A Study of Interactions of Selected Combinations of Subgrade and Base Course Subjected to Repeated Loading

J. A. HAVERS,* *Harland Barthowlomew and Associates;* and
E. J. YODER, *Joint Highway Research Project, Purdue University*

This paper reports the results of a laboratory study to investigate the effects of repetitive loading on selected combinations of subgrades and base courses. Two subgrades were studied: a highly plastic clay from Bedford, Ind., derived from the weathering of limestone rock and pedologically classified as a Frederick soil; and a clay of medium plasticity obtained from the B horizon of the Wisconsin Drift in the vicinity of Lafayette, Ind., and pedologically classified as a Crosby soil. Two gradations of base course were studied, both of which were well-graded mixtures of glacial gravel with a maximum size of ¾ in. The first of these, designated as "open-graded," had no material passing the No. 80 U. S. sieve; the second, referred to as "dense-graded," had 7 percent by weight passing the No. 200 U. S. sieve.

Two types of loading were utilized: "single-acting," in which the loading piston periodically applied loads while continually remaining in contact with the base course; and "double-acting," in which the loading piston returned to a zero position after each load application, hence had a length of stroke which increased as the deflection in the base course-subgrade system increased. A total of 40,000 load repetitions was applied to each specimen at intervals of 4 sec., with each load sustained for 0.3 sec.

The laboratory study was designed as a complete factorial experiment to investigate at two levels the factors of subgrade type, base course type, subgrade compaction, base course compaction, and applied pressure. The subgrade was compacted statically in 7-in. I.D. lucite cylinders to 95 percent of the unit weights obtained in both the standard and modified AASHO compaction tests, while a combination of vibration and dynamic compaction was used to place base course samples on the compacted subgrade at relative densities of 0.75 and 0.95. Both double-acting and single-acting tests were performed on combinations of subgrades and base courses at 10-psi and 40-psi applied pressures. Similar tests were also performed directly on the subgrades and on the base courses.

Open-graded base courses were found generally superior to dense-graded bases, inasmuch as tests with the more permeable base course resulted in smaller total deflection and a lesser weight of pumped material. Similarly, combinations with the more plastic Frederick subgrades were found to perform slightly better than those with the less plastic Crosby subgrades. Increasing the compaction of the subgrade was found decidedly beneficial for all samples, although an increase in the base course compaction appeared to have little effect. An increase in pressure accelerated the onset of pumping and increased its severity.

● PUMPING of rigid pavements consists of the ejection of water and subgrade soil through joints, cracks, and along the edge of the pavements caused by the downward slab movement actuated by the passage of heavy vehicle

* Formerly Joint Highway Research Project, Purdue University.

loads over the pavement after accumulation of free water on or in the subgrade (*22*).

The conditions necessary for the development of destructive pavement pumping are believed to be as follows (*29*):

1. The subgrade must have soil characteristics that will develop a soil-water slurry or mud under the repetitive action of the slab.
2. Free water must be available to permit the formation of the soil-water slurry.
3. Traffic loads must be heavy enough to cause the pavement slab to deflect appreciably under the application of the axle load to the joint or the free edge of the slab.
4. The frequency and weight of traffic must be great enough to overstress the slab, after reduction of subgrade support by pumping, to develop cracking and subsequent settlement.

Pumping of rigid pavements in Indiana first became apparent as a problem about 1943 (*17*) and rapidly increased in severity. Surveys made for the Indiana Highway Department showed that although pumping had been practically non-existent in 1940, by 1943 approximately 6 percent of the total mileage of rigid pavement was affected. This had increased to 12 percent by 1947 (*16*) and a 1954 survey (unpublished) showed a further increase to 21 percent.

Early surveys showed that rigid pavements placed directly on granular subgrades were not subject to pumping and this led to the introduction of thin layers of granular material for use as a filter course between the pavement and fine-grained subgrades. These materially reduced pumping of the subgrade, but for some combinations of base and subgrade resulted in pumping or "blowing" of the base course (*15*). It became apparent, therefore, that attention must be directed to the gradation of the base course material as related to the magnitude and frequency of the loads imposed through the overlying pavement, and as related to the characteristics of the underlying subgrade.

The investigations reported herein were part of a contracted study on pumping of rigid pavements conducted under a contract between the Purdue Research Foundation and the Arctic Construction and Frost Effects Laboratory, Corps of Engineers, U. S. Army. A field investigation on pumping of highway and airfield pavements was included as a part of the over-all investigation. These data, however, are not included in this report but constitute a separate report.

PURPOSE AND SCOPE

The laboratory study was initiated in an attempt to evaluate, under controlled laboratory conditions, the relative influence of subgrade and base course type on the pumping of rigid pavements. In developing techniques for this study it was postulated that pavement pumping might result from two separate processes.

For the first of these to be operative, it is necessary that small accumulations of free water be present directly under a rigid pavement slab. Such a condition might conceivably exist during a frost melting period or after prolonged rainfall, because perfect contact between slab and base course is generally not maintained at all points and at all times. Deflection of the loaded pavement slab will cause this water to flow laterally over the surface of the base course to outlets at cracks, joints and pavement edges. Soil particles may be carried along with the water, and a mixture of water and soil ejected from beneath the pavement. Such movement of soil is erosional in nature, and will tend to become progressive. The size of soil grains which may be removed by this process will be governed by the pavement deflection, the clear space between the pavement and the base course, and the size of the openings through which the particles may escape. Observations of locations at which pumping has actually occurred have shown that particles ¼ in. in diameter, or even larger, may be thus removed from beneath the pavement.

This erosional type of pumping has been graphically described in the final report on the Maryland Test Road (*29*, p. 54) which reads:

> If these four conditions (necessary for the onset of pumping) are present on a concrete road, the following order of related events will occur:
>
> 1. When the first heavy axle load is applied there will be a deflection of the slab and the subgrade will be deformed in proportion to the magnitude of the downward movement of the slab.
> 2. After the removal of the applied load the deflected slab returns to its original alignment and a certain degree of loss of subgrade contact will occur at the critical deflection points.
> 3. This loss of subgrade contact with the pavement creates a space under the slab which, if given access to free water, quickly becomes filled and softening of the top layer of subgrade soil begins.
> 4. Subsequent deflections of the slab, under successive applications of load, increase the size of the area of non-subgrade contact with the slab and at the same time develops the soil water slurry which is ejected in increasing amounts during the downward bending of the slab under the applied loads.
> 5. As this slab-subgrade action is repeated the deflection for the same intensity of load application increases in proportion to the loss of subgrade contact and the stress in the slab increases until a point is reached where the developed stress results in the cracking of the pavement. After the slab cracks, faulting and settlement occur, with further application of loads.

A second type of pumping could conceivably result from the movement of fine soil particles into or through the base course, actuated by pore water pressures within the subgrade and by a kneading action at the contact surface between the subgrade and base course. To create this condition, it is necessary that the soil have a high degree of saturation so that appreciable pore water pressures will result from small deflections of the loaded pavement. It is further necessary that the base course immediately above the subgrade shall have openings of sufficient size to permit the entrance and movement of the finer soil particles. Removal of the finer particles of a densely-graded base course by similar means is also a possibility, and the same criteria apply for its occurrence.

Intermixing of the subgrade soil and the base course at the place of contact is related to pavement faulting rather than to pavement pumping, since ejection of soil particles need not take place. The possibility of such mixing occurring is, however, related to the relative gradation of the subgrade and base course. Large pavement deflections will tend to promote such mixing, as will the presence of free water above cohesive subgrades.

Two types of tests were therefore designed to investigate the postulated methods of pumping. In the first, referred to as "single-acting," the loading piston remained in contact with the base course at all times and merely applied loads at a controlled magnitude and rate. In the second type, known as "double-acting," the loading piston was initially in contact with the base course but returned to its zero position after each application, hence the length of stroke was equal to the total deflection in the system. The factors selected for detailed investigation were as follows:

1. Pressure on the subgrade-base course structure.
2. Subgrade type.
3. Base course type.
4. Subgrade compaction.
5. Base course compaction.

Because of the large number of tests involved in investigating every possible combination of factors, it was decided that only two levels of each factor would be studied. Values for these (Table 1) were selected to give as wide a range as

TABLE 1
SELECTED TEST CONDITIONS

Factor	Level 1	Level 2
Pressure	10 psi	40 psi
Subgrade type	CL (Crosby)	CH (Frederick)
Base type	Open-graded	Dense-graded
Subgrade compaction	95% Std. A.A.S.H.O.	95% Mod. A.A.S.H.O.
Base compaction*	$D_r = 0.75$	$D_r = 0.95$

* D_r = density ratio as specified by Lane (*10*).

possible of test conditions, yet remain within the realm of field conditions, with the choice of 40 psi for the highest level of pressure possibly being an exception. This intensity exceeds that generally measured beneath rigid pavements (*5*) and was selected to accentuate the effect of pressure on the variables studied. Each specimen was subjected to 40,000 load applications. Prior to all tests the subgrade was permitted to absorb water from beneath for a period of three days and the base course was filled with water to the top of the loading piston before testing, since this was considered representative of a critical condition in the field performance of rigid pavements.

In addition to the tests on each combination of subgrade and base course, a test series was performed in which the subgrade was loaded directly with no intervening base course. A few tests were also performed on the base course alone in order to determine the extent of degradation during the course of the test.

PREVIOUS WORK ON FILTERS

The need for a filter layer under pavements is recognized in the current design specifications of the Corps of Engineers (*19*), which read as follows:

> Where the combined thickness of pavement and base over a frost susceptible subgrade is less than the design depth of frost penetration, the following additional design requirements shall apply:
>
> (a) For both flexible and rigid pavements, the bottom 4 inches of base as a minimum shall consist of any non-frost-susceptible gravel, sand, screenings, or similar material and shall be designed as a filter between the subgrade soil and overlying base-course material to prevent mixing of the frost-susceptible subgrade with the base during and immediately following the frost-melting period. The gradation of this filter material shall be determined in accordance with criteria presented in Paragraph 2-11 of Chapter 2, Part XIII, of the Engineering Manual (*21*), with the added overriding limitation that the filter material shall, in no case, have more than 3 percent by weight finer than 0.02mm. Experience indicates that a non-frost-susceptible sand is particularly suitable for this filter course. On the other hand, experience shows that a fine-grained subgrade soil will work up into an improperly graded overlying gravel or crushed stone base course under the kneading action of traffic during the frost-melting period, if a filter course is not provided between the subgrade and base course.
>
> (b) For rigid pavements, the 85 percent size (the size particle for which 85% of the material by weight is finer) of filter or regular base-course material placed directly beneath pavements shall be equal to or greater than ¼ inch in diameter. The purpose of this requirement is to prevent loss of support by pumping soil through the joints of rigid pavements.

The filter requirements, as given in the reference (*21*) are as follows:

> (a) General — Placing backfill in trenches where drain pipes are located should serve a dual purpose; it must prevent the movement of particles of the soil to be drained and it must be pervious enough to allow free water to enter the pipe without clogging it with fine particles of soil. The material selected for backfill is called "filter material."
>
> (b) Theoretical design of filter material — In order to fulfill the purpose of a filter material, an empirical design based upon a modification of the original method developed by K. Terzaghi has been established, substantiated by tests conducted on protective filters used for the protection of soils in the construction of earth dams.
>
> To prevent clogging the pipe with small particles infiltrating through the openings, the following requirements must be satisfied:
>
> $$\frac{\text{85 percent of filter material}}{\text{size of opening in pipe}} \geqq 2$$
>
> To prevent the movement of particles in the protected soil, the following conditions must be satisfied:
>
> $$\frac{\text{15 percent size of filter material}}{\text{85 percent size of protected soil}} \leqq 5$$
>
> When the protected soil is plastic and without sand or silt partings, the 15 percent size of the filter material need not be less than 1 mm.

To permit free water to reach the pipe, the filter material must be many times more pervious than the protected soil. It has been found that this condition is fulfilled when the following requirements are satisfied:

$$\frac{\text{15 percent size of filter material}}{\text{15 percent size of protected soil}} \geqq 5$$

The empirical relationship between size of filter and size of material which is to be protected was first proposed by K. Terzaghi (*14*, p. 50), for the design of inverted filters to control seepage pressures under dams on permeable foundations. His proposed criteria for filter design were related to the grain size curves for the filter and base material by the following requirements:

(a) The 15 percent size of the filter material should be at least four times as large as the 15 percent size of the base material.

(b) The 15 percent size of the filter material should not be more than four times as large as the 85 percent size of the base material.

In 1939, at Harvard University, Bertram (*4*) made a study of filter requirements by placing uniform sizes of sand and crushed quartz into 2-in. diameter lucite tubes 6 in. in length and permitting vertical drainage under various hydraulic heads. The results showed that, for the materials investigated, a filter meeting the following gradation requirements would successfully prevent the movement of base material into the filter, over a range of hydraulic gradients between 6 and 20:

1. In the tests performed, the 15 percent size of the filter material was 10 to 15 times as large as the 15 percent size of the base material. In all tests except one, ratios between 8 and 10 of 15 percent size of filter to 15 percent size of base material proved stable.
2. The 15 percent size of the filter material was not more than 6 times as large as the 85 percent size of the base material. Extreme care was taken to avoid disturbance from shocks while performing the tests.

A few tests were performed with graded materials, but the number was insufficient to establish critical size ratios. Bertram recognized the desirability of a series of tests on graded materials, however, and suggested that such a study be conducted.

In 1941 the U. S. Corps of Engineers at Vicksburg, Miss. conducted a series of tests (*25*) to examine the validity of existing design requirements for filters. A granular filter was placed in a permeameter, covered with a fine sand base material, and subjected to downward flow. Tests were performed in which the finer sizes were successively removed from the filter until the limiting gradation was reached. The conclusions from the study were in part as follows:

1. A fine material will not wash through a filter material if the 15 percent size of the filter material is less than five times as large as the 85 percent size of the fine base material.
2. In addition to meeting the above size specifications, the grain size curves for filter and base materials should be approximately parallel in order to minimize washing of the fine base material into the filter material.
3. Filter materials should be packed densely in order to reduce the possibility of any change in the gradation due to movement of the fines.
4. A filter material is no more likely to fail when flow is in an upward direction than otherwise, unless the seepage pressure becomes sufficient to cause flotation or a "quick" condition of the filter.

The desirable ratio of 15 percent size of filter material to 15 percent size of base material was not determined. For the typical grain size distribution curves included with the report, this ratio varied from 2.7 to 18. When downward flow was utilized, the materials were tested with a hydraulic gradient which was approximately equal to two.

Partially from the findings of these studies, the Corps of Engineers adopted its present specifications for filter design. It should be recognized that, in all the investigations reported thus far, the filter requirements were determined from seepage tests performed on cohesionless base materials. Particular care was taken throughout the test to prevent any disturbance of the materials by vibrations or shocks. The design of protective filters for saturated cohesive base materials subjected to repetitive dynamic loading apparently was not studied, although several investigations pointed out the desirability of investigating this condition (*4*, *1*, *22*). Similarly, the influence of variation in the grading of a filter on its performance was not thoroughly examined, although the critical limitations for the upper and lower sizes received detailed attention.

Keene (*8*) has reported on studies performed by the Connecticut Highway Department to examine the validity of present criteria for the design of filters for highway subdrains. The results indicated that piping ratios (ratio of the D_{15} size of the filter material to the D_{85} size of the subgrade material) of four for uniform soils and considerably higher than five for well-graded soils would be satisfactory.

Tatum (*13*), in a series of tests for the Virginia Department of Highways, investigated the effect of repetitive loading on combinations of subgrade and base course. Two subgrades, an MH and an ML, were used in this study. Pressures ranging from 13.5 to 58.6 psi were applied by means of a cam and weighted lever, with the loading piston always remaining in contact with the test samples. Minor pumping of the subgrade into a stone base was observed, with the more silty ML moving somewhat more readily than the MH.

Barber and Sawyer (*1*) further extended the concepts of filter design by performing a limited series of tests in which typical base course materials were submerged and subjected to repetitive loading. A loading piston remained in contact with the base course throughout the tests, and load was repeatedly applied by a weighted beam actuated by a rotating cam. After 10,000 repetitions of a load of 4 kips per square foot (27.8 psi), a small amount of pumping had occurred in samples of gravel which contained 10 percent or more by weight passing the No. 200 sieve. Combinations of filter material and base material were not studied, although it was recognized that a fine base material might be intruded into a coarse filter layer by such a test procedure. The authors suggested that the exact ratios of permissible grain sizes for subgrade and base course should be given further study.

Seed, Chan, and Monismith (*12*) reported the results of repetitive loading tests on a partially saturated silty clay of medium plasticity. The soil was compacted to densities varying from 95 to 105 percent of that obtained in a modified AASHO compaction test (*18*) using kneading compaction followed by static compaction to produce a final degree of saturation ranging from 92 percent to 97 percent. Specimens 1.4 in. in diameter and 4.0 in. in height were trimmed from the compacted soil, confined under a lateral pressure of 14.2 psi, and loaded repetitively with an axial stress of 40 psi by means of a lever-type loading frame. From 50,000 to 100,000 stress repetitions were applied, with each load sustained for one second. The interval between loadings was varied between 3 and 20 applications per minute, and the authors concluded that up to at least 100,000 applications of stress, the specimen deformation depended only on the number of stress applications and was not affected by the frequency of application. A limited number of tests indicated that this conclusion is also valid to frequencies as low as one application per minute (*12*, p. 551).

It appears that the problem of filter protection for cohesionless soils under static loading conditions has been investigated in detail, and satisfactory criteria have been established for the design of such filters. Criteria have similarly been proposed, although with little supporting experimental data, for the design of filters over cohesive soils, with the same type of loading. Except for data presented by Tatum (*13*), however, no experimental studies have been reported to establish the validity of these filter criteria when applied to the design of a base course between a rigid pavement and a fine-grained subgrade. In this situation, dynamic applications of stress are repeatedly applied during the life of the pavement. An adequate filter must not intermix excessively with the subgrade, must restrict any infiltration by the subgrade, and must itself remain internally stable.

TEST EQUIPMENT

To perform the desired series of tests on combinations of subgrades and bases, it was first necessary to design repetitive loading equipment with adjustable cycling time and a suitable range of pressures. A study of the possible loading systems indicated that one actuated by compressed air would permit the rapid application and release of load, while retaining the desired flexibility of operation. Accordingly, a testing machine (see Figures 1 and 2) was prepared by mounting commercially available parts in a loading frame constructed locally.

Compressed air at 100-to 110-psi outlet pressure was supplied by an air compressor powered by a 7½-hp electric motor. From the compressor tank a 1-in. diameter galvanized pipe led through an air filter to remove moisture and any

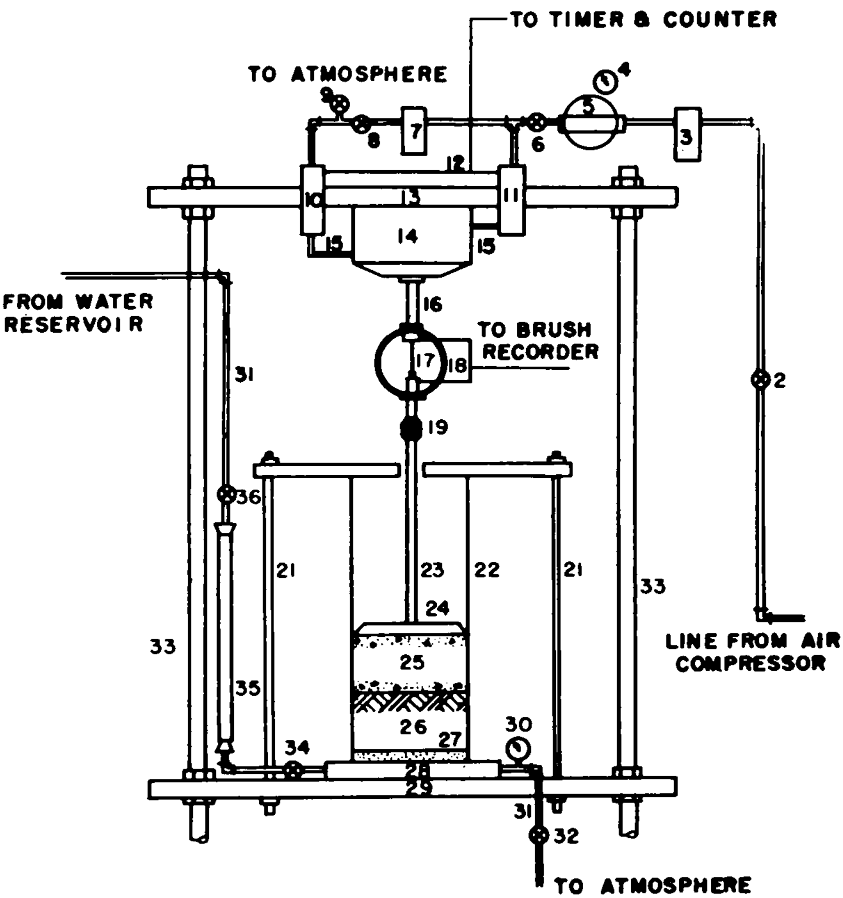

Figure 1. Schematic diagram of repetitive loading equipment.

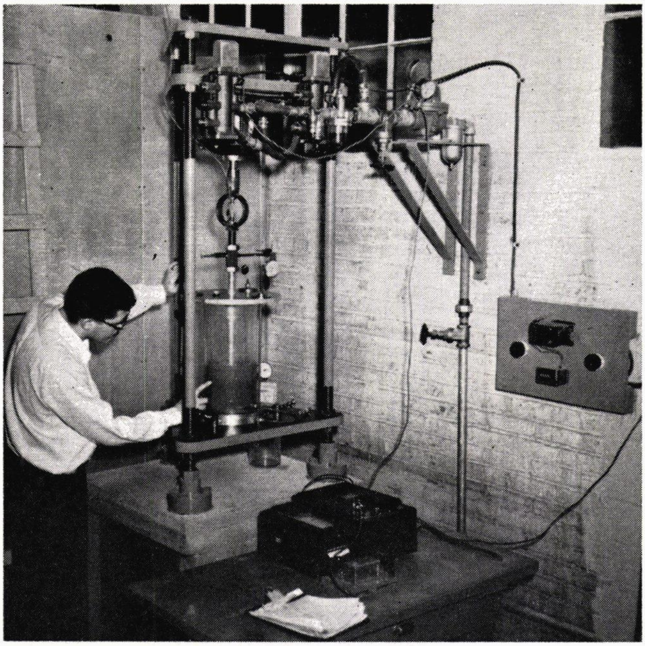

Figure 2. Repetitive loading equipment.

foreign particles from the air, and thence into a pressure regulator. This regulator, of the diaphragm type, was found to regulate the outlet pressure quite accurately while still permitting the sudden and intermittent flow of air required to produce the repetitive type of loading.

The line then passed through an air line lubricator and branched to enter two electrically-controlled valves, each of which was connected to one end of an air cylinder. Mounted vertically to the upper platen of a loading frame and affording a downward stroke of from 0 to 2 in. for the loading piston. A loading head attached to the piston applied load directly to samples of subgrade and base course placed on the lower platen beneath the air cylinder. The total load which was applied could be controlled by adjusting the pressure regulator, while both the duration of load and the time interval between successive load applications could be regulated through the valves by means of a double-acting timer. Any desired number of loading cycles between 0 and 99,999 could be preset by means of a predetermined counter. Manual valves and switches were so arranged that one bellows valve could be removed from the system if desired, resulting in a single-acting stroke of the loading piston rather than its normal reciprocating action.

The regulator could be adjusted to approximately the desired pressure for any test series by observing a dial gage connected directly to the pressure dome of the regulator. More precise pressure regulation, as well as adjustment of the loading cycle, was accomplished by the use of a linear variable differential transformer. This was mounted in a 4,000-lb capacity proving ring and was initially calibrated against known loads in a hydraulic testing machine. Subsequent adjustments of the transformer to compensate for zero drift were readily accomplished by balancing output voltage with calibrated impedances.

The proving ring and transformer formed an integral part of the loading piston, remaining in place throughout all tests. Voltage output from the transformer was recorded directly as a load-time curve on a recording oscillograph.

Adjustments of the pressure regulator and the timer were continued until this load-time curve showed the desired characteristics for each test series.

MATERIALS TESTED

Soils

Two soils were used as subgrade material in this study. The first, a yellowish-brown silty clay was obtained in the immediate vicinity of Lafayette, Ind. Known pedologically as a Crosby soil (B horizon), it occurs in the Wisconsin Drift areas of Indiana, Michigan and Ohio, forming extensive till plains of level to undulating topography. Atterberg limits of this soil, performed on the entire sample at field moisture, are as follows:

Plastic limit = 21.0
Liquid limit = 39.4
Plasticity index = 18.4
Flow index = 10.6

The second subgrade soil was a reddish-colored, highly plastic clay formed in place from the weathering of limestone rock, and classified pedologically as a Frederick soil. It is developed on the rolling topography of the impure limestone region of Virginia, Tennessee, Maryland and Indiana, and is distinguished by its highly developed internal drainage in the undisturbed state. When remolded, however, its open structure is destroyed and the soil becomes very plastic and difficult to work. Plasticity of this soil also increases as the bed rock is approached. The particular soil used in this study was obtained close to bedrock in a highway cut approximately one mile south of Bedford, Ind. Atterberg limits of this soil, performed on the entire sample at field moisture, are as follows:

Plastic limit = 29.2
Liquid limit = 92.4
Plasticity index = 63.2
Flow index = 23.2

A third soil, pedologically classified as a Vigo silt, was used as a filler to supply the required percentage passing the No. 200 sieve in preparing samples of dense-graded base course. This deeply-weathered silt in the slightly undulating uplands of the Illinoian drift areas of southwestern Indiana.

Due to the lack of humid storage space it was not possible to preserve these soils at their field moisture content. All soils were therefore air dried in the laboratory, processed and stored until required. The results of routine laboratory tests performed on the soils in this condition are presented in Table 2.

Base Course Materials

The base course materials consisted primarily of glacial gravel from the lower Wabash River terrace, and were obtained near Lafayette, Ind. A small quantity of dune sand from northern Indiana was added to supply the fraction between No. 80 and No. 200 sieves, and Vigo silt was used for the fraction passing the No. 200 sieve, as previously noted.

Two gradations of base course were selected for study in these tests. Both were well-graded mixtures, with a maximum size of ¾ in. (Figure 3). However, one gradation had 7.0 percent by weight finer than the No. 200 sieve, while the other contained no sizes finer than the No. 80 sieve. These bases, hereafter referred to as "dense-graded" and "open-graded," were selected as typical of present-day construction in the Midwest after a study had been made of the construction and performance data of several highways and airfields.

The dense-graded base course did not completely satisfy the Corps of Engineers' frost requirements (*19*), because it contained 4.0 percent by weight finer than 0.02 mm instead of the specified maximum of 3 percent. Its gradation was similar to base course materials used extensively throughout the Midwest. These base courses have shown performance ranging from excellent to good. In some cases pavements in Illinois, Indiana and Ohio have shown considerable "blowing" distress when built over this type of base course.

TABLE 2
RESULTS OF CLASSIFICATION TESTS ON SOILS USED IN STUDY

Soil Characteristic	Soil Type				
	Crosby CL		Frederick CH		Vigo ML
	Sp. gr. 2.69		Sp. gr. 2.80		Sp. gr. 2.70
Size distribution:					
Gravel, % (> # 4 sieve)	0		0		0
Sand, % (< # 4 > # 200)	18.0		14.0		19.7
Silt and Clay, % (< # 200)	82.0		86.0		80.3
Standard compaction:	STD. AASHO	MOD. AASHO	STD. AASHO	MOD. AASHO	Not performed
Optimum moisture content, %	19.2	13.5	27.9	19.5	
Maximum dry unit weight, pc	107.4	119.3	91.8	106.7	
Atterberg limits:					
Liquid limit	38.5		88.5		29.9
Plastic limit	20.6		27.8		23.3
Plasticity index	17.9		60.7		6.6
Flow index	10.7		24.0		8.5

The open-graded base course studied in these tests was graded to satisfy the Corps of Engineers' frost requirements with respect to the percent by weight finer than 0.02 mm. However, it fails to satisfy the filter requirements proposed by Terzaghi (*14*) and substantiated by Bertram (*4*) and the Corps of Engineers' tests at Vicksburg (*25*), because the ratio of its 15 percent size to the 85 percent size of either the Crosby or the Frederick subgrade exceeds five. It does, however, satisfy the filter criteria proposed by Keene (*8*) for filters over cohesive subgrades. It represented base courses which have not shown distress from pumping and blowing in Indiana.

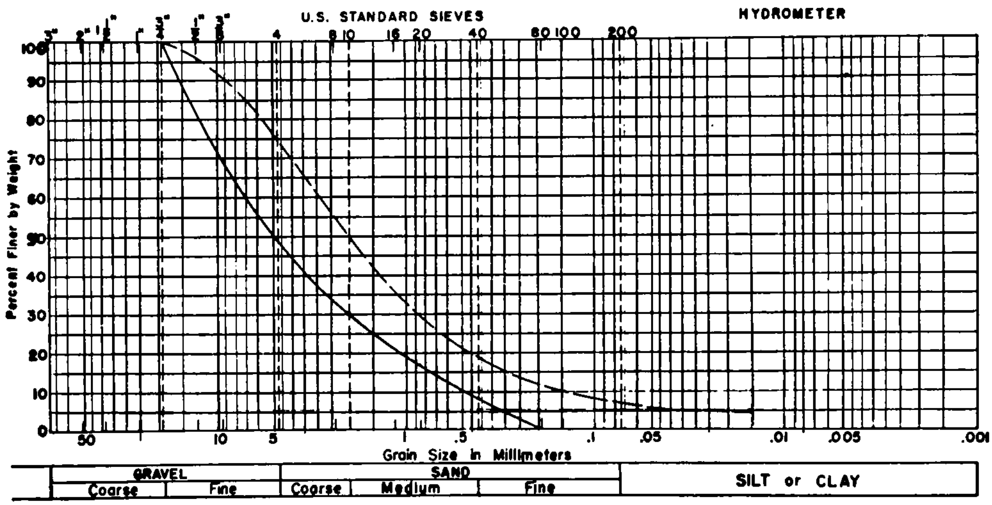

Figure 3. Grain size distribution of base course.

PROCEDURES

Compacting Subgrades

A quantity of air-dried powdered soil, approximately 0.03 lb in excess of that required to form a specimen 7.17 in. in diameter and 4.0 in. in height when compacted to the particular unit weight being studied, was weighed into a tared pan. It was then mixed by hand to the required moisture content, periodically spraying in distilled water, taking extreme care to obtain a uniform mixture of the soil and water.

The moist soil was placed in a lucite cylinder and compacted to the required density. The dry unit weight corresponding to each level of subgrade compaction was considered to be the peak point of a static compaction curve for the subgrade studied. For one series of tests the subgrade samples were compacted to 95 percent of standard AASHO; for another 95 percent of modified AASHO was adopted. The soils were compacted statically from both ends using the compactive pressures indicated in Table 3. These

TABLE 3
PREPARATION OF SUBGRADE SAMPLES (STATIC COMPACTION REQUIREMENTS)

Soil Type	Design Unit Weight, pcf	Equivalent Static Pressure, psi	Static Optimum Moisture, %
Crosby	102.0[1]	70	22.3
	113.3[2]	500	16.1
Frederick	87.2[1]	90	33.5
	101.4[2]	400	24.5

[1] 95 percent standard AASHO.
[2] 95 percent modified AASHO.

compaction pressures were determined from the results of preliminary tests, shown in Figures 4 and 5.

After compaction the subgrade samples were permitted to absorb moisture from the bottom for about 60 hr. Swell measurements were made during this period. After absorption the cylinder with the soil was fitted to an aluminum base plate, after which the base course was placed directly on top of the subgrade.

Base Course Compaction

Based on the recommendation of Lane (*10*), D'Appolonia (*6*), and others, it was considered desirable to base the compaction requirements of the base course on some relative density criterion, rather than to specify an arbitrary percentage of the maximum unit weight obtained in a dynamic compaction test.

For simplicity, compaction was specified in terms of a density ratio, D_r, analagous to that proposed by Lane (*10*). This was calculated from

$$D_r = \frac{d_n - d_o}{d_{100} - d_o} \qquad (1)$$

in which:

- d_n = dry density, pcf, of compacted specimen;
- d_o = dry density, pcf, loosest state from laboratory test for minimum density (this is determined by placing dry soil in a cylinder using a spoon to prevent appreciable fall — a 4-in. diameter Proctor cylinder is used for sands; for gravel, either a 6- or 7-in. diameter cylinder is used);
- d_{100} = dry density, pcf, maximum feasible density obtained in the laboratory.

Maximum densities for Eq. 1 were determined by vibrating submerged specimens for 10 min. with a surcharge of about 75 lb. Values determined in this manner were compared with the peak values in Figure 6. The greater of these was then abitrarily considered as d_{100} in the calculations.

The minimum density, d_o, was determined by pouring the oven-dry base course from a scoop into a 6-in. diameter mold 4.5 in. in depth, with a fall not exceeding 2 in.

Relative densities of 0.95 and 0.75 had been selected for investigation in this study, and the unit weight, d_n corresponding to each of these was readily calculated for each base course by substituting the experimental values of d_{100}

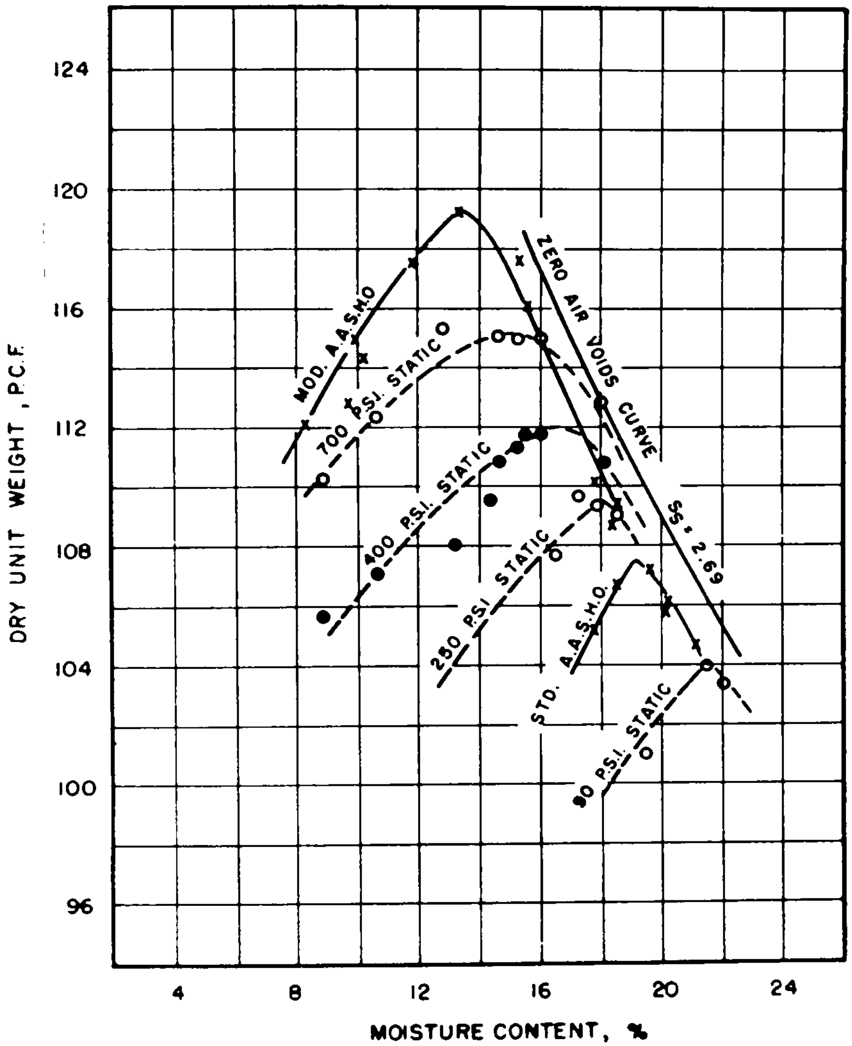

Figure 4. Compaction curves for Crosby subgrade.

and d_o in Eq. 1. These values are shown in Figure 6.

At the completion of the subgrade soaking period, the base was placed on the subgrade at a moisture content slightly greater than optimum in two layers of approximately equal thickness, each of which was compacted with 25 blows from a 5.5-lb steel tamping rod with a 2-in. diameter face falling 6 in. The loading head used in the pumping test, consisting of an aluminum disc 1 in. in thickness and 6.97 in. in diameter, attached to a 1¼-in. diameter aluminum shaft, was then placed on top of the base course. Any further compaction required to form a specimen 4.0 in. in height was accomplished by lightly tapping the end of the shaft, as well as the sides of the cylinder, with a leather mallet.

Repeated Loading Tests

The lucite cylinder containing the com-

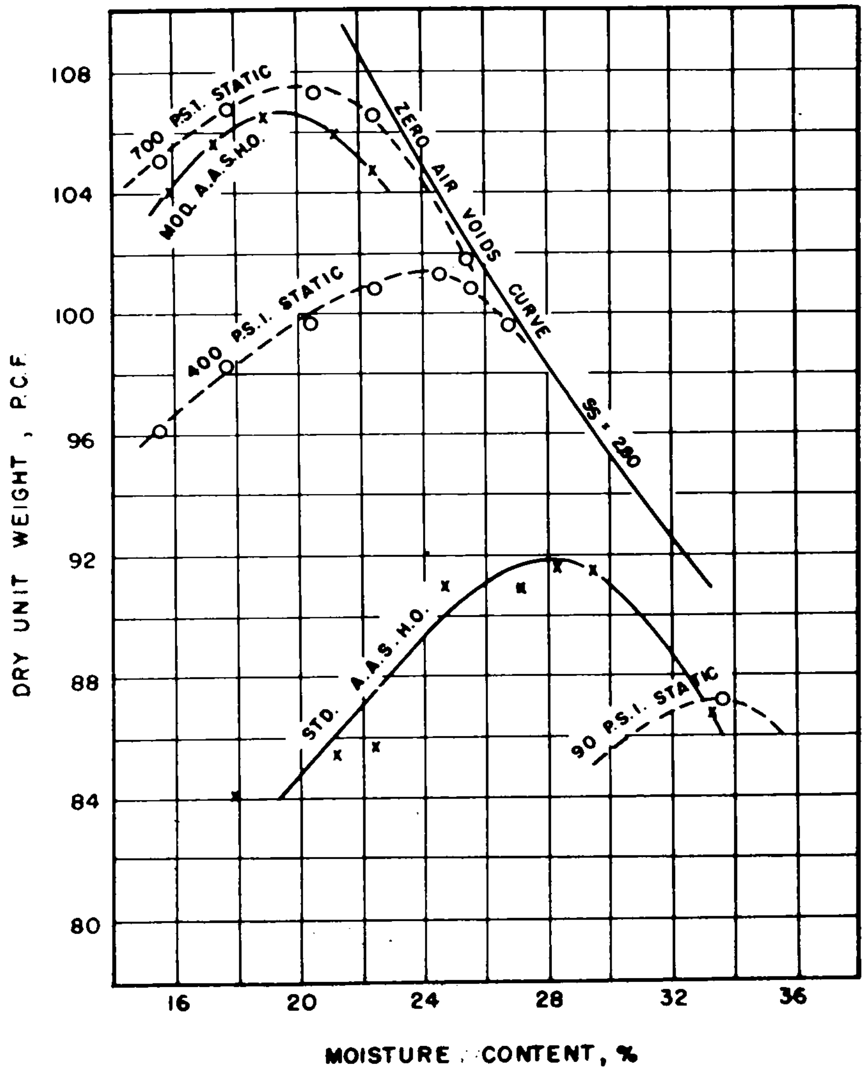

Figure 5. Compaction curves for Frederick subgrade.

pacted subgrade and base course was next placed in the repetitive loading machine. Water was added to the base course through an opening in the cover plate until the free water level was at or slightly above the bottom of the loading head. The valves leading to the standpipe and reservoir were then opened and water was allowed to flow through the porous stone and discharge to the atmosphere. This was continued until air bubbles were no longer visible in the discharge.

The discharge valve on the water line was next closed, allowing the static reservoir pressure of approximately 2¾ psi to act on the bottom of the subgrade for 12 hr. At the end of this time it was opened briefly to remove any further accumulation of air, then closed until the static pressure was re-established. The valve leading to the standpipe was closed

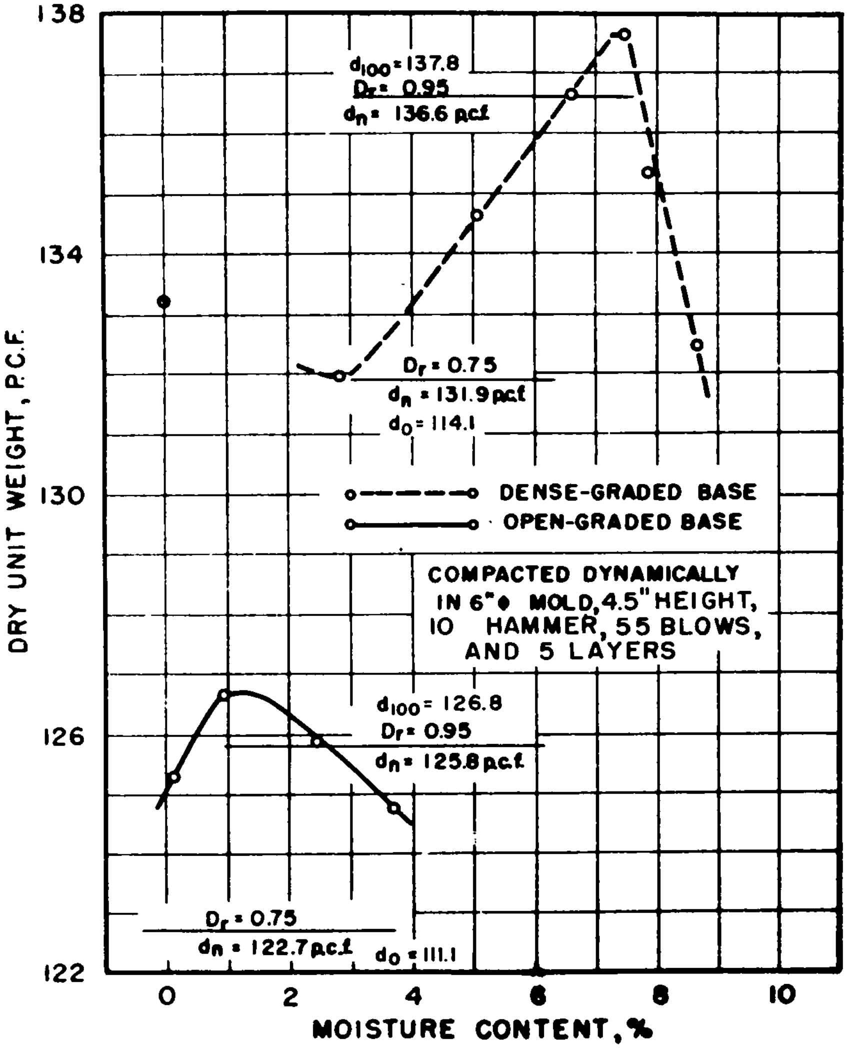

Figure 6. Compaction curves for base course.

to prevent water from entering or leaving the system, and the sample was ready for testing.

During each test deflections were measured and visual observations of the performance of subgrade and base were recorded. At the end of 40,000 load applications the material pumped above the piston was separately removed, then dried and weighed. When the quantity of pumped material was sufficient, grain-size analyses and Atterberg limit tests were subsequently performed. The base course and subgrade were then extruded and the base separated from the subgrade. The base course was dried and weighed, then washed over a No. 200 sieve to determine the increase (if any) in this size fraction. Sieve analyses were also performed on the washed base course. The subgrade was measured and a record made of its condition. In some cases moisture profiles of the subgrade were taken; in other cases the entire sub-

TABLE 4
CODING SYSTEM USED TO DESCRIBE INDIVIDUAL TESTS

Factor	Symbol	Level	
		1	2
Subgrade type	A	Crosby	Frederick
Base course type	B	Open-graded	Dense-graded
Subgrade compaction	C	95% std. AASHO	95% mod. AASHO
Base course compaction	D	$D_r = 0.75$	$D_r = 0.95$
Applied pressure	*E*	10 psi	40 psi
Number of load applications	*N*	2,000 (DA) 10,000 (SA)	5,000 (DA) 40,000 (SA)

grade was dried and weighed to permit a comparison of the total weight after test with the initial weight.

RESULTS

Coding System

In presenting the results of these tests, a coding system was introduced to describe the samples. This system, adhered to throughout the remainder of this report, is shown in Table 4. Factors are indicated by a capital letter and their corresponding levels are indicated by a subscript Arabic numeral.

Values of Measured Variables

The variables measured for each test were as follows:

1. Total weight of material pumped to top of base.
2. Cumulative deflection of the loading piston.
3. Increase in weight of the passing No. 200 sieve fraction within the base.

Where sufficient soil was available, grain-size analyses and Atterberg limit determinations were performed on the entire sample of pumped material. A sieve analysis was also made of the base course at the end of each test, for comparison with the original gradation. The net increase in the weight of passing No. 200 material above the top of the subgrade was calculated by adding the passing No. 200 fraction of the total weight of material pumped to the top of the base (computed from a hydrometer analysis) to the increase in weight of the passing No. 200 fraction within the base course.

The cumulative deflections for samples in each test series were plotted as ordinates against the logarithm of the number of applied loads, as shown in Figures 7 to 10 inclusive. Because the degree of base course compaction apparently had little effect, mean values for the deflections corresponding to the two levels of this factor were used in preparing the composite deflection curves. Two values of factor *N* (number of applied loads) were then selected so that they, with their corresponding deflections, would plot on the steeper portion of the cumulative deflection curves. For the single-acting tests 10,000 and 40,000 load applications were chosen as representative. The deflections in the double-acting series A tests, however, increased so rapidly with the number of load applications that the loading equipment, for some samples, was operating at its full 2-in. stroke soon after 5,000 loads

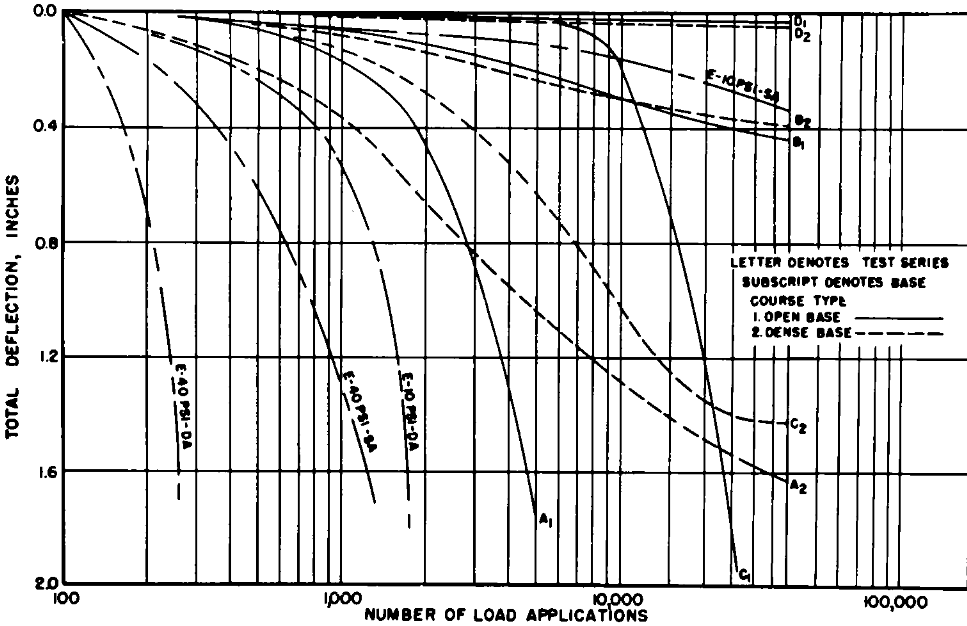

Figure 7. Deflection curves for combinations with standard Crosby subgrades.

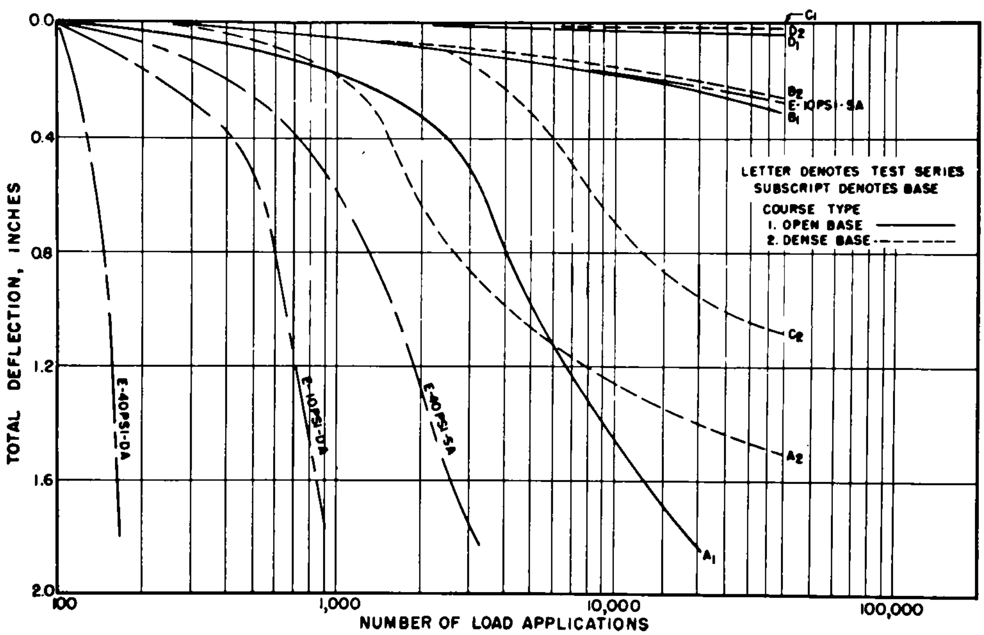

Figure 8. Deflection curves for combinations with standard Frederick subgrades.

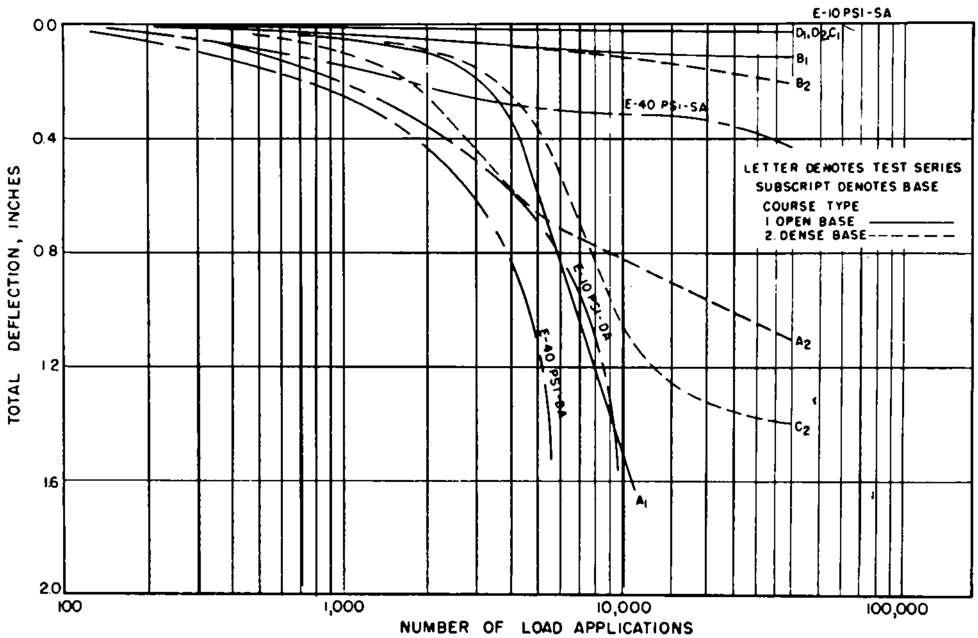

Figure 9. Deflection curves for combinations with modified Crosby subgrades.

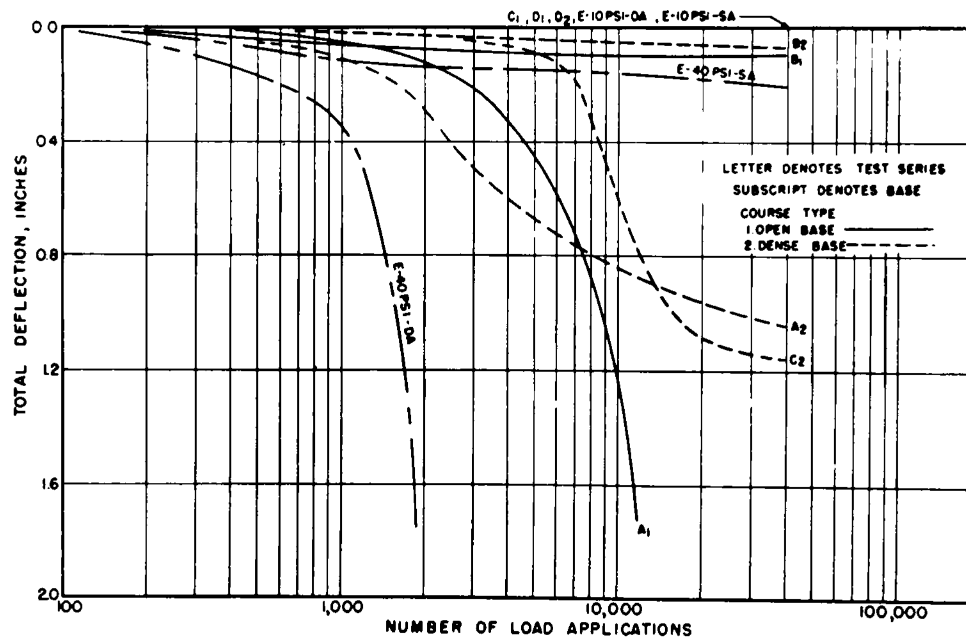

Figure 10. Deflection curves for combinations with modified Frederick subgrades.

had been applied. This value was accordingly selected as the higher level of factor N for analysis of the double-acting tests, and $N = 2{,}000$ was taken as the corresponding lower level.

Values of the following variables, both measured and computed, are given in Tables 5, 6, and 7 for each of the test series performed:

TABLE 5
RESULTS OF REPETITIVE LOADING TESTS

Measured Variable	Crosby CL								Frederick CH							
	Open Base				Dense Base				Open Base				Dense Base			
	95% Std. AASHO		95% Mod. AASHO		95% Std. AASHO		95% Mod. AASHO		95% Std. AASHO		95% Mod. AASHO		95% Std. AASHO		95% Mod. AASHO	
	$D_r =$ 0.75	$D_r =$ 0.95	$D_r =$ 0.75	$D_r =$ 0.95	$D_r =$ 0.75	$D_r =$ 0.95	$D_r =$ 0.75	$D_r =$ 0.95	$D_r =$ 0.75	$D_r =$ 0.95	$D_r =$ 0.75	$D_r =$ 0.95	$D_r =$ 0.75	$D_r =$ 0.95	$D_r =$ 0.75	$D_r =$ 0.95
(*a*) SERIES A																
Total defln. at 2,000 rep., in. x 100	25	45	16	4	77	54	18	33	40	17	12	2	80	44	20	35
Total defln. at 5,000 rep., in. x 100	150	172	45	70	126	77	50	82	122	80	64	7	120	92	35	94
Wt. of material pumped to top of base, g	1982	2231	1732	1824	1766	1576	904	1274	1707	1736	1523	1409	1632	1549	1195	1339
Increase in p200 material in base, lb	2.35	2.06	1.22	2.10	0.95	0.86	1.45	0.85	1.34	1.90	1.73	1.47	0.85	0.80	0.65	1.05
Increase in p200 material above top of subgrade, lb	4.27	4.64	3.40	3.87	2.97	2.91	2.69	2.37	3.33	4.01	3.39	2.90	2.54	2.51	1.91	2.57

TABLE 5 (Continued)

Measured Variable	Crosby CL								Frederick CH							
	Open Base				Dense Base				Open Base				Dense Base			
	95% Std. AASHO		95% Mod. AASHO		95% Std. AASHO		95% Mod. AASHO		95% Std. AASHO		95% Mod. AASHO		95% Std. AASHO		95% Mod. AASHO	
	$D_r =$ 0.75	$D_r =$ 0.95	$D_r =$ 0.75	$D_r =$ 0.95	$D_r =$ 0.75	$D_r =$ 0.95	$D_r =$ 0.75	$D_r =$ 0.95	$D_r =$ 0.75	$D_r =$ 0.95	$D_r =$ 0.75	$D_r =$ 0.95	$D_r =$ 0.75	$D_r =$ 0.95	$D_r =$ 0.75	$D_r =$ 0.95
(*b*) Series B																
Total defln. at 10,000 rep., in. x 100	32.0	24.2	9.7	10.6	26.5	22.7	11.0	13.0	21.0	17.2	11.4	7.0	19.8	13.2	4.0	6.9
Total defln. at 40,000 rep., in. x 100	50.0	37.6	13.0	10.8	41.0	29.6	15.0	26.4	35.4	25.7	12.0	7.3	26.9	23.3	4.7	10.2
Wt. of material pumped to top of base, g	23.5	9.0	1.1	0.2	444.6	258.2	136.6	201.9	51.7	22.9	18.2	9.2	173.8	168.7	59.4	86.5
Increase in p200 material in base, lb	0.51	0.66	0.08	0.14	0.22	0.20	0.04	0.12	0.40	0.30	0.08	0.09	0.15	0.15	0.10	0.09
Increase in p200 material above top of subgrade, lb	0.54	0.68	0.08	0.14	0.73	0.47	0.16	0.40	0.47	0.34	0.10	0.10	0.43	0.40	0.16	0.22

TABLE 5 (Continued)

(c) SERIES C

Measured Variable	Crosby CL								Frederick CH							
	Open Base				Dense Base				Open Base				Dense Base			
	95% Std. AASHO		95% Std. AASHO		95% Std. AASHO		95% Mod. AASHO		95% Std. AASHO		95% Mod. AASHO		95% Std. AASHO		95% Mod. AASHO	
	$D_r =$ 0.75	$D_r =$ 0.95	$D_r =$ 0.75	$D_r =$ 0.95	$D_r =$ 0.75	$D_r =$ 0.95	$D_r =$ 0.75	$D_r =$ 0.95	$D_r =$ 0.75	$D_r =$ 0.95	$D_r =$ 0.75	$D_r =$ 0.95	$D_r =$ 0.75	$D_r =$ 0.95	$D_r =$ 0.75	$D_r =$ 0.95
Total defln. at 2,000 rep., in. x 100	1	1	0	0	18	33	12	5	0	0	0	0	11	5	5	2
Total defln. at 5,000 rep., in. x 100	3	3	1	0	56	68	46	25	0	0	0	0	45	15	14	4
Total defln. at 20,000 rep., in. x 100	153	130	7	0	123	149	137	134	1	0	0	0	101	90	115	103
Wt. of material pumped to top of base, g	2178	2154	29	4	1429	1533	1759	1835	13	4	6	4	1287	1126	1568	1334
Increase in p200 material in base, lb	2.36	2.28	0.57	0.24	0.53	0.60	0.44	0.52	0.51	0.23	0.16	0.14	0.45	0.55	0.45	0.41
Increase in p200 material above top of subgrade, lb	4.40	4.42	0.62	0.25	2.01	2.19	2.07	2.24	0.54	0.24	0.17	0.15	1.79	1.89	1.83	1.76

TABLE 5 (Continued)

Measured Variable	Crosby CL								Frederick CH							
	Open Base				Dense Base				Open Base				Dense Base			
	95% Std. AASHO		95% Mod. AASHO		95% Std. AASHO		95% Mod. AASHO		95% Std. AASHO		95% Mod. AASHO		95% Std. AASHO		95% Mod. AASHO	
	$D_r =$ 0.75	$D_r =$ 0.95	$D_r =$ 0.75	$D_r =$ 0.95	$D_r =$ 0.75	$D_r =$ 0.95	$D_r =$ 0.75	$D_r =$ 0.95	$D_r =$ 0.75	$D_r =$ 0.95	$D_r =$ 0.75	$D_r =$ 0.95	$D_r =$ 0.75	$D_r =$ 0.95	$D_r =$ 0.75	$D_r =$ 0.95
(*d*) Series D																
Total defln. at 10,000 rep., in. x 100	2.2	2.4	2.1	1.8	4.4	1.4	2.7	0.9	3.9	4.0	0.9	1.1	1.8	2.2	1.5	2.2
Total defln. at 40,000 rep., in. x 100	2.9	3.0	3.7	2.3	6.6	1.6	4.3	1.2	4.5	5.3	1.0	0.7	3.9	3.0	1.2	1.7
Wt. of material pumped to top of base, g	0.0	0.9	0.4	1.5	6.1	15.9	7.3	5.9	1.3	0.6	0.5	0.6	4.2	7.1	3.0	12.1
Increase in p200 material in base, lb	0.04	0.02	0.02	0.04	0.16	0.14	0.21	0.17	0.03	0.01	0.02	0.01	0.16	0.19	0.23	0.19

TABLE 6
INCREASE IN PASSING 200 FRACTION OF BASE RESULTING FROM DOUBLE-ACTING LOADING*
(SERIES F TESTS)

Open-Graded Base Course		Dense-Graded Base Course	
10 psi	40 psi	10 psi	40 psi
0.7%	1.5-37.5%	1.0%	1.8-32.1%

* Increase in the p200 fraction of the base due to single-acting loading was negligible for samples with small deflections at the end of the test, as shown by the results of series B and D.

1. Cumulative deflection of the loading piston after 10,000 load applications for series B and D, and after 2,000 load applications for series A and C.
2. Cumulative deflection of the loading piston after 40,000 load applications for series B and D, and after 5,000 load applications for series A and C.
3. Total weight of material pumped to the top of the base.
4. Increase in the weight of the passing No. 200 sieve fraction within the base.
5. Increase in the weight of the passing No. 200 sieve fraction above the top of the subgrade.

To facilitate their analysis, the individual tests were grouped as follows into several test series. Each series, except for series F, consists of 16 individual tests.

1. Series A tests: double-acting tests at 40-psi applied pressure on combinations of subgrade and base course.
2. Series B tests: single-acting tests at 40-psi applied pressure on combinations of subgrade and base course.
3. Series C tests: double-acting tests at 10-psi applied pressure on combinations of subgrade and base course.
4. Series D tests: single-acting tests at 10-psi applied pressure on combinations of subgrade and base course.
5. Series E tests: double-acting and single-acting tests, at both 40-psi and 10-psi applied pressure, on the subgrade only.
6. Series F tests: double-acting and single-acting tests, at both 40-psi and 10-psi applied pressure, on the base course only.

DISCUSSION OF RESULTS

In studying the results, several trends may be perceived. Some are well defined and may be rightly considered as indicating the true effect of one or more factors on the variables studied; others undoubtedly reflect the inherent variations due to chance differences in sample preparation, method of testing, and mea-

TABLE 7
RESULTS OF SERIES E REPETITIVE LOADING TESTS (SUBGRADE ONLY, NO BASE COURSE)

Loading	Subgrade	Load, psi	Wt. of Material Pumped, g	Total Deflection, in. x 100[1]				
				1,000 Rep.	2,000 Rep.	5,000 Rep.	10,000 Rep.	40,000 Rep.
Single-acting	Crosby std.	10	198.0	6	7	10	15	33
		40	1,848.9	131	—	—	—	—
	Crosby mod.	10	104.0	0	0	0	0	1
		40	585.0	14	22	66	140	—
	Frederick std.	10	272.2	6	9	13	16	26
		40	1,631.4	59	126	—	—	—
	Frederick mod.	10	0	0	0	0	0	0
		40	352.2	11	13	15	15	20
Double-acting	Crosby std.	10	—	130	—	—	—	—
		40	—	—	—	—	—	—
	Crosby mod.	10	—	20	36	68	—	—
		40	—	25	44	114	—	—
	Frederick std.	10	—	198	—	—	—	—
		40	—	—	—	—	—	—
	Frederick mod.	10	—	0	0	0	0	0
		40	—	33	—	—	—	—

[1] All single-acting tests were continued for 40,000 load repetitions, but all double-acting tests were stopped after maximum deflection (2-in. stroke) had occurred.

surement of the test variable. Trends in the latter category should not be interpreted as representative of the true performance of the combinations studied. It is important, therefore, to establish the probable validity of any trends which appear in the data.

Relative Accuracy in Measurement of Test Variables

Before considering the significance of the results, an attempt will be made to appraise the relative accuracy of the measured variables. Of these, it is believed that the weight of material pumped to the top of the base could be measured most accurately. This pumped material collected chiefly on the top of the loading piston, hence could be easily separated from the base course.

The values of cumulative deflections are considered to be of comparable precision, because these were direct measurements with a dial indicator calibrated in 0.001-in. divisions. However, the deflections appeared to be affected by such features as initial seating of the loading piston, uniformity of compaction of the base course, and arrangement of the top layer of base particles. To reduce the effects of initial inequalities, the zero reading for the cumulative deflections was taken after 100 load repetitions. A few check tests performed in connection with series A (double-acting, 40 psi) and series C tests (single-acting, 10 psi) indicated that variations as large as 20 percent of the total deflection would occasionally occur when the total deflection at the end of the test was small.

The measurement of the increase in weight of the passing No. 200 fraction of the base course is believed to be the least accurate. To determine this quantity, it was first necessary to separate the base from the subgrade. For some samples, such as a dense-graded base course on a modified subgrade, this separation could be accurately made. However, where extensive intermixing of the subgrade and base had occurred, as with an open-graded base course on a standard subgrade, the separation became to some extent a matter of judgment.

Statistical Analysis of Trends

To aid in establishing the validity of the several trends, the measured variables were analyzed statistically, using standard analysis of variance techniques (*3*). Such an analysis is believed valuable as a guide in determining the importance of the several factors. To detect any effects other than very large ones by means of variance analyses, however, it is necessary to reduce the inherent test variation or to increase the number of samples tested for each given condition. As indicated in the preceding discussion, the reproducibility of specimens and of variable measurement was not exact, despite extreme care in the performance of the tests. Because it was not considered feasible to perform more than one test for each condition, the reliability of the analysis was therefore increased by combining the variance of the less-significant factors to obtain a pooled estimate of the residual term, which was then used to test the remaining factors for significance with a smaller value of α. Based on the recommendations of the Purdue Statistical Laboratory, the following method was used: All variances were tested for significance against the initial residual term, using an α-level of 0.25. All factors and interactions not significant at this level were then combined to form a pooled estimate of the residual term, and the remaining terms tested against this for significance with $\alpha = 0.05$. The use of a combined estimate of residual variance for significance testing increased the precision with which real trends could be detected and increased the confidence which could be placed in the validity of the findings.

Having determined the significant factors according to this method, it was considered desirable to make an estimate of the extent to which each contributed to the total variance. This was done by considering each series as a fixed model (*3*, p. 331) and writing the expected mean squares associated with each significant factor. The contribution of each to the total variance could then be directly computed and expressed as a percentage of the total variance. Each significant interaction was plotted for detailed study. Since only two levels of each factor were included in this study, it was necessary to assume linear variation in plotting the interactions, although it was recognized that some different type of variation might very well exist. Additional studies using other levels of applied pressure and compaction, as well as different gradations of base course and types of subgrade, would be of value in checking the validity of this assumption of linearity.

Analysis of the Data

Series A Tests (40 psi, D.A.)

(A) Subgrade Type. In general, slightly more material was pumped to the top of base courses on Crosby subgrades than those on Frederick subgrades. Similarly, base courses on Crosby subgrades deflected slightly more than those on Frederick subgrades after 5,000 load applications, although no significant difference in performance was noted at 2,000 load applications. Base courses on Crosby soils showed a considerable increase over those on Frederick soils in the amount of passing No. 200 material moved above the top of the subgrade. The soil type had no significant effect on the increase in passing No. 200 material within the base course itself.

(B) Base Course Type. Considerably more material was pumped to the top of the open-textured bases than to the top of the dense-textured bases. Specimens using the open gradation deflected appreciably less than those using the dense gradation after 2,000 load applications, although no significant difference was apparent after 5,000 load applications. As compared with samples using dense-graded bases, those with open-graded bases showed a greater increase in the passing No. 200 fraction of the base and in the passing No. 200 fraction above the top of the subgrade.

(C) Subgrade Compaction. Increasing the compaction of the subgrade decreased the weight of material pumped to the top of the base course, decreased the deflection after both 2,000 and 5,000 load applications, and reduced the increase in passing No. 200 material above the top of the subgrade. It had no significant effect on the passing No. 200 increase within the base course itself.

(D) Base Course Compaction. Increasing the compaction of the base course had no direct effect on the variables measured in this study.

(N) Number of Load Applications. Increasing the number of load applications from 2,000 to 5,000 increased the total deflection for all combinations of base course and subgrade tested.

(AB) Interaction Between Subgrade Type and Base Course Type. Dense-graded bases were equally effective on Crosby and Frederick subgrades in reducing the weight of material pumped to the top of the base course. Open-textured bases, however, were less effective on Crosby subgrades than on Frederick subgrades in reducing the value of this same variable. For dense-textured bases, the subgrade type had little effect on the weight of pumped material.

Specimens using dense-graded bases had deflected about the same amount after 5,000 load applications regardless of soil type. However, open-textured bases on Crosby subgrades had deflected appreciably more than similar bases on Frederick subgrades in the same period. The least deflection occurred with an open-graded base on a Frederick subgrade, whereas the greatest deflection occurred with an open-graded base on a Crosby subgrade.

(BC) Interaction Between Base Course Type and Subgrade Compaction. Increasing the compaction of the subgrade was more effective for samples using open-textured bases than for those using less-permeable bases, in reducing the deflection after 5,000 load applications.

(CD) Interaction Between Subgrade Compaction and Base Course Compaction. Increasing the compaction of base courses on standard subgrades reduced

deflection after 5,000 load applications, whereas increasing the compaction of base courses on modified subgrades increased the amount of deflection.

(ABD) Interaction Between Subgrade Type, Base Course Type, and Base Course Compaction. The most beneficial effect of an increase in base compaction on reducing deflection occurred with an open-graded base course on a Frederick subgrade.

(BCD) Interaction Between Base Course Type, Subgrade Compaction, and Base Course Compaction. Increasing the compaction of the less-permeable bases on modified subgrades increased deflection after 2,000 and 5,000 load applications. For all other combinations of base course and subgrade compaction, increasing the compaction of the base course decreased deflection.

(BCN) Interaction Between Base Course Type, Subgrade Compaction, and Number of Load Applications. In studying the increase in deflection produced by increasing the number of load applications from 2,000 to 5,000, it appeared that open-textured bases on standard subgrades showed a greater than average increase in deflection.

Series B Tests (40 psi, S.A.)

(A) Subgrade Type. Samples with Crosby subgrades had deflected more after 10,000 and 40,000 load applications than those with Frederick soil. The type of soil had no significant effect on the weight of material pumped to the surface, on the increase in the passing No. 200 fraction within the base, or on the increase in the passing No. 200 fraction above the top of the subgrade.

(B) Base Course Type. Combinations of subgrades and dense-graded base courses pumped considerably more material to the top of the base, whereas those with open-textured base courses showed a slightly greater increase in the passing No. 200 fraction within the base.

(C) Subgrade Compaction. Increasing the compaction of the subgrade decreased the weight of material pumped to the top of the base, materially decreased the deflection at 10,000 and 40,000 load applications, and reduced the passing No. 200 increase within the base and above the top of the subgrade.

(D) Base Course Compaction. Increasing the compaction of the base course had no direct significant effect on any of the variables studied.

(N) Number of Load Applications. Increasing the number of load applications from 10,000 to 40,000 produced a small increase in the total deflection.

(AB) Interaction Between Subgrade Type and Base Course Type. In comparing the weight of material pumped for different combinations, it appeared that open-textured base courses were equally effective over both Crosby and Frederick subgrades. However, dense-graded base courses were considerably more effective over Frederick subgrades than over Crosby subgrades in reducing the weight of material pumped to the top of the base course. The best combination was an open-graded base on a Crosby subgrade, but the worst pumping occurred with the less-permeable base on a Crosby subgrade.

(BC) Interaction Between Base Course Type and Subgrade Compaction. Increasing the subgrade compaction caused a greater decrease in the deflections after 40,000 load applications and in the passing No. 200 increase within the base for samples using the more permeable base course than for those with the dense-graded base course. On modified subgrades, both base courses had approximately the same increase in their passing No. 200 fraction, but on standard subgrades the open-graded bases had a considerably larger passing No. 200 increase.

(CD) Interaction Between Subgrade Compaction and Base Course Compaction. Increasing the base course compaction reduced the deflection of base courses on standard subgrades, but had little effect on the deflection of bases on modified subgrades.

(CN) Interaction Between Subgrade Compaction and Number of Load Applications. The deflection of specimens with

standard subgrades increased more rapidly with increasing number of load applications than the deflection of those with modified subgrades.

Series C Tests (10 psi, D.A.)

(A) Subgrade Type. Specimens with Crosby subgrades had deflected more, after 20,000 load applications, than those with Frederick subgrades. Similarly, the samples with Crosby subgrades pumped more material to the top of the base course and had a greater passing No. 200 increase within the base and above the top of the subgrade.

(B) Base Course Type. Samples with dense-graded base courses deflected more than those with open-graded base courses, pumped more material to the surface, and had a greater increase in the passing No. 200 fraction above the top of the subgrade. Combinations with open-textured base courses had a greater increase in the passing No. 200 fraction within the base itself.

(C) Subgrade Compaction. Increasing the compaction of the subgrade decreased the deflection at 20,000 load applications, reduced the passing No. 200 increase within the base and above the top of the subgrade, and reduced the weight of material pumped to the top of the base course.

(D) Base Course Compaction. Increasing the compaction of the base course slightly reduced the deflection occurring between 5,000 and 20,000 load applications.

(N) Number of Load Applications. Increasing the number of load applications from 5,000 to 20,000 produced a large increase in total deflection.

(AB) Interaction Between Subgrade and Base Course Type. The open-textured bases were more effective over Frederick subgrades than over Crosby subgrades in reducing the weight of material pumped and the passing No. 200 increase within the base and above the top of the subgrade. The best combination was an open-graded base on a Frederick subgrade. The subgrade type had little effect on the passing No. 200 increase of dense-graded bases, but had a large effect on the passing No. 200 increase of the more permeable base.

(AC) Interaction Between Subgrade Type and Subgrade Compaction. Increasing the subgrade compaction had little effect for Frederick subgrades, but for Crosby subgrades reduced the deflection after 20,000 load applications, the weight of material pumped, and the passing No. 200 increase within the base and above the top of the subgrade.

(BC) Interaction Between Base Course Type and Subgrade Compaction. Increasing the subgrade compaction had little effect for specimens with dense-textured base courses, but appreciably reduced the deflection after 20,000 load applications, the weight of material pumped, and the passing No. 200 increase within the base and above the top of the subgrade for combinations with open-textured base courses.

(BN) Interaction Between Base Course Type and Number of Load Applications. The deflection of samples with dense-graded bases increased more rapidly than that of samples with open-textured base courses, as the number of load applications was increased from 5,000 to 20,000.

(ABC) Interaction Between Subgrade Type, Base Course Type, and Subgrade Compaction. Increasing the subgrade compaction was most effective for the open-graded base on Crosby subgrades. This substantially reduced the deflection, the weight of material pumped, and the passing No. 200 increase within the base and above the top of the subgrade.

(ABN) Interaction Between Subgrade Type, Base Course Type, and Number of Load Applications. Increasing the number of load applications from 5,000 to 20,000 increased the deflection for all specimens except those with open-graded bases on Frederick subgrades.

(ACN) Interaction Between Subgrade Type, Subgrade Compaction, and Number of Load Applications. Specimens with the more permeable bases on standard subgrades showed the greatest increase in deflection due to an increase

from 5,000 to 20,000 in the number of load applications.

(BCN) Interaction Between Base Course Type, Subgrade Compaction, and Number of Load Applications. Increasing the number of load applications from 5,000 to 20,000 increased the deflection for all samples except those with open-graded bases on modified subgrades.

(ABCN) Interaction Between Subgrade Type, Base Course Type, Subgrade Compaction, and Number of Load Applications. Increasing the number of load applications from 5,000 to 20,000 increased the deflection of all samples except those with the more permeable base on Frederick subgrades and on modified Crosby subgrades.

Series D Tests (10 psi S.A.)

(A) Subgrade Type. Base courses on Crosby subgrades showed a slightly greater deflection than those on Frederick subgrades after 40,000 load applications.

(B) Base Course Type. Dense-graded bases had more material pumped to their surface than did the open-graded bases. The latter, however, showed a slightly larger increase in the passing No. 200 fraction.

(C) Subgrade Compaction. Increasing the compaction of the subgrade decreased the deflection after 10,000 and 40,000 load applications.

(D) Base Course Compaction. Increasing the compaction of the base course decreased the deflection after 40,000 load applications and slightly lessened the passing No. 200 increase within the base.

(N) Number of Load Applications. Increasing the number of load applications from 10,000 to 40,000 caused a slight increase in total deflection.

(AC) Interaction Between Subgrade Type and Subgrade Compaction. Increasing the subgrade compaction had a greater effect on Frederick subgrades than on Crosby subgrades in reducing deflection.

(AD) Interaction Between Subgrade Type and Base Course Compaction. Increasing the compaction of base courses on Frederick subgrades had little effect; increasing the compaction of base courses on Crosby subgrades produced a large decrease in deflection. The greatest deflections occurred with $D_r = 0.75$ base courses on Crosby subgrades; the least deflections occurred with $D_r = 0.95$ base courses on the same type of subgrade.

(BD) Interaction Between Base Course Type and Base Course Compaction. Increasing the compaction of open-graded bases had little effect; increasing the compaction of dense-graded base courses reduced the deflection. The least favorable combination occurred when an open-textured base course, compacted to 0.75 relative density, was placed on either subgrade.

(ABC) Interaction Between Subgrade Type, Base Course Type, and Subgrade Compaction. The greatest decrease in deflection produced by an increase in subgrade compaction was obtained with combinations using an open-textured base course on Frederick subgrades. Increasing the compaction of Crosby subgrades overlain by the more permeable base had little effect on deflection.

(ABD) Interaction Between Subgrade Type, Base Course Type, and Base Course Compaction. Increasing the compaction of the base course was most effective in decreasing deflections of dense-graded bases on Crosby subgrades. The effect on other combinations was slight.

(BCD) Interaction Between Base Course Type, Subgrade Compaction, and Base Course Compaction. Increasing the compaction of the base course decreased deflection for all samples except for those with open-graded bases on standard subgrades.

Series E Tests (Subgrade Only)

Under double-acting loading, standard Frederick subgrades deflected more rapidly than the corresponding standard Crosby subgrades. This was also the case for modified subgrades subjected to 40-psi double-acting loading. Under 10-psi double-acting loading, however, a modified Frederick subgrade had no appreciable deflection at the end of 40,000 load applications, whereas a modified Crosby subgrade had rapidly failed under similar loading conditions.

Under 10-psi single-acting loading, standard Crosby and Frederick subgrades deflected at approximately the same rate, although neither Crosby nor Frederick modified subgrades had deflected appreciably at the end of 40,000 load applications. Under 40-psi single-acting loading, both standard and modified Crosby subgrades deflected more rapidly than the corresponding Frederick subgrades.

The weight of pumped soil was not measured for the double-acting tests, because for these the number of load applications was varied for each test. In the single-acting tests, more material was generally pumped from Crosby subgrades than from Frederick subgrades. An exception to this was a standard Frederick subgrade under 10-psi loading, which pumped more material than a standard Crosby subgrade under the same loading.

Series F Tests (Base Course Only)

The results of a limited series of repetitive loading tests on the base course alone are presented in Table 6. These tests, intended to delineate the extent to which degradation of the base course might be present, consisted only of double-acting tests, because the results of the previous series indicated that base degradation in single-acting tests, if present at all, was of necessity slight.

The larger values of passing No. 200 increase listed for the 40-psi D.A. tests were obtained by applying 40,000 repetitions of load to uncompacted base course samples. The lesser values shown for these same tests are considered applicable to bases which remain compact throughout the loading period and experience only surface abrasion. These latter percentages are only intended to represent the probable order of magnitude of the passing No. 200 increase resulting from degradation, as they were obtained by extrapolating the results of preceding tests.

Series A and C Combined (10 and 40 psi D.A.)

(A) Subgrade Type. Samples with Crosby subgrades had deflected slightly more after 5,000 load applications than those with Frederick subgrades, had pumped more material to the top of the base course, and had a greater increase in passing No. 200 material above the top of the subgrade.

(B) Base Course Type. Samples with dense-graded base courses deflected more than those with open-graded base courses and pumped more material to the top of the base course. The more permeable base course had a greater increase in passing No. 200 material within the base and above the top of the subgrade.

(C) Subgrade Compaction. Increasing the subgrade compaction reduced the deflection, the weight of material pumped to the top of the base course, and the increase in passing No. 200 material above the top of the subgrade.

(D) Base Course Compaction. Increasing the compaction of the base course had no direct effect on the variables studied.

(E) Applied Pressure. Increasing the applied pressure from 10 psi to 40 psi caused a major increase in the total deflection, weight of material pumped to the top of the base course, and passing No. 200 increase within the base and above the top of the subgrade.

(BC) Interaction Between Base Course Type and Subgrade Compaction. Increasing the compaction of the subgrade had little effect on the increase in passing No. 200 material above the top of the subgrade for combinations with dense-textured bases, but materially reduced this variable for combinations with open-textured bases. The base course type had little effect on the passing No. 200 increase above modified subgrades.

(BE) Interaction Between Base Course Type and Applied Pressure. The base course type had little effect on the weight of material pumped when the applied pressure was 40 psi. At 10-psi applied pressure, however, the less perme-

able base pumped appreciably more than the open-textured base course.

(CE) Interaction Between Subgrade Compaction and Applied Pressure. The deflection of specimens with standard subgrades increased more rapidly due to an increase from 10 psi to 40 psi in applied pressure, than combinations with modified subgrades.

(ABC) Interaction Between Subgrade Type, Base Course Type, and Subgrade Compaction. The greatest reduction in weight of material pumped, resulting from an increase in subgrade compaction, was obtained for combinations of open-graded base courses on Crosby subgrades.

(ABE) Interaction Between Subgrade Type, Base Course Type, and Applied Pressure. The increase in deflection resulting from an increase from 10 psi to 40 psi in applied pressure was greatest for combinations of open-textured bases on Crosby subgrades.

(BCE) Interaction Between Base Course Type, Subgrade Compaction, and Applied Pressure. The increase in deflection resulting from an increase from 10 psi to 40 psi in applied pressure was greatest for combinations with open-graded bases on standard subgrades.

(ABDE) Interaction Between Subgrade Type, Base Course Type, Base Compaction, and Applied Pressure. Samples with open-graded $D_r = 0.75$ bases deflected more, due to an increase from 10 psi to 40 psi in applied pressure, than those with dense-graded $D_r = 0.75$ bases. Crosby subgrades with open-textured $D_r = 0.95$ bases and Frederick subgrades with dense-textured $D_r = 0.95$ bases deflected more rapidly, due to the same pressure increase, than other combinations of subgrade with $D_r = 0.95$ base courses.

(ABCE) Interaction Between Subgrade Type, Base Course Type, Subgrade Compaction, and Applied Pressure. Combinations of standard Crosby subgrades with open-textured bases pumped more than other combinations when the applied pressure was increased from 10 psi to 40 psi. The same increase in pressure had little effect on specimens with modified subgrades and dense-graded bases, but produced a large increase in the weight of material pumped for combinations of modified subgrades with the more permeable base course.

(BCDE) Interaction Between Base Course Type, Subgrade Compaction, Base Course Compaction, and Applied Pressure. Increasing the applied pressure from 10 psi to 40 psi had little effect on samples with dense-textured $D_r = 0.75$ bases on modified subgrades. The same pressure increase caused a large increase in the deflection of samples with open-graded bases on standard subgrade.

Series B and D Tests Combined (10 and 40 psi S.A.)

(A) Subgrade Type. Specimens with Crosby subgrades had deflected slightly more after 10,000 and 40,000 load applications than those with Frederick subgrades.

(B) Base Course Type. Samples with dense-graded base courses had pumped more material to the top of the base than those with open-graded base courses.

(C) Subgrade Compaction. Increasing the compaction of the subgrade decreased the deflection at 10,000 and 40,000 load applications, reduced the passing No. 200 increase within the base, and slightly reduced the weight of material pumped to the top of the base course.

(D) Base Course Compaction. Increasing the compaction of the base course slightly decreased the total deflection after 40,000 load applications.

(E) Applied Pressure. Increasing the applied pressure from 10 psi to 40 psi caused a major increase in total deflection, weight of material pumped to the top of the base, and passing No. 200 increase within the base.

(AB) Interaction Between Subgrade Type and Base Course Type. Samples with open-textured base courses pumped approximately the same amount of material, regardless of subgrade type. However, the dense-graded base on Crosby subgrades pumped considerably more material to the surface than the same base on Frederick subgrades. The best com-

bination was an open-textured base on a Crosby subgrade, whereas the severest pumping occurred with a dense-textured base on a Crosby subgrade.

(AE) Interaction Between Subgrade Type and Applied Pressure. At 10-psi applied pressure the subgrade type had little effect on total deflection after 10,000 load applications. At 40-psi applied pressure, however, specimens with Crosby subgrades had deflected more than those on Frederick subgrades for the same number of load applications.

(BC) Interaction Between Base Course Type and Subgrade Compaction. Increasing the compaction of the subgrade was more effective in reducing the passing No. 200 increase within the base for samples using open-textured bases than for those with the less permeable base. The largest passing No. 200 increase within the base occurred with open-graded bases on standard subgrades; the least passing No. 200 increase resulted for the same type of base course on modified subgrades.

(BE) Interaction Between Base Course Type and Applied Pressure. At 10-psi applied pressure, approximately the same weight of material was pumped regardless of base course type. At 40-psi, however, dense-textured base courses had pumped considerably more than open-textured base courses.

Increasing the applied pressure from 10 psi to 40 psi produced only a slight increase in the passing No. 200 fraction of dense-graded bases, but caused a major increase in the passing No. 200 fraction of open-graded bases. At 10 psi the best samples were those with the more permeable base; at 40 psi the less permeable base had the smaller passing No. 200 increase.

(CE) Interaction Between Subgrade Compaction and Applied Pressure. At 10-psi applied pressure the compaction of the subgrade had little effect on the total deflection. At 40-psi applied pressure, however, specimens with standard subgrades had deflected appreciably more than those with modified subgrades. similarly, increasing the applied pressure from 10 psi to 40 psi had little effect on the passing No. 200 increase of base courses on modified subgrades, but greatly augmented the passing No. 200 increase of base courses on standard subgrades.

(ABE) Interaction Between Subgrade Type, Base Course Type, and Applied Pressure. In considering the weight of material pumped to the top of the base course, increasing the applied pressure from 10 psi to 40 psi had little effect for samples with open-graded base courses. However, the same pressure increase caused considerably more pumping for samples with the less permeable base course. The greatest increase in pumping due to an increase in applied pressure occurred with dense-graded-bases on Crosby subgrades.

(BCE) Interaction Between Base Course Type, Subgrade Compaction, and Applied Pressure. Increasing the applied pressure from 10 psi to 40 psi caused the largest passing No. 200 increase within the base for combinations of open-graded bases on standard subgrades.

Interpretation of Results

It is apparent from the preceding section that the behavior of base-subgrade combinations in the repetitive loading tests cannot be explained solely by a consideration of the direct effects of the factors selected for investigation (subgrade type, base course type, subgrade compaction, base course compaction, magnitude of applied pressure, and number of load repetitions), because interactions between these consistently account for a large percentage of the assignable variance.

The soils used in this study were referred to as Crosby and Frederick in accordance with their pedological classification. It should be recognized, however, that the initial drying and preliminary processing of these soils undoubtedly produced important changes in their character, hence they can no longer be expected to behave in precisely the same manner as naturally-occurring Crosby and Frederick soils. As used in this study, the soils could perhaps be more correctly described as laboratory-prepared samples of a clay of medium plasticity (CL) and a highly plastic clay (CH). Use of two levels of the "subgrade type" factor, therefore, permits a comparison of the behavior of two clays of widely differing plasticity rather than of two known soils.

It is of interest to note that, in several respects, the CH subgrades appeared to perform better than the CL subgrades when combinations of base course and subgrade were tested by repetitive loading. This difference in performance, although not large, is consistent throughout the test series. Thus, in the single-acting series (B and D), combinations with Crosby subgrades deflected more than those with Frederick subgrades; whereas in the double-acting series, combinations with Crosby subgrades deflected more, pumped more soil to the top of the base, and moved more passing No. 200 material from the subgrade. In the single-acting tests performed on the subgrade alone (series E), the Crosby subgrades again deflected more rapidly than the corresponding Frederick subgrades. The difference in performance was less consistent for the double-acting tests on the subgrades because here, if failure occurred, the subgrades prepared from Frederick soils apparently deflected more rapidly than the Crosby subgrades. This variation from the performance repeatedly observed in tests of combinations of subgrade and base course offers supporting evidence to the statement that the interactions developed between the subgrade and the base course may play an important role.

When evaluated in a single loading test such as the C.B.R., according to the prevailing practice in flexible pavement design, the Crosby appeared somewhat superior to the Frederick.

The discrepancy between the effect of a single load and of repetitive loading was anticipated by Seed, Chan, and Monismith (*12*, p. 541), who state as follows:

> Most methods of pavement design now in use are based on an index of soil strength determined by some type of test in which the total load is slowly applied over a period of several minutes. These indices of strength have been correlated empirically with the performance of soil underlying actual pavements and thus provide a fairly reliable index for design. It does not, however, necessarily follow that a strength index determined under conditions of slow stress increase will satisfactorily indicate the performance of the soil under conditions of repeated loading. If soils having the same strength index behave in similar fashion under repeated loading, then any difference between the effects of repeated loads and gradually increased loads will be taken into account in the empirical correlation with pavement performance.
>
> If, however, soils having the same strength index are affected to different extents by repeated loading, then the correlation of strength index with pavement performance can only be approximate.

In all of the tests performed in this study the water level was kept slightly above the top of the sample with no drainage permitted during the tests, because a limited series of introductory tests had indicated that such a closed system afforded the most severe test. Subgrade pumping apparently did not occur if the water level was below the bottom of the loading piston. The difference in performance directly attributable to subgrade type was found to be slight; it is entirely possible that this difference could be obscured in actual pavements by variations in water retention characteristics of the soils, relative topographic position, and climatic variables. Thus, a Frederick subgrade, located in a region of higher precipita-

TABLE 8

RESULTS OF CALIFORNIA BEARING RATIO TESTS ON CROSBY AND FREDERICK SUBGRADES

Soil Type	Subgrade Compaction	Moding Moisture	Soaked C.B.R.
Crosby	95% std. AASHO	Optimum	8+
Frederick	95% std. AASHO	Optimum	5
Crosby	95% mod. AASHO	Optimum	16
Frederick	95% mod. AASHO	Optimum	5

tion, might in fact pump more quickly than a Crosby subgrade if water were present a greater proportion of the time to form a closed system between the pavement, base, and subgrade.

The difference in performance of open-graded bases and dense-graded bases was more pronounced. A visual study was made of the behavior of the various combinations during testing, and a characteristic sequence of events observed. When double-acting loading was applied to a combination with an open-type base, the subgrade would either remain stationary or would gradually move upward through the granular layer. If it did not move entirely through the base during the tests, the deflections remained small. However, if the subgrade moved completely through the base course, the deflections abruptly increased.

Plots of total deflection as ordinate against the logarithm of the number of load applications as abscissa thus showed a characteristic shape. The initial portion of the deflection curve had a relatively flat slope, as shown in curves A_1 and C_1 (Figure 9). If the subgrade had not worked through the base by the end of the test the slope of this deflection curve remained essentially constant, as shown in curves D_1 and C_1 (Figure 9). If, however, the subgrade pumped completely through the granular layer, a sharp downward curvature would result, as shown by curve A_2 of Figure 9. An increase in subgrade compaction appeared to increase the number of load applications required to produce this abrupt increase in curvature (curves A_1 and C_1, Figures 7 and 9), whereas an increase in pressure accelerated the onset of this change in slope (curves A_1 and C_1, Figures 7 to 10).

When double-acting tests were performed on combinations with dense-textured bases the subgrade, if it moved at all, moved readily but at a slower rate than into the more permeable bases. The base course itself eroded at a fairly constant rate. Thus, typical deflection curves for combinations of subgrade and base course in which pumping occurred (curves A_1 and A_2, Figures 7 to 10) initially show a greater deflection for the dense-graded base courses. If the subgrade pumped completely through the open-graded bases, however, the deflections rapidly increased until they equalled, and ultimately exceeded, those of similar combinations with dense-graded base courses. Because an undesirably large deflection had occurred before the less permeable base became superior to the open-textured type, it appeared that the later performed more satisfactorily.

This same sequence of events, to a reduced scale, occurred in the single-acting tests. Under successive load applications the finer particles of the dense-graded bases were pumped upward and collected on the loading piston, while the subgrades moved upward slowly and through the more permeable base courses.

The description of base course and subgrade pumping given in the preceding served to explain the results of the laboratory pumping tests. In series A, the large applied pressure and double-acting type of loading accelerated the pumping. Thus, although the combinations of subgrades with dense-graded bases initially deflected more than those with open-textured bases, by the end of the test subgrade pumping had been sufficiently developed so that samples with the more permeable bases moved more passing No. 200 material from the subgrade and pumped more material to the surface of the base. In series C, the lower applied pressure was insufficient to develop pumping in several of the specimens with open-graded base courses, hence samples with dense-graded base courses moved more passing No. 200 material from the subgrade and pumped more material to the surface of the base. Similarly, in the single-acting tests (series B and D), the dense-graded bases pumped more than the open and had a greater passing No. 200 increase above the top of the subgrade.

The more permeable base courses, as was anticipated, generally had the greater passing No. 200 increase within the base. An exception to this was the series D in which the low applied pressure, in conjunction with the single-acting type of loading, was apparently insufficient to cause extensive intermixing of the subgrade with open-textured base courses. It was first believed that the loading in series D tests had been insufficient to produce pumping of either the base or the subgrade, and the greater weight of material pumped by dense-textured base courses, although significant in a statistical analysis, was attributed to segregation of particles within the base resulting from vibratory compaction. The greater passing No. 200 increase exhibited by these bases, however, could only be attributed to pumping of the subgrade. As a matter of interest, one test with a dense-graded base course was subjected to 100,000 repetitions of 10-psi S.A. loading, at the end of which period an appreciable amount of base material had been pumped to the surface. This served to confirm the earlier conclusion that dense-textured bases pumped more than open-textured bases in 10-psi S.A., as well as in 40-psi S.A. tests.

Increasing the compaction of the subgrade, without exception, proved beneficial. For specimens with open-graded bases, as previously suggested, it either prevented subgrade pumping entirely or increased the number of load applications required to produce pumping. Its apparent effect with dense-graded base samples was to produce a more rigid subgrade-base structure, which deflected less under a given load, hence reduced the rate at which base course erosion progressed.

The combined effects of subgrade type, base course type, and subgrade compaction are strikingly illustrated in series C tests (10 psi, D.A.). Here a standard Crosby subgrade soil with an open-textured base pumped extensively, while a standard Frederick subgrade with the same base course did not pump. Substitution of a modified Crosby subgrade for the standard Crosby subgrade again prevented pumping. The effect of applied pressure can be evaluated by comparing these results with those of series A (40 psi, D.A.), in which all combinations with open-graded base courses pumped severely.

The general effect of an increase in base course compaction from $D_r = 0.75$ to $D_r = 0.95$ was to reduce the total deflection. This trend was not well defined, and accounted for only a small percentage of the assignable variance. The inconclusive nature of these results may be attributable, at least in part, to the difficulties in accurate base course compaction as described previously in this report.

An increase from 10 psi to 40 psi in the applied pressure accelerated the onset of both subgrade pumping and base course erosion. Samples with standard subgrades were more adversely affected by this pressure increase than were similar specimens with modified subgrades. The greatest increase in deflection and intermixing occurred with open-textured base courses on standard subgrades. From the variance analyses of the combined series A-C and B-D, this increase in pressure appeared as the largest single factor affecting the deflection of all samples.

Increasing the number of applied loads from N_1 to N_2 increased the deflections in all test series, with the larger effect occurring in the double-acting series A and C. The reason for this becomes apparent when the composite deflection curves shown in Figures 7 to 10 are examined. The numbers of load applications represented by N_1 approximately correspond to the points at which the deflection curve of pumping specimens abruptly trend downward, whereas N_2 represents the number of load applications required to produce deflections near the maximum for the testing equipment (2 in.). Hence, an increase from N_1 to N_2 in the number of applied loads produced a large increase in the deflection of the violently pumping samples found in series A and occasionally in series C.

The few tests performed in series F indicated that a large degree of degradation could result, with both open-graded and dense-graded base courses, due to repetitive loading. Evaluation of the extent to which this degradation occurred in tests on combined samples, however, became extremely difficult. For those tests in series C in which small deflections occurred, as well as in the single-acting tests of series B and D, it is likely that any degradation which occurred was slight. The severest degradation in series F occurred in double-acting tests on loosely compacted samples where the loading piston was operating at full stroke throughout the greater part of the test. Therefore, in those tests in series A and C in which large deflections occurred, it seems probable that fairly extensive base degradation was also present, although the subgrade soil in the pumped material would certainly have a cushioning effect in reducing abrasion. Such degradation of the base course would explain the consistently low values obtained for the Atterberg limits on the passing No. 200 fraction of the pumped material in these test series. The maximum values of degradation obtained in this test series are considered somewhat unrealistic, however, because the type of test was much too severe. They perhaps serve to indicate a safe upper limit for the degradation which could conceivably have occurred in any of the other tests.

Fortunately, the results of series F indicated that degradation of the base, if present, was about the same for open-graded bases as for dense-graded ones. The chief effect of such degradation, therefore, would be to increase the apparent differences between those samples which deflected a large amount and those which had small deflections at the end of the test period. Any difference in performance attributable to base course type should be but slightly affected.

CONCLUSIONS

For the laboratory tests described in this report, under the stated boundary and initial conditions, the following conclusions appear justified:

1. Although the effect of subgrade type was not pronounced, samples with Frederick subgrades were, for the same conditions of test, slightly superior to those with Crosby subgrades. After the full number of loads had been applied, the specimens with Crosby subgrades had generally deflected more, pumped more material to the surface of the base course, and moved more passing No. 200 material from the subgrade.

2. Samples with open-textured base courses deflected less under repeated loads than those with dense-textured bases, until the total deflections had increased to a point where structural failure of an overlying pavement could be postulated. Intermixing of the subgrade and granular material was most extensive with the open-graded bases, as shown by their greater passing No. 200 increase and by visual observation of the samples after testing. Specimens with the less permeable base, however, had more passing No. 200 material moved from the subgrade and more material pumped to the surface of the base course. If selection of base-course type is feasible in a given situation, it is recommended that one with an open-textured gradation be chosen.

3. Because the open gradation proved superior to the less permeable one despite the fact that the latter satisfied several accepted criteria for the design of filters (*4*) (*14*) (*25*) and the open one did not, it appears possible that these criteria are not fully adequate for the design of a filter to which repetitive loading is applied, when the filter is placed over a fine-grained subgrade. This is recognized in part by the current Corps of Engineers' filter requirements (*21*), which state that the D_{15} size of a filter placed over a subgrade which is plastic and contains no sand or silt partings need not be less than 1 mm.

4. Increasing the compaction of the subgrade in every case decreased the deflections, decreased the weight of material pumped, and the amount of passing No. 200 material moved from the subgrade. If this improvement can be shown to be permanent, a high degree of compaction of the subgrade should afford an inexpensive and generally applicable method of improving the performance

of rigid pavements placed on fine-grained subgrades.

5. For pumping to occur in these tests, it was found necessary that the water level to be raised at least to the bottom of the loading piston so as to form a closed system with the base course and subgrade. As applied to a pavement, this would suggest that removal of subgrade material by pumping can occur only at those periods when the water table is at or above the surface of the base course.

6. The magnitude of the applied pressure was found to have a major effect on the variables studied, with the larger pressure tending to produce greater deflections, more extensive intermixing, and an accelerated pumping of both subgrade and base course as compared with small pressure. It is indicated, therefore, that within the obvious economic limitations it should be beneficial to reduce the contact pressure between the pavement and the base course by increasing the thickness of the pavement slab.

7. Increasing the number of load applications increased the total deflection of the subgrade-base course combination for all samples tested.

8. Large deflections and a large applied pressure promoted degradation of the base course during the tests. The extensive degradation that apparently occurred for some of the samples tested, however, is not considered a likely occurrence beneath pavements in service.

REFERENCES

1. BARBER, E. S., AND SAWYER, C. C., "Highway Subdrainage." Proc. Highway Research Board, 31:663-646 (1952).
2. BELCHER, D. J., GREGG, L. E., AND WOODS, K. B., "The Formation, Distribution and Engineering Characteristics of Soils." Highway Research Bull. No. 10, Purdue Univ. (Jan. 1943).
3. BENNETT, C. A., AND FRANKLIN, N. L., "Statistical Analysis in Chemsity and the Chemical Industry," pp. 502-514. John Wiley & Sons, Inc., New York (1954).
4. BERTRAM, G. E., "An Experimental Investigation of Protective Filters." Soil Mechanics Series No. 7, Graduate School of Engineering, Harvard Univ. (Jan. 1940).
5. BUCHANAN, S. J., AND KHURI, F. I., "Elastic and Plastic Properties of Soils and Their Influence on the Continuous Support of Rigid Pavements." Research report prepared for Corps of Engineers, U. S. Army (June 1954).
6. D'APPOLONIA, ELIO, "Loose Sands — Their Compaction by Vibroflotation." Spec. Tech. Publ. No. 156, pp. 147-153. Amer. Soc. for Testing Materials (1953).
7. KARPOFF, K. P., "The Use of Laboratory Tests to Develop Design Criteria for Protective Filters." Paper presented at 58th Ann. Meeting, A.S.T.M., Atlantic City, N. J. (June 27, 1953).
8. KEENE, PHILIP, "Underdrain Practice of the Connecticut Highway Department." Proc. Highway Research Board, 24:377 (1944).
9. LAMBE, T. W., "Soil Testing for Engineers." John Wiley & Sons, Inc., New York (1951).
10. LANE, KENNETH S., "Providence Vibrated Density Test." Proc. Second Intern. Conf. on Soil Mechanics and Foundation Eng., 4:243-247 (1948).
11. LEONARDS, G. A., "Strength Characteristics of Compacted Clays." *Trans.* Amer. Soc. Civil Eng., 120: 1420 (1955).
12. SEED, H. B., CHAN, C. K., AND MONISMITH, C. L., "Effects of Repeated Loading on the Strength and Deformation of Compacted Clay." Proc. Highway Research Board, 34:541-558 (1955).
13. TATUM, C. W., "Report on Exploratory Tests with Repeated Loading Device." (Unpublished) Virginia Council of Highway Investigation and Research, Charlottesville, Va. (Mar. 1953).
14. TERZAGHI, KARL, AND PECK, RALPH B., "Soil Mechanics in Engineer-

ing Practice," p. 27. John Wiley & Sons, Inc., New York (1948).

15. VOGELGESANG, CARL E., "Effectiveness of Granular Bases for Preventing Pumping of Rigid-Type Pavements." Thesis, professional degree of Civil Engineer, Purdue Univ. (1951).
16. WOODS K. B., GREEN, F. H., AND SWEET, H. S., "Pavement Pumping Correlated with Traffic Loads." Proc. Highway Research Board, 27:209-231 (1947).
17. WOODS, K. B., AND SHELBURNE, T. E., "Pumping of Rigid Pavements in Indiana." Proc. Highway Research Board, 23:301-316 (1943).
18. — "Airfield Pavement Design, Flexible Pavements." Eng. Manual for Military Construction, Part XII, Chap. 2, Corps of Engineers, U. S. Army, Par. 3(b) Appendix (b) (July 1951).
19. — "Airfield Pavement Design, Frost Conditions," Eng. Manual for Military Construction, Part XII, Chap. 4, Corps of Engineers, U. S. Army (Oct. 1954).
20. — "Airfield Pavement Design, Rigid Pavements," Eng. Manual for Military Construction, Part XII, Chap. 3, Corps of Engineers, U. S. Army (Mar. 1954).
21. — "Drainage and Erosion Control — Subsurface Drainage Facilities For Airfields." Eng. Manual for Military Construction, Part XIII, Chap. 2, Corps of Engineers, U. S. Army (July 1946).
22. — "Final Report of Project Committee No. 1, Maintenance of Concrete Pavements as Related to the Pumping Action of Slabs." Proc. Highway Research Board, 28:284 (1948).
23. — "General Provisions and Criteria." Eng. Manual for Military Construction, Part XII, Chap. 1, Corps of Engineers, U. S. Army July, 1946).
24. — "Highway Materials, Part II, Tests." Spec. T99-49, Amer. Assn. of State Highway Officials, Washington, D. C. (1955).
25. — "Investigation of Filter Requirements for Underdrains." Tech. Memo. No. 183-1, U. S. Waterways Experiment Station, Vicksburg, Miss. (Nov. 1941).
26. — "Manual for Frost Condition Evaluation of Airfield Pavements in the Zone of Interior." (Draft), Corps of Engineers, U. S. Army, (July 1953).
27. — "Pavement, Flexible, Select-Material Base Course, Spec. CE 807.1" Corps of Engineers, U. S. Army (Mar. 1946, rev. 1952).
28. — "Rigid Pavement Pumping Experience Frost Investigations, 1953." Arctic Construction and Frost Effects Lab., New England Div., Corps of Engineers, U. S. Army (Apr. 1954).
29. — "Road Test One-MD." Spec. Report 4, Highway Research Board, Washington, D. C. (1952).
30. — "Standard Specifications for Road and Bridge Construction and Maintenance," p. 186. State Highway Commission of Indiana (1952).