibrated in increments of 10 sec, vertical measurements being taken after each 10-sec interval until a maximum density was attained.

Each base course gradation was subjected to two vibratory tests of this nature and the greater density value of the two taken as the maximum vibrated density. In nearly every instance, a maximum density was attained within 90 sec and in most cases within 60 sec. Grain size analyses of vibrated samples indicated that this short term of vibration caused a minimum of aggregate breakage even in the most open-graded samples.

Minimum densities of base course materials were determined by pouring samples loose into a cylinder of known volume, the smaller value of three trials being accepted as minimum density value.

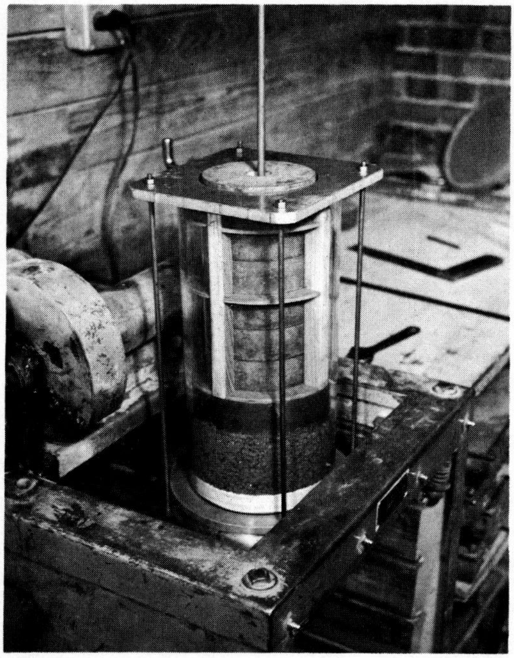

Figure 5. Vibrated density apparatus mounted in the Gibson mechanical testing screen.

Repetitive Loading Tests

All subgrade samples were compacted in a 7-in inside diameter lucite cylinder to 90 percent of the maximum density obtained by following the modified AASHO procedure. To accomplish compaction of the subgrade, the moisture content of the soil was adjusted to the optimum value, and the soil compacted statically from both ends to a height of 4 in. at the required density. Compacted subgrade samples were then permitted to absorb water for a 50-hr period prior to placing the base course.

In order to provide a significant basis for comparison of base course samples, it was decided to utilize the concept of relative density rather than compacting the base course samples to some arbitrary percentage of a dynamic test.

For simplicity, the relative density of a compacted sample was expressed in terms of density ratio, D_r, given by:

$$D_r = \frac{d_n - d_0}{d_{100} - d_0}$$

in which

d_n = dry density, pcf, of compacted specimen;
d_0 = dry density, pcf, loosest state from laboratory test for minimum density; and
d_{100} = dry density, pcf, maximum feasible density obtained in the laboratory.

This expression is analogous to that proposed by Lane (25) and is similar to Terzaghi's relative density (31, p. 27) but has the advantage that specific gravity of solids need not be determined. The two yielded results, which are quite similar, as shown by Lane (25). The concept of density ratio, as described above, was used in this study.

It was decided to compact base course samples to a density ratio of 90 percent, which might be considered a minimum requirement in order to limit objectionable consolidation and settlement under heavy traffic loads. At the completion of the subgrade soaking period, the base course material was carefully placed in two equal layers onto the compacted subgrade surface inside the lucite cylinder. Each layer was then compacted to a height of 2 in. by tamping lightly with a 2-in. diameter, 5.5-lb tamping rod; and then by applying several sharp blows with a leather mallet to a compaction head placed on the base course surface.

The combined base course-subgrade sample was next placed in the repetitive load apparatus. Before testing was commenced, the base course was saturated from above and the porous stone upon which the subgrade rested was saturated from below under a positive hydraulic head. At all times during the test, the water level in the lucite cylinder remained at or above the base course surface.

The repetitive loading apparatus was preset to deliver a 25-psi load of 0.3-sec duration to the base course surface every 4 sec. A total of 40,000 repetitions of this load was applied to each subgrade-base course combination. Periodic measurements of the permanent and elastic deformations of the system were made throughout each test by means of a linear variable differential transformer (Fig. 2).

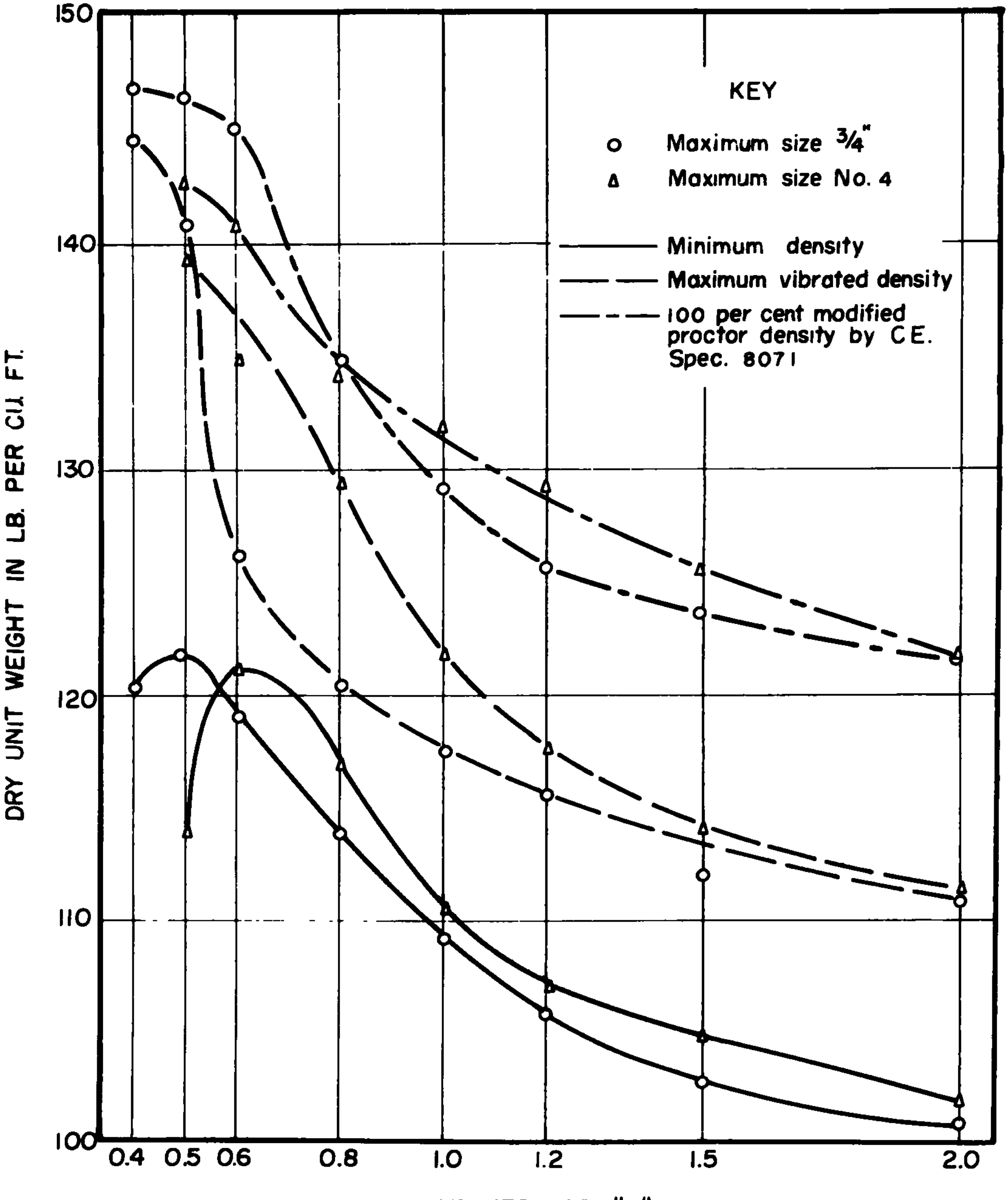

Figure 6. Comparison of density values for different base course gradations.

As each test was completed, any material that had been pumped above the surface of the base course was removed, dried, weighed, and subjected to a sieve analysis. For the more open-graded samples, note was taken of the extent of subgrade intrusion into the base course, if discernable. The entire sample was then extruded by means of a screwjack, and grain size analyses were performed on the base course to determine any changes which may have occurred in its gradation.

RESULTS

The results of the density and repetitive loading tests on the 23 subgrade-base course combinations are summarized in the following figures and tables. Figures 6 and 7 show the results of density tests performed on each base course sample. Values of maximum and minimum density are plotted against the logarithm of the n values for the graded aggregates and the logarithm of the nominal grain size for the uniform aggregates.

TABLE 1

TEST RESULTS FOR SAMPLES WITH 3/4 IN BASE COURSE

Sample	Material moved to top of base course			Weight of minus No 200 Material in base course			Increase in minus No. 200 mtrl. above subgrade (gm)
	Total weight moved (gm)	Weight minus No 200 mtrl. moved (gm)	percent minus No. 200	Before (gm)	After (gm)	Net Increase (gm)	
¾ - 0.4	206	143	69.4	676	539	-137	6
¾ - 0.5	121	103	85.1	378	290	-88	15
¾ - 0.6	81	70	86.4	204	148	-56	14
¾ - 0.8	0	0	-	64	68	4	4
¾ - 1.0	0	0	-	22	25	3	3
¾ - 1.2	0	0	-	4	39	35	35
¾ - 1.5	0	0	-	0	262	262	262
¾ - 2.0	0	0	-	0	151	151	151

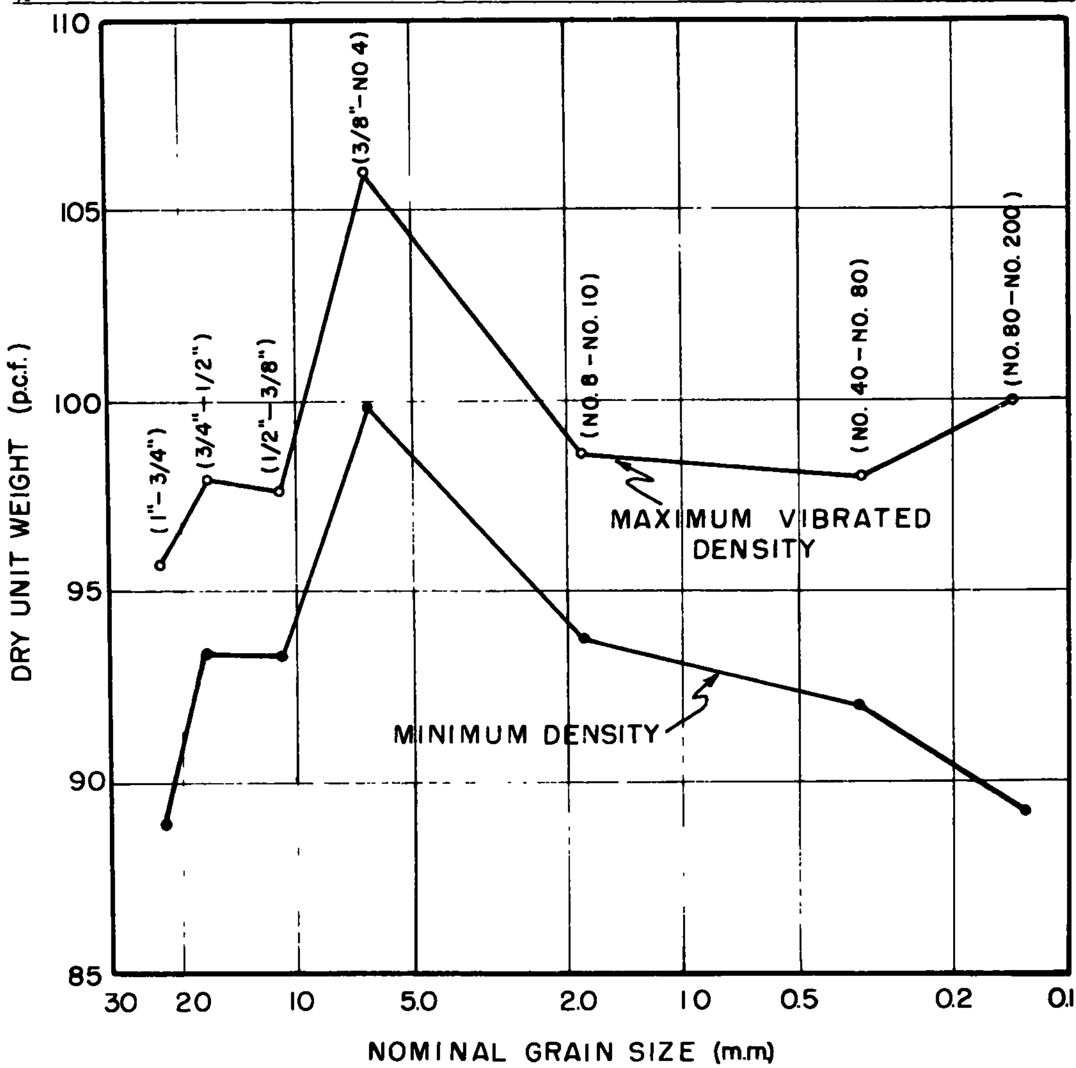

Figure 7. Density values of uniform graded materials.

In Figures 8, 9, and 10 the total deflection (permanent plus elastic) of each sample is plotted as an ordinate against the logarithm of the number of load applications. In each case, deflection readings were not commenced until after 100 applications of the 25-psi load in order to allow for adequate seating of the loading head. For this reason, the zero deflection is shown at 100 load repetitions.

At the termination of each test, grain size analyses were performed on different

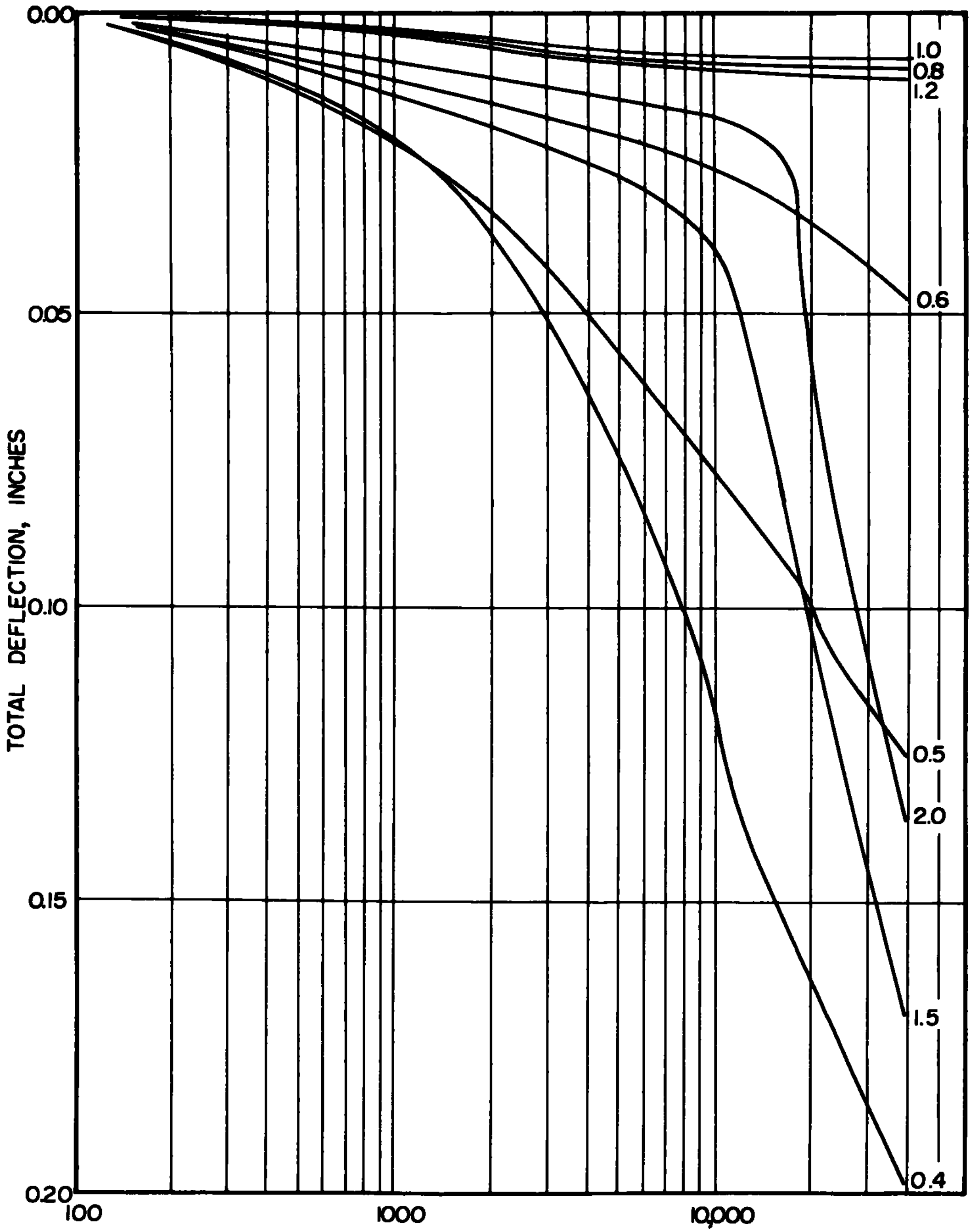

Figure 8. Deflection curves for samples with gravel base course.

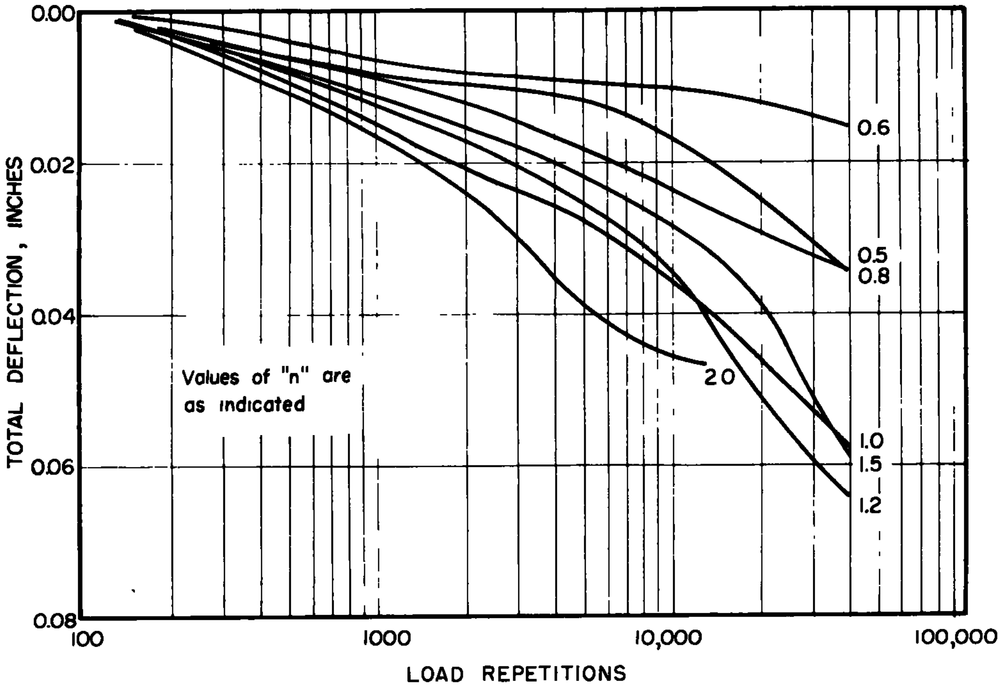

Figure 9. Deflection curves for samples with sand base course.

portions of the base course sample or, as in a few cases, on the base course as a whole to determine any change in gradation which may have occurred as a result of the repetitive loading. In addition, a grain size analysis was performed on any material which had been pumped to the top surface of the base course. From these data the increase in minus No. 200 material in the base course, the weight of minus No. 200 material moved to the top of the base course, and the increase in minus No. 200 material above the subgrade were computed and recorded in Tables 1, 2, and 3.

The transparent lucite cylinder, which was used to confine subgrade-base course

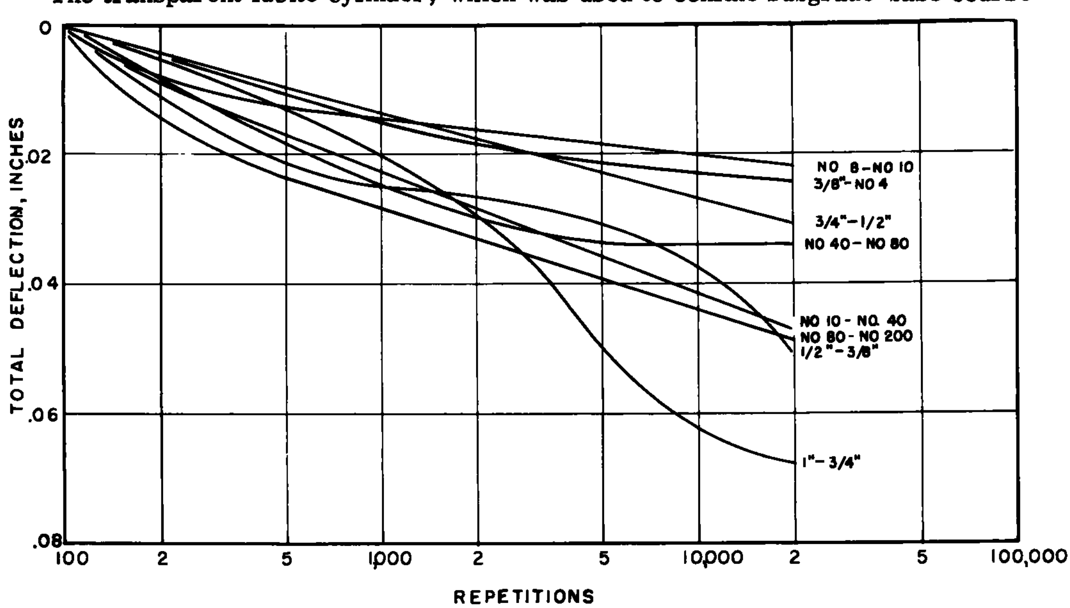

Figure 10. Deflection curves for samples with uniform graded base course.

TABLE 2

TEST RESULTS FOR SAMPLES WITH NO. 4 BASE COURSE

Sample	Material moved to top of base course			Weight of minus No. 200 Material in base course.			Increase in minus No. 200 mtrl. above subgrade (gm)
	Total weight moved (gm)	Weight minus No. 200 mtrl. moved (gm)	percent minus No. 200	Before (gm)	After (gm)	Net increase (gm)	
4 - 0.5	15	8	53.4	736	723	-13	-5
4 - 0.6	0	0	-	481	478	3	3
4 - 0.8	0	0	-	200	204	4	4
4 - 1.0	0	0	-	82	80	-2	-2
4 - 1.2	0	0	-	36	51	15	15
4 - 1.5	0	0	-	9	33	17	17
4 - 2.0	0	0	-	0	24	24	24

samples, permitted a visual inspection of specimens at any time during the testing procedure. The vertical intrusion of subgrade soil into the base course was considered to be significant in five of the graded samples and three of the uniform samples. In the three most open-graded sands (n = 1.2, n = 1.5, and n = 2.0), subgrade intrusion appeared to be only slight, not exceeding ¼ - ½ in. in extent, whereas intusion to approximately 1½ in. was observed in two of the open-graded gravels (n = 1.5 and n = 2.0). These observations were supported by grain size analyses performed on the base courses after testing. The pumping of fine soil to the base course surface was observed in the case of three specimens with dense-graded gravels (n = 0.4, n = 0.5, and n = 0.6) but in only one case where a sand base course was used (n = 0.5), and then only to a small degree.

DISCUSSION

In order to evaluate properly the test results presented in the preceding pages, it is essential that the reader be familiar with the framework of test conditions in which the repeated load tests were performed, the degree of precision obtained in the preparation of samples, and the accuracy with which results were measured.

Applied Load

Each subgrade-base course sample was subjected to repetitions of a 25-psi load applied at the base course surface for a 0.3-sec duration and at a 4.0-sec interval between load applications. The 0.3-sec load duration was short enough to approximate the sinusoidal type load-time characteristics of a deflecting pavement slab which accompany the passage of vehicular traffic and was sufficiently long to allow development of the full 25-psi load before release. A 4.0-sec interval was also more than adequate to allow complete release of one load before the application of another. A 25-psi load intensity may be somewhat in excess of that generally measured under a rigid pavement, which is at least 8 in. in thickness (5, p. 45); but it was chosen in order to magnify differences in performance between different subgrade-base course samples. Such a load intensity would not, however, be unreasonable for the construction period, which time may be critical in many respects from the standpoint of over-all pavement performance and quality.

Subgrade Compaction

All subgrade samples were compacted to approximately 90 percent of the maximum dry unit weight obtained by the

TABLE 3

TEST RESULTS FOR SAMPLES WITH UNIFORM-GRADED BASE COURSE

Sample	Increase of minus No. 200 above subgrade (grams)
1-in. - ¾-in.	-
¾-in. - ½-in.	163
½-in. - ⅜-in.	95
⅜-in. - No. 4	45
No. 8 - No. 10	21
No. 10 - No. 40	17
No. 40 - No. 80	10
No. 80 - No. 200	10

modified AASHO test (2). The Corps of Engineers, U.S. Army (9) requires this degree of compaction as a minimum for both cut and fill sections with the exception of those composed of cohesionless sand. This requirement, however, may be slightly below the average degree of compaction required by the various state highway departments.

Base Course Compaction

All base course samples were compacted to a density ratio of 90 percent which involved determination of the values d_0 and d_{100}. The values obtained for minimun density, d_0 can be considered as highly reliable since the procedure followed is one that is well accepted (17, 25) and in no case did the weights obtained from successive trials with the same sample vary by more than 0.06 lb. Determination of maximum density values, d_{100}, however, was admittedly quite arbitary, being in each case an average of the maximum modified AASHO dry unit weight (according to CE Spec. 807.1) and a maximum dry unit weight obtained by a procedure of mechanical vibration.

The maximum dry unit weight obtained by dynamic compaction according to CE Spec. 807.1 has been in the past taken for d_{100} (17), but in this case it was suspected to give values somewhat higher than the true maximum density, particularly for the more open-graded materials. The dynamic compaction used is a rather severe test, causing a considerable amount of aggregate breakage such that the densities obtained are not those of the original gradation but, rather, of some new gradation resulting from an alteration of the original material. Shelburne (28) showed that the breakage of aggregate due to mixing, rolling, traffic, and the Los Angeles Abrasion Test results in gradations which tend to approach Fuller's curve of maximum density. This same tendency could be presumed to exist in the dynamic compaction test. If so, it would be reasonable to assume that one would obtain unit weights in the dynamic test which would be higher than had no breakage occurred. Since the dynamic compaction test performed according to CE Spec. 807.1 applies considerable agitation and compactive effort to a granular sample, it is conceivable that unit weights approximating a maximum density could be obtained if no breakage were to occur and that densities are obtained in this test which are probably higher than for the unaltered material.

As a matter of interest, grain size analyses were performed on two samples of each gravel and sand base course gradation after having been subjected to dynamic compaction according to CE Spec. 807.1. The results of these analyses are shown in Table 4 as a tabulation of increase in percent finer than the various sieve sizes against base course gradation. It can be seen that the greater aggregate breakage does occur in the more open-graded materials with the production, in each case, of amounts of minus No. 200 material in excess of 1.2 percent and in most cases more.

Optimum moisture content has little significance for these materials from the standpoint of compaction control since any water in excess of that required to coat the aggregate surface is not retained but merely passes through the sample. These observations plus the aggregate breakage encountered and the inherent difficulties involved in developing compaction curves for this sort of material strongly support the rather well-accepted contention that such a dynamic compaction test is of little value in clarifying the true density characteristics of a fairly clean granular material.

The vibrated density test which was used, on the other hand, was believed to give values which were lower than true maximum density. It has been pointed out (17) that a greater surcharge and intensity of vibration would probably result in higher dry unit weights. One advantage of this test, however, lay in the fact that a maximum density could, in most cases, be obtained within 60 sec of vibration. Grain size analyses performed on samples which had been vibrated revealed that this short term of vibration resulted in only minor amounts of aggregate breakage.

The method of determining d_{100}, thus, was arbitrarily chosen and may be subject to some criticism. Fortunately, however, the degree of base course compaction was found to have little direct effect on the values of the measured variables in such a test (17). It was observed in this investigation that the principal effect of a lower degree of base course compaction was to cause a greater initial settlement within the first 100 or 200 loadapplications, presumedly, within the base course primarily. Thus,

TABLE 4

TABULATION OF AGGREGATE BREAKAGE IN THE DYNAMIC COMPACTION TEST (GRADED BASE COURSE MATERIALS)

Values of n	Sieve size - increase in percent finer than								
	¾ in.	½ in.	⅜ in.	No. 4	No. 10	No. 20	No. 40	No. 80	No. 200
	Maximum aggregate size, ¾ in.								
0.4	0.0	-	2.3	3.6	1.1	2.3	2.3	1.8	1.4
0.5	0 0	-	0.2	3.1	0.5	2.4	2.5	2.2	1.6
0.6	0.0	-	4.2	6.0	2 1	2.9	2.7	2.3	1.6
0.8	0.0	0.4	6.1	8.3	4.1	3.3	2.9	2.6	1.8
1.0	0.0	5.6	12.1	12.1	6.3	5.2	4.7	4.5	3.7
1.2	0.0	9.7	15 5	15.7	8.1	6.1	5.2	4.5	3.7
1.5	0.0	12.0	19.2	19.6	9.3	6.9	6.1	5.4	4.8
2.0	0.0	9.9	11.9	11.9	3.7	2.6	2.1	2.0	1.6
	Maximum aggregate size, No. 4								
0.5	-	-	-	0.0	1.0	3.4	4.0	3.9	1.2
0.6	-	-	-	0.0	2.8	3.8	4.9	4.3	1.6
0.8	-	-	-	0.0	1.8	4.0	5.3	4.6	2.0
1.0	-	-	-	0.0	2.6	5.2	5.1	4.8	2.2
1.2	-	-	-	0.0	3.9	5.9	5.8	5.0	2.9
1.5	-	-	-	0.0	5.4	6.1	4.0	2.7	1.6
2.0	-	-	-	0.0	9.6	7.2	4.8	3.6	2.7

any deformation or lack of deformation which might have resulted from discrepancies between base course densities as compacted and true density ratio of 90 percent could very well have been masked by the fact that deflection readings were not plotted until 100 repetitions of the 25-psi load had been applied.

A comparison of the various density values which were determined experimentally is shown in Figures 6 and 7. It is interesting to note how critical, with respect to attainable unit weights, a small change in aggregate gradation may be within certain gradational ranges.

Measurement of Test Results

Of the values measured during and immediately after each repeated load test, the deflection of the subgrade-base course systems was considered to be the most reliable. All that was required was a linear calibration between vertical movement of the transformer core and the pen of the oscillograph recorder. This calibration was checked frequently during each test and the equipment was at no time found to require adjustment. The recorded deflections, therefore, were dependent only upon the performance of the test specimens acting under the imposed conditions. No difficulty was encountered in maintaining the magnitude, duration and frequency of loading constant from test to test or for the duration of any single test. Chance variation in the preparation of subgrade samples and the difficulties already discussed in connection with the placement of base course samples undoubtedly account for a large part of the apparent inconsistencies in the test results.

The measurement of the weight of soil pumped to the surface of the base course was also considered to be highly reliable as most of this material was contained on top of the loading head and around the sides between the loading head and the cylinder wall. Observations made during testing permitted a visual measurement of the movement of the soil. The validity of the measurement of the increase in minus No. 200 material in the base course depended to a large extent on the care that was taken in separating the base course aggregate from the subgrade soil after extrusion of the tested specimen from the lucite cylinder. This was comparatively easy in the case of specimens with sand base courses where the interface was fairly well defined. In the case of specimens with gravel base courses, however, separation was more difficult and somewhat arbitrary in a few cases, particularly where subgrade soil had been extensively intruded into the more open-graded bases.

Interpretation of Results

The transparent lucite cylinder which was used to contain the test specimens allowed visual inspection of performance while the repeated load tests were in progress and

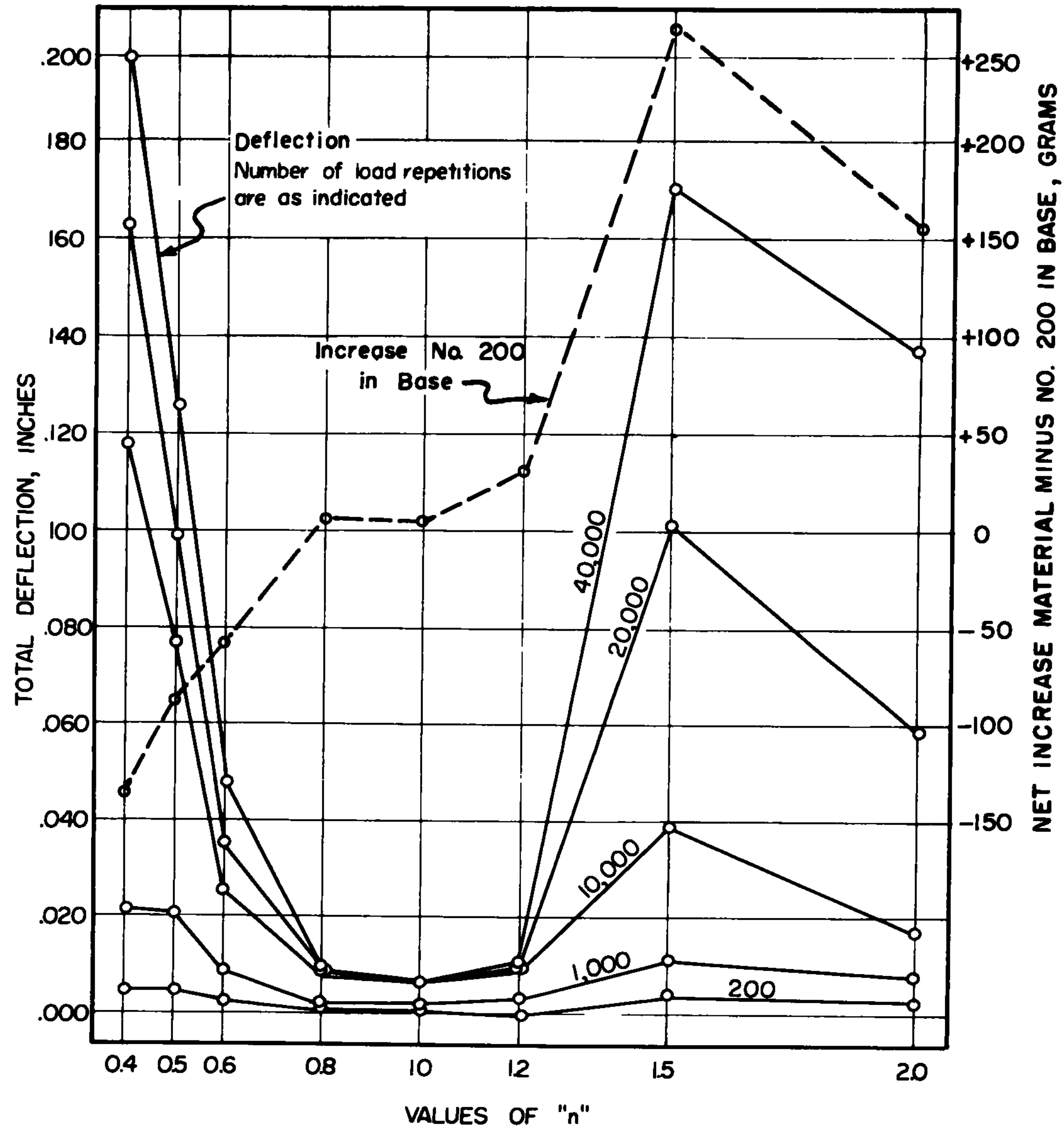

Figure 11. Deflection versus gradation for samples with gravel base course.

provided a means of observing the intrusion of subgrade soil into the base course and the movement of fine soil within the base course to the base course surface. These observations were substantiated by deflection measurements made during each test and by values measured immediately after the completion of each test.

Test specimens with gravel base courses exhibited pumping of fine soil to the surface of the three denser-graded base course samples and intrusion of subgrade soil into the three most open-graded. The uniform-graded samples exhibited subgrade intrusion in the case of the three most open gradations. Each of these two failure conditions tended to produce a characteristic type of load-deflection curve when total deflections were plotted as ordinates against the logarithm of load repetitions as abscissa. If substantial intrusion of subgrade soil occurred, the deflection curve remained, initially, rather flat and then sloped downward abruptly. This trend is seen in Figure 8 for samples n = 1.5 and n = 2.0. If, on the other hand, no intrusion occurred but substantial material was pumped to the base course surface, the curve showed deflections which were initially greater than those recorded for test specimens with the more

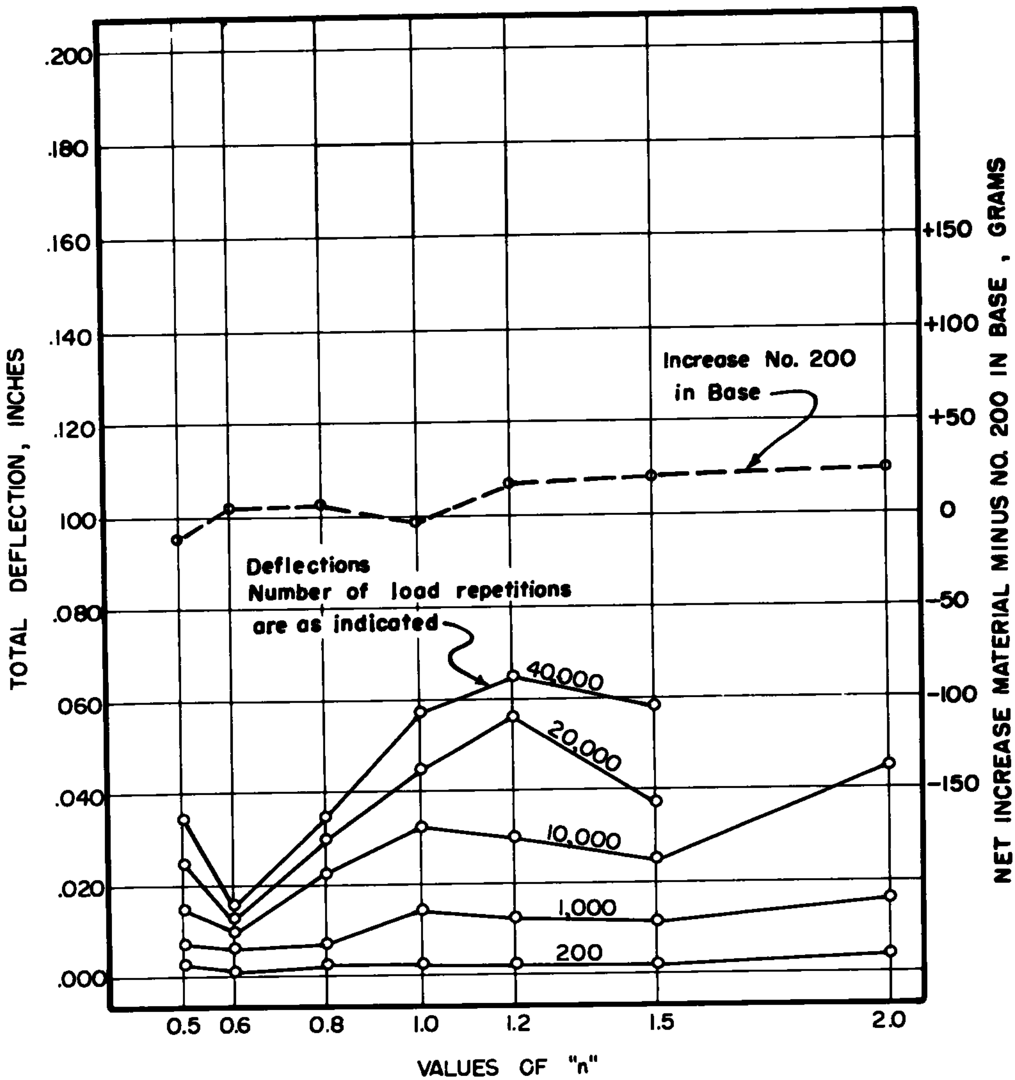

Figure 12. Deflection versus gradation for samples with sand base course.

open-graded bases in which pumping either occurred to a lesser extent or not at all (Fig. 8, samples n = 0.4 and n = 0.5). Some specimens, however, with base course samples of an intermediate gradation exhibited neither pumping nor subgrade intrusion and resulted in smaller subgrade-base course deflections. A plot of the deflections occurring in each specimen at different repetitions of load (Figs. 11, 12, and 13) indicates that there may be an optimum gradation which when compacted to a high relative density over a good subgrade will result in minimum deflections of the subgrade-base course system.

In all cases when specimens with gravel base courses were tested, a good correlation was found between large deflections and the maladies of base course pumping and subgrade intrusion, and it might be concluded that if a base course gradation could be selected that would resist these latter two effects, deflection of the subgrade-base course system could be held to a minimum in any given situation and pavement cracking and faulting resulting from lack of foundation support might be retarded.

Table 1 indicates minor increases in minus No. 200 soil above the subgrade for base course samples that experienced no visible intrusion of subgrade soil (samples

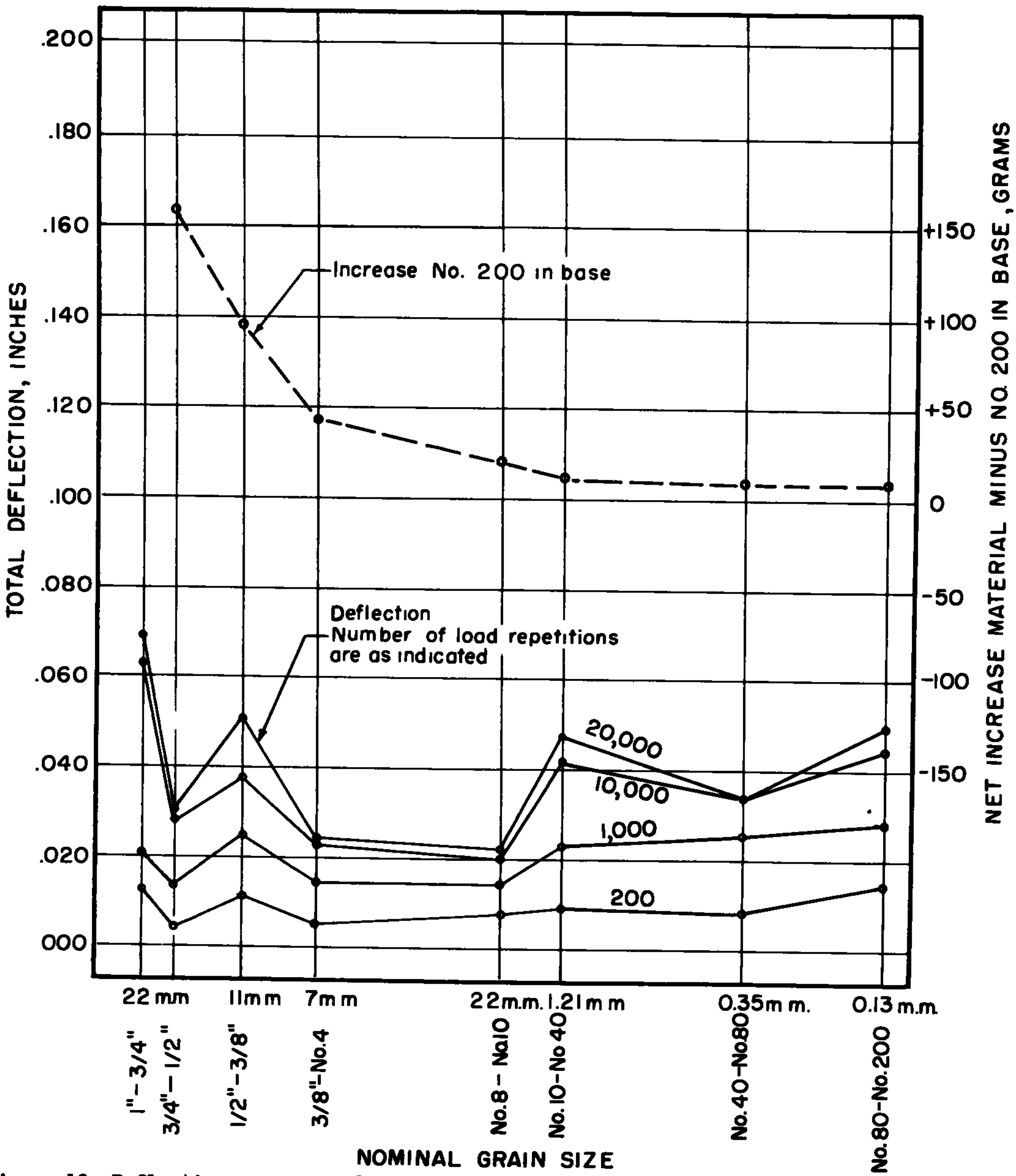

Figure 13. Deflection versus gradation for uniform base course; Crosby subgrade, 25 psi.

n = 0.4 through n = 1.0). This minus No. 200 material was believed to reflect the difficulties encountered in separating the base course sample from the subgrade soil. One rather obvious inconsistency is that sample n = 2.0 showed smaller deflections (Fig. 11) and less increase in minus No. 200 material in the base than did the less open-graded sample n = 1.5. This could probably be attributed in small part to chance differences in subgrade sample preparation but was felt to be due mainly to the great difficulty in obtaining uniformity in the base course and preventing segregation during placing which was particularly evident with the open-graded gravels.

In only one case (n = 0.5) did a test specimen with a sand base course exhibit pumping of fine soil from the base, and this was very minor in extent (Table 2). In three cases (n = 1.2, n = 1.5, and n = 2.0) a small amount of subgrade intrusion was noted. This also was shown to be minor in extent by the results of a grain size analysis performed on the base course sample after testing (Table 2). In general, specimens with sand base courses showed less material pumped to the base course surface, less intrusion of subgrade soil and small deflections over a wider range of gradation than those with gravel base courses, even though greater percentages of minus No. 200 soil existed in the sand samples than in corresponding gravels.

Intrusion of subgrade soil into the base course was experienced for the three more open samples of the uniform graded base courses. Data appearing in Figure 13 appears to substantiate the data for the graded materials in as much as the larger pore sizes reflected by the gravel samples permit a greater intrusion of subgrade soil than those of a similarly graded sand.

The one gravel sample ($n = 0.4$) and the two sands ($n = 0.5$ and $n = 0.6$), which meet the filter requirements adopted by the Corps of Engineers (10), are all dense-graded materials which appeared to allow no significant intrusion of subgrade soil during the repeated load tests. From the results of this series of tests, it appears that the criteria may be adequate for the prevention of subgrade intrusion and, in fact, somewhat conservative since it excludes most of those samples in which no significant intrusion occurred. More important, perhaps, is the fact that most materials that would meet the requirements of these criteria for the particular soil used in this study would probably be susceptible to the pumping of material to the base course surface if subjected to the conditions imposed on the specimens tested.

It can be said that a gravel base course sample graded between the limits expressed by the formulas $p = 100(\frac{d}{D})^{0.7}$ and $p = 100(\frac{d}{D})^{1.2}$ would probably perform satisfactorily (no excessive deflections due to subgrade intrusion or base course pumping) if subjected to the condition of this repeated loading test. In practice, these limits might be extended to include a wider range of gradation since less severe conditions of load would be anticipated. All else being equal, base courses constructed with a coarse sand could be expected to perform satisfactorily over a wider range of gradation than those constructed with a larger sized material.

CONCLUSIONS

Based on the results of this laboratory investigation and the experience gained in conducting it, the following conclusions appear to be justified:

1. Under the proper conditions of moisture and load, a dense-graded base course material with an appreciable percentage of material finer than the No. 200 mesh sieve could be expected to have some of its finer soil sizes removed by a pumping action and a very open-graded base course material could be expected to be contaminated by the intrusion of subgrade soil. In this series of tests, movement of soil to the base course surface occurred where an excess of 3 percent by weight of soil finer than the No. 200 mesh sieve was present in the gravel bases and where an excess of 12 percent was present in the sands.
2. Since a good correlation was found to exist between large subgrade-base course deflections and either the intrusion of subgrade soil into the base course or the removal of fine soil from the base course by pumping action, it is concluded that an appreciable degree of subgrade intrusion or base course pumping will result in objectionable deflections of the subgrade-base course system.
3. The principal effect of a decrease in the degree of base course compaction appeared to be a greater initial settlement within the early service life of the subgrade-base course system primarily within the base course.
4. An optimum range of gradation appears to exist within which a base course sample may experience neither significant subgrade intrusion nor movement of fine soil to the base course surface. For the series of laboratory tests on specimens with gravel base course, this range existed approximately between the grain size distribution curves expressed by the formulas $p = 100(\frac{d}{D})^{0.7}$ and $p = 100(\frac{d}{D})^{1.2}$. In practice, this range could be extended in anticipation of less severe conditions of loading.

5. All else being equal, base courses constructed with a coarse sand can be expected to perform satisfactorily over a wider range of gradation than those with a larger maximum particle size.

6. If a base course material is graded within this optimum range and compacted to a high relative density over a well prepared subgrade, deflections of the subgrade-base course system should not exceed that amount generally considered as tolerable for rigid pavements (about 0.05 in.).

7. With respect to the density test performed on each of the fifteen base course gradations:

a. The unit weights that can be attained with a granular material are a function of the gradation of that material with a maximum value attainable when the aggregate is graded to some approximation of Fuller's theoretical curve of maximum density.

b. There is a certain range of gradation about Fuller's curve where small changes in the grain size distribution of an aggregate markedly effect the unit weights that can be attained.

c. There is a significant amount of aggregate breakage in the dynamic compaction test according to CE Specification 807.1 (13); such that, in some cases unit weights may be indicated for a given material that exceed the maximum unit weight that can be attained for that material when its gradation is not altered by breakage.

8. It appears that the filter criteria adopted by the Corps of Engineers, U.S. Army (10) for the protection of thin base courses against the intrusion of subgrade soil are adequate and, in fact, are somewhat conservative, insofar as intrusion resulting from a kneading action is concerned.

9. The results of this investigation indicate that more consideration should be given to sand as a more satisfactory base course material than gravel.

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