direction. Finally the curb lines of the tertiary north-south street are extended through the intersection, again avoiding a duplication with previously formed areas, to produce the add length in a north-south direction. The sum of the diagonal through length, the east-west add length, and the north-south add length is the total length of pavement in the intersection.

Figure 17 illustrates the same intersection with different directional controls, east-west as primary, diagonal as secondary and north-south as tertiary. Other multiple intersections, with varying combinations of directional control, are shown in Figures 18, 19, 20, 21 and 22.

This discussion has been restricted to a description of the control procedures for individual intersections of various types. The application of these principles will solve the problem of lengths for any intersection, and will provide for positive length control in any desired direction without duplication when applied to all of the streets in a given area (Fig. 23).

DEPARTMENT OF DESIGN

C. N. Conner, *Chairman*

THE COOPERATIVE PROJECT ON STRUCTURAL DESIGN OF NONRIGID PAVEMENTS

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SYNOPSIS

This paper is a progress report of the Investigation of Nonrigid Pavement Design being undertaken as a cooperative project between the Highway Research Board, the Asphalt Institute and the Public Roads Administration. The investigation was planned and begun during the war period. Included is a statement of objectives, a discussion of the methods of approach, an account of the construction of the test pavement, and finally a discussion of test apparatus and testing techniques.

While some preliminary data of a highly significant character have already been secured, the present discussion is concerned primarily with a detailed description of the project. Considerable laboratory work is involved, but the main part of the investigation deals with the construction and testing, both under moving and plate load tests, of sections of pavement laid outdoors on natural subgrade soils.

Interest in the problems of structural design of the bituminous or nonrigid pavement grew enormously during the war period. To determine how thick such pavements should be to accommodate heavy airplanes, research work of a scope that would never have been considered feasible in peace time was undertaken. Most of the work was carried on under the supervision of engineers of the U. S. Army and Navy. In spite of the fact that much of the work had to be planned and executed in as short a period of time as possible, a great deal of useful and pertinent information was developed. It has served to bring about a much clearer perspective of the problem and has resulted in the development of several methods of thickness design that have considerable merit.

The scope of the cooperative investigation is sufficiently comprehensive to permit examination, study, and intercorrelation of all known theories and methods of design.

The principal objectives of the investigation include:

1. The development, by means of field bearing and moving wheel load tests on full-size pavement sections, of fundamental data on the load supporting value of nonrigid

pavement surfacings of various thicknesses in combination with various base course thicknesses and degrees of subgrade support.

2. The correlation of the field data with appropriate laboratory tests for the purpose of determining whether or not tests of the latter nature may subsequently be used by themselves as a basis for a sound method for the design of the thickness of the pavement.

3. The correlation of the field data with in-place determinations of the density, moisture content, California bearing ratio and North Dakota cone values of the base course and subgrade components.

Figure 1. Aerial View of Test Track

DESCRIPTION OF TEST PAVEMENT SECTIONS

The sections of test pavement were built out-of-doors with standard highway construction equipment. They are arranged in the form of an oval test track having parallel tangents 800 ft. in length connected at the ends with circular curves of 200-ft. radius. The test sections themselves are confined to the tangents of the track, the connecting curves serving to provide a means of travel for the vehicles that will be used to apply moving loads to a portion of the width of the pavement.

The site of the experiment is near Hybla Valley, Virginia, on a tract of Government-owned land adjacent to US Route 1 about 10 mi. south of Washington, D. C. An aerial photograph of the test area is shown in Figure 1. The exact location for the track was selected after making a very thorough soil survey of the entire tract. While this survey revealed the presence of a fairly uniform soil formation throughout the location selected, it was decided to take every reasonable precaution to insure having a homogeneous subgrade on which to lay the test pavement. This was accomplished by building embankments of a selected soil to a height of 5 ft. on the line of the tangents of the track. The equipment and methods used in the placement of the embankments will be described later in the paper. The soil was placed at

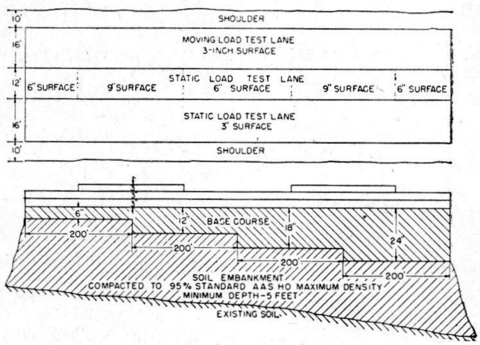

Figure 2. Plan and Profile Views of Oval Track Pavement

moisture contents within a selected range and was compacted to a specified density.

Plan and profile views of the completed test pavement on the north tangent are shown in Figure 2. It consists of four sections, each 200 ft. in length and 44 ft. in width. The thickness of the base course, as indicated, ranges from 6 to 24 in. The pavement, transversely, is divided into three lanes, the outer two being 16 ft. in width and the inner 12 ft. The thickness of the bituminous surface in the outer lanes is 3 in. and that of the inner lane varies from 6 to 9 in., half (100 ft.) of each section being 6 in. and half 9 in. Later in the report factual data will be presented relative to the design and composition of the base course and bituminous surface.

In connection with the investigation as a whole it was recognized that a considerable amount of exploratory work would have to be done in the development of test equipment and in the standardization of methods of load testing as well as of sampling and testing the different pavement components. This work necessitated the construction of a preliminary or auxiliary test pavement on which, to date, a great variety of work of an exploratory nature has been done.

Plan and profile views of the auxiliary pavement are shown in Figure 3. The total length of this pavement is 300 ft. It consists of three sections, the base and surface course thicknesses of which are indicated on the drawing.

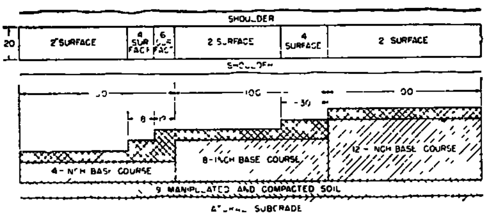

Figure 3. Plan and Profile Views of Auxiliary Pavement

CONSTRUCTION OF TEST PAVEMENTS

The auxiliary and oval test track pavements were built in an area containing soils of about the same physical characteristics. Table 1 indicates the typical physical characteristics of the natural earth subgrade used for the auxiliary test pavement and the selected earth borrow required for the construction of the 80C-ft. tangents of the oval test track.

Although the soils used for the subgrades of these test pavements were quite similar, the method of design and construction was different. The subgrade of the tangents of the oval test track (Fig. 2) was built as embankment, and the subgrade of the auxiliary test pavement (Fig. 3) was constructed as an all cut section in the undisturbed soil.

The embankments on the oval track are 5 ft. high and were built with selected earth borrow compacted in 4-in. layers to at least 95 percent of standard AASHO maximum density at moisture contents less than 2 percent above the optimum. The subgrade of the auxiliary test pavement consisted of the natural soil with the upper 9-in. layer of the subgrade manipulated and compacted to the same minimum compaction requirements specified for the embankments of the oval track. The field control of the subgrade compaction consisted of making moisture tests of soils before rolling and in-place density and moisture tests after compaction. Tests were made for each 400 cu yd of material compacted and whenever areas were found to have less than the required density they were reworked and recompacted until satisfactory in-place densities were obtained.

TABLE 1

TYPICAL PHYSICAL CHARACTERISTICS OF SUBGRADE SOIL FOR AUXILIARY TEST PAVEMENT AND OVAL TEST TRACK

Compaction Data

Standard AASHO		Army 4-in mold[a]		Army 6-in mold[b]	
Optimum moisture	Max. dry density	Optimum moisture	Max. dry density	Optimum moisture	Max. dry density
percent	*Lb per cu ft*	*percent*	*Lb per cu ft*	*percent*	*Lb per cu ft*
19.6	105.1	14.4	120.0	13.3	119.8

Bearing Test Data

Method	Bearing ratio after immersion[c]	Dry density	Mosture content[d]	Moisture content of top inch	Volume change after 96 hr
	percent	*Lb per cu ft*	*percent*	*percent*	*percent*
Army	2.0	106.3	21.8	30.0[e]	2.0
California	2.0	112.1	18.4	28.7[e]	13.5

Test Constants

Mech analysis: Pass No. 10	Pass No. 40	Pass No. 200	LL	PI	Shrinkage ratio	Shrinkage limit	CME	FME	Sp Gr
percent	*percent*	*percent*							
100	95	71	51	27	1.9	15	35	30	2 76

[a] Method described in U. S. Engr. Manual, Mar 1943—25 blows per layer

[b] 56 blows per layer.

[c] Bearing ratio at 0 1-in. penetration.

[d] Based on dry weight.

[e] 10-lb surcharge

In general, the moisture content of the natural soil was slightly above that required for satisfactory compaction. The excess soil moisture was removed during the manipulation operation before starting the compaction operations. The placement, manipulation, and compaction operations were arranged so that a 4-in. layer of soil could be placed over the entire length and width of the 800-ft tangent during each day of construction.

Several precautions were taken to avoid construction delays induced by adverse weather conditions. Before completing each day's work the surface of the embankment was shaped with motor patrol graders and rolled with a pneumatic tired roller to minimize any ponding of water on the embankment in the event of a rain. Likewise, the selected earth borrow area was graded and maintained free from surface irregularities to avoid ponding of water. The selected earth borrow was removed in shallow layers by pan scrapers along the line of the prevailing ground slopes and drainage ditches were maintained to insure adequate drainage of the borrow area.

TABLE 2
DESIGN CHARACTERISTICS OF STABILIZED AGGREGATE BASE COURSE

Sieve size	Specification limits[a]	Auxiliary pavement base course[b]	Oval test track base course[b]
In.	*Percent*	*Percent*	*Percent*
1½	100	100	100
1	100	99	95
¾	70–100	90	85
⅜	50– 80	67	67
No. 4	35– 85	56	55
No. 10	25– 50	47	46
No 40	15– 30	24	20
No. 200	5– 15	9 5	6
LL	25 max	17	17
PI	6 max	4	3
In-place density[c]	.	130	136
No tests averaged	...	13	70

[a] AASHO Stabilized Aggregate Base Course Specification B-1
[b] Average of all tests
[c] Dry density in lb per cu ft

After the subgrades for both test pavements were completed they were shaped and re-rolled to the alinement and cross-sections designated by the plans. During the course of the construction of these test pavements it was found necessary to finish the auxiliary test pavement prior to the completion of the oval test track. Certain experimental design data on pavement thickness, compaction of the stabilized aggregate base course, and probable performance of the bituminous wearing course under static loading were needed to plan the final design of the base and wearing courses for the 800-ft tangent of the oval test track. The auxiliary test pavement designed for this preliminary study was constructed with 4-, 8-, and 12-in. base courses with several thicknesses of bituminous wearing courses (Fig. 3).

The stabilized aggregate mixture used for the base course of the auxiliary test pavement was designed to conform with the AASHO B-1 grading specification for stabilized aggregates. However, in the case of the oval test track this specification was modified to permit the use of commercial coarse aggregate containing a slight amount of oversize material (passing 1½-in. sieve retained on the 1-in. sieve). Table 2 indicates the design characteristics of the stabilized aggregate base course mixtures for both test pavements.

TABLE 3
SPECIFICATION REQUIREMENTS FOR BITUMINOUS MIXTURES

The mineral aggregates (crushed limestone coarse aggregate and natural river sand fine aggregate) combinations were controlled by the following limitations:

Constituent	Passing sieve	Retained sieve	Auxiliary test pavement A-2[a]	Oval test track pavement: Binder A-2-a II[a]	Oval test track pavement: Surface A-2-a IV[a]
	In	*In.*	*Percent*	*Percent*	*Percent*
Coarse Aggregate	1½	1	0–5		
	1½	¾		14–48	
	1	½	15–25		
	¾	⅜		3–45	18–50
	¾	No. 4	20–35		
	⅜	No. 4			3–36
	No 4	No. 10	5–15	5–15	9–22
Subtotal.			60–70	55–75	50–65
Fine Aggregate	No 10	No. 40		3–21	5–22
	No 40	No. 80		6–25	9–27
	No. 80	No. 200		3–16	5–18
	No 10	No 200	25–35		
Mineral filler	No 200		4–6	4–6	5–8
Subtotal.			30–40	25–45	35–50
Total Mineral Matter			100	100	100
Percent of total mix	Mineral Aggregates		92–95	93–95	92–94
	Asphaltic Cement[b]		5–8	5–7	6–8
Total Mix—*percent*			100	100	100

[a] Asphalt Institute, Dense Graded Aggregate Specification, Hot Mix Type
[b] Asphaltic cement, 85 to 100 penetration, Specification Fed. SS-A-706-b.

These stabilized aggregate mixtures were prepared by blending commercial coarse and fine aggregates on a weight basis at the aggregate plant. After the preweighed batches of aggregates were hauled to the project site, pulverized binder soil was added to each batch from a proportioning bin and the materials were uniformly mixed in a concrete paving mixer. The necessary compaction moisture was added during the mixing operations.

The stabilized aggregate base courses were built using standard construction procedures. The material was spread in 3-in. layers and compacted by means of smooth face and pneumatic tire rollers until the required density was obtained.

The essential differences between the base courses of these test pavements were in the thickness and compaction requirements. The base course of the auxiliary test pavement was compacted to an in-place dry density of 130 lb per cu ft and was built with three thicknesses, 4, 8, and 12 in. The base course for the 800-ft tangent of the oval test track was compacted to an in-place dry density of 135 lb per cu ft and was constructed with four thicknesses, 6, 12, 18, and 24 in.

The asphaltic prime coat which was applied to the surface of the completed base course was the same for both test pavements. MC-1 was applied at a rate of 0.25 gal per sq yd. The bituminous concrete pavement was placed after the prime had been thoroughly cured.

The bituminous concrete paving mixture was of the hot plant-mixed type conforming to the design requirements usually specified for highway construction. Table 3 gives the specification requirements of the two paving mixtures. The placement and compaction operations were similar to those recommended for highway construction of this pavement type. Typical views of the construction of the auxiliary and oval track pavements are shown in Figures 4 and 5 respectively.

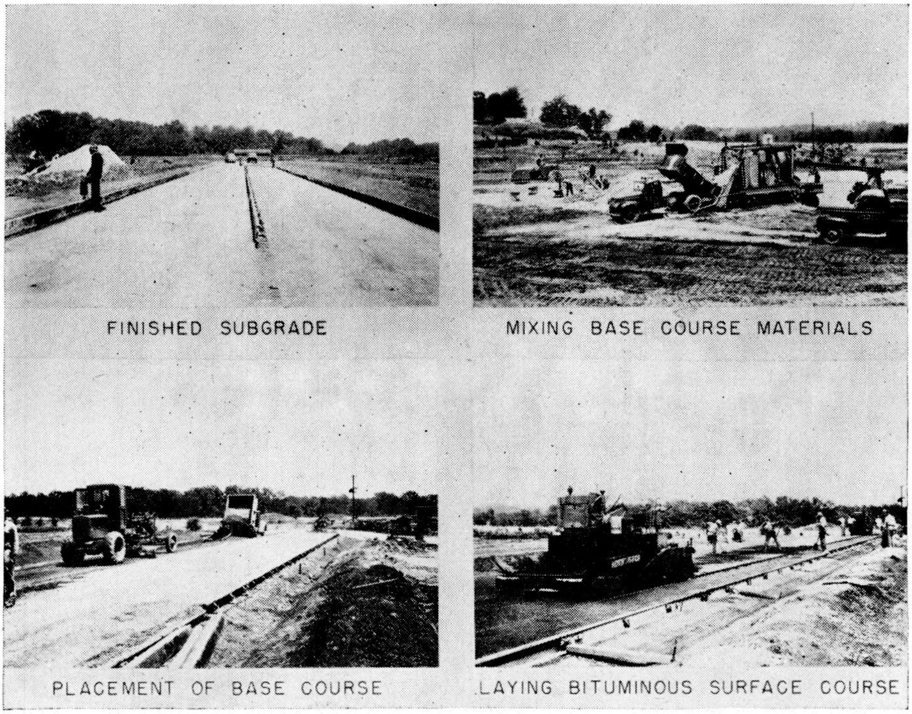

Figure 4. Typical Construction Views of Auxiliary Test Pavement

SUBGRADE STUDIES OF AUXILIARY TEST PAVEMENT

A limited study of the behavior of the subgrade beneath the base course of the auxiliary test pavement was made to investigate the effect of the climatic factors, rainfall and temperature, upon subgrade strength

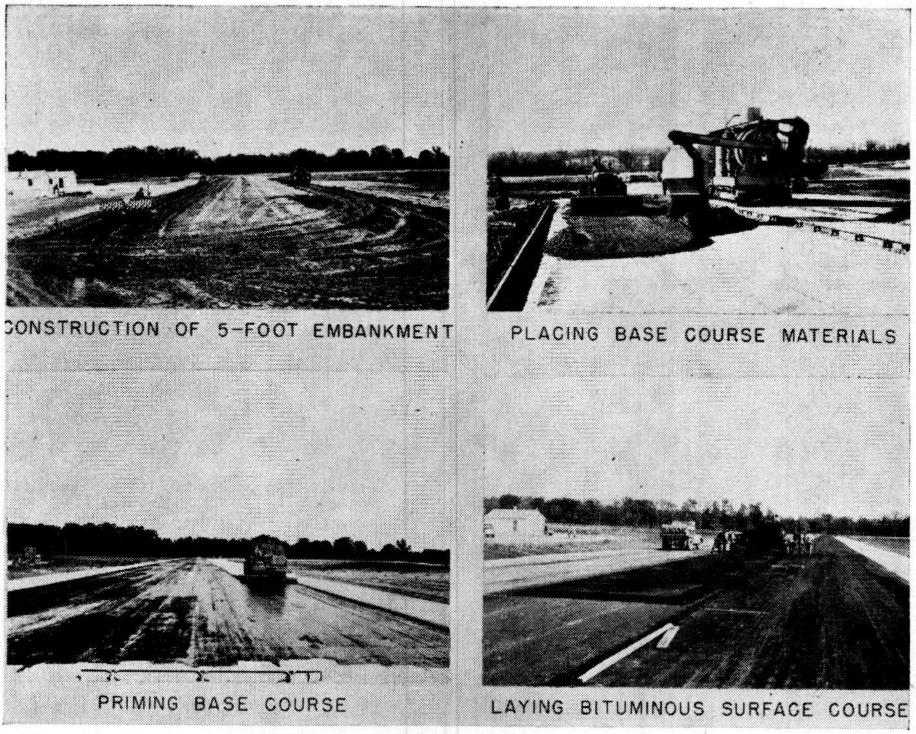

Figure 5. Typical Construction Views of Oval Test Track Pavement

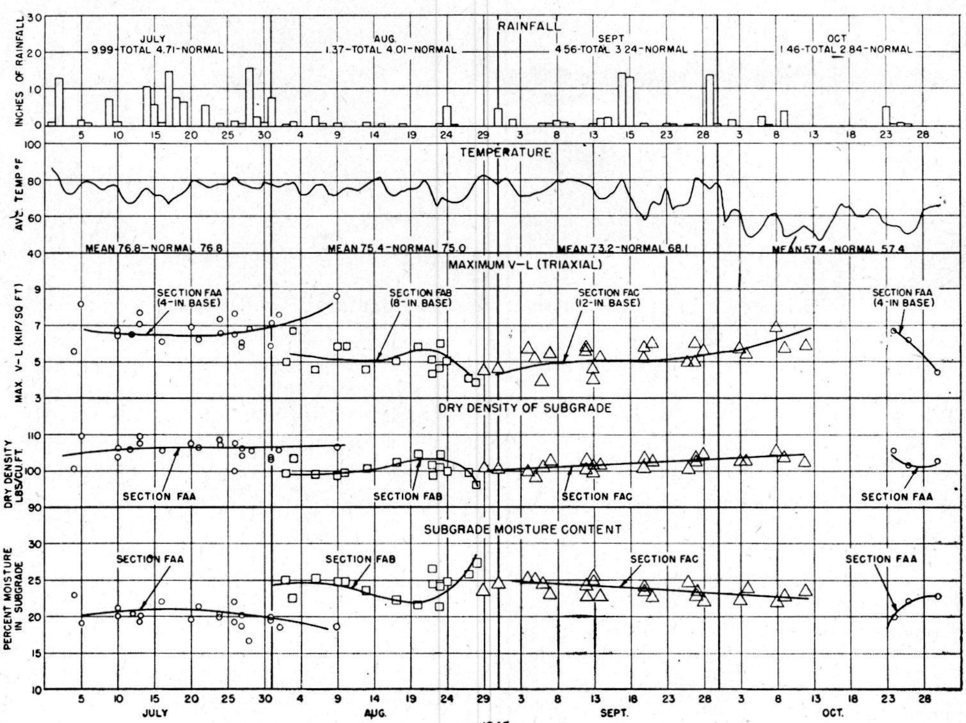

Figure 6. Relation Between Weather Conditions, Moisture Content, Density, and Max V-L for Subgrade Soil Samples Taken Under the Base Course

(Max V-L)[1], density, and moisture content. The initial work was confined for the most part to the study of the behavior of the 9-in. compacted layer of soil directly beneath the base course. However, at periodic intervals the moisture gradient was determined for the natural subgrade to a depth of approximately 36 in. to obtain relative data for comparison of moisture movements at various elevations within the zone that might be influenced by the proposed plate loading of the test pavement.

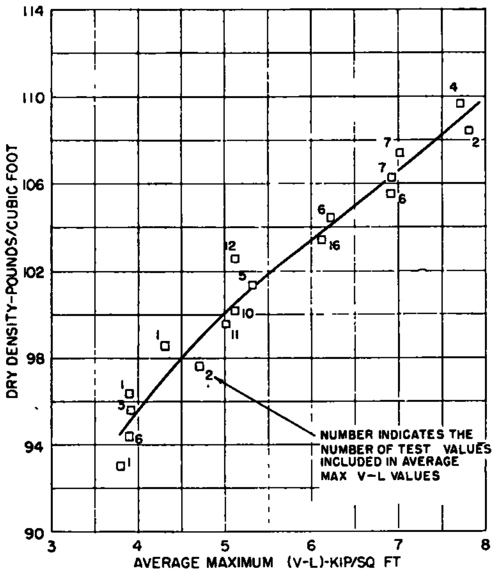

Figure 7. Relation of Max V-L (Triaxial Shear) with Density

The variations of subgrade strength, subgrade density, and moisture content of the 9-in. compacted subgrade layer are shown in Figure 6. A comparison of these data show the following trends:

1. The subgrade strength (Max V-L) varies directly as the density and inversely as the moisture content of the subgrade soil.
2. The moisture content gradually increases with time and with the seasonal drop in average daily temperature.
3. Minor variations in strength, density, and moisture content appear to be related to the monthly fluctuations in the climatic factors, namely, temperature and rainfall.

The general relations between these variables were obtained from the averaging of a number of individual test results. Figures 7 and 8 indicate the relations between the average strength (Max V-L) with the dry density and the moisture content of the compacted 9-in. subgrade layer.

The relation of average modulus of elasticity of the subgrade soil, calculated from the triaxial compression test data, with moisture

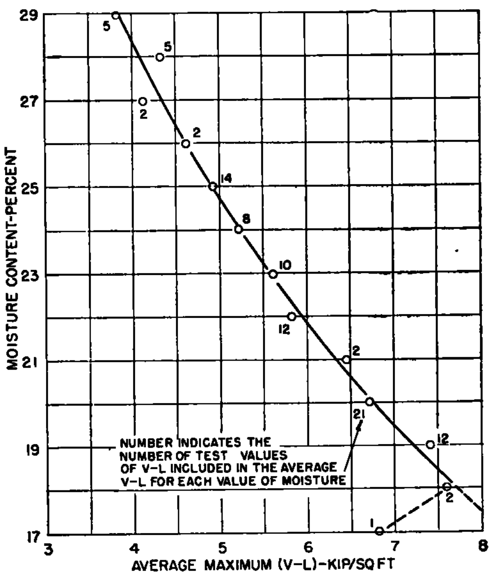

Figure 8. Relation of Max V-L with Moisture

content and density of the subgrade is shown in Figure 9. The modulus varies directly as the density and inversely as the moisture content of the subgrade.

The average seasonal subgrade strength (Max V-L), density, and moisture content of the soils in the 9-in. compacted layer for several seasons of the year are tabulated in Table 4. A study of these data show that the strength of the soil in the subgrade varies with the seasons; being lowest during the spring and fall and highest in the summer. The strength varies inversely with the moisture content and directly as the density of the subgrade soil. These seasonal variations emphasize the need of planning comparative pavement evaluation tests so that they can

[1] The subgrade strength (Max. V–L) as used in this study refers to the maximum difference between the vertical and lateral pressures measured by the triaxial compression test.

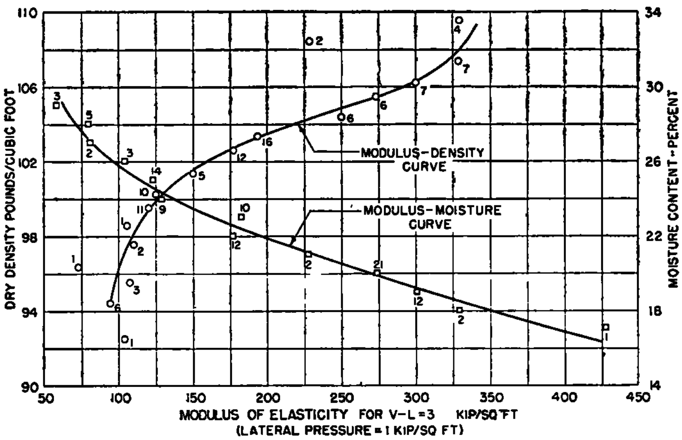

Figure 9. Relation of Modulus of Elasticity with Moisture and Density for Subgrade of Auxiliary Test Tangent

be made during periods when the climatic factors are uniform. Adverse changes in climate affect both the strength of the subgrade and pavement. Both of these strength values must be considered in the evaluation of pavement test data.

TABLE 4

SEASONAL VARIATIONS IN SUBGRADE MOISTURE-DENSITY-STRENGTH DATA UNDER THE 4-IN. BASE[a]

Type of test	Jul 10 to 15	Oct 24 to 25	Nov 23 to 27	Jan 10 to 11	Mar 4
No. of tests averaged	5	3	2	2	4
Ave. moisture—*percent*	20.0	21.7	28.3	29.0	28.5
Ave. dry density—*lb per cu ft*	105.6	103.3	95.0	93.5	95.5
Ave. Max (V-L)—*kip per sq ft*	7 0	5.8	3.5	3.4	4 7
Ave. saturation—*percent*	89	91	98	96	98

[a] All tests were sampled from area approximately 55 ft in length during 1945 and 1946.

The periodic variations in subgrade moisture content at several elevations below the three thicknesses of base course of the auxiliary test pavement are shown in Table 5. A study of these data shows that there appear to be both horizontal and vertical fluctuations in the subgrade moisture found beneath the base course. Reversals in the subgrade moisture contents at various elevations seem to occur for no apparent reason. Perhaps minor variations in texture or structure of the undisturbed subgrade soil in the form of thin lenses of silt and fine sand or seepage planes may be one of the causes for the erratic fluctuations in the subgrade moisture beneath the test sections.

It was noticed during field examinations of the general area that in some instances during

TABLE 5

VARIATIONS IN SUBGRADE SOIL MOISTURE AT SEVERAL ELEVATIONS BELOW THE SURFACE OF THE SUBGRADE AT VARIOUS TIMES OF THE YEAR (1945–1946)

Location of Sampling Area	Depth Below Bottom of Base Course	Moisture Content for Date Sampled—*Percent*										Moisture Range			Average Moisture Content
		Aug 30	Sept 27	Oct 16	Oct 31	Jan 11	Feb 20	Mar 5	Mar 20	Apr 2	Apr 16	Min	Max	Difference	
	in.											%	%	%	%
Natural subgrade[a]	3	17.7	17.7	17.7	18.0	22.5	20.5	26.9	22.0	22.2	20.7	17.7	26.9	9.2	20.6
4-in. base section	1	20.9	19.7	20.6	21.3		22.5		22.3	21.7	23.0	19.7	23.0	3.3	21.5
8-in. base section	1	27.1	26.6	27.8	26.8		26.6		28.8	27.0	24.8	24.8	28.8	4.0	26.9
12-in base section	1	23.2	24.2	24.5	22.7		24.6		24.3	24.7	20.1	20.1	24.7	4.6	23.5
Natural subgrade[a]	14	25 8	35.1	35.3	38.5	35.3		22.1	21.9	24.3	24.8	21.9	38.5	16.6	30.4
4-in. base section	10	23.1	23.5	25.0	22.9		23.3	28.2	29.2	24 3		22.9	29.2	6.3	24.9
8-in. base section	10	19.4	25.0	22.6	21.7		25.6	25.2	24.6	25.9	22.7	19.4	25.9	6.5	23.6
12-in. base section	10	23.9	24.4	24.7	25.9		22.9	20.6	26.3	28.5	18 2	18.2	26.3	8.1	23.9
Natural subgrade[a]	26	31.9	31.7	30.1	31.0	35.7	36.6	33.5	36.0	30.7	32.3	30.1	35.7	5.6	33.0
4-in. base section	22	26.8	26.3	25.0	24.7	25.6	24.0	22.2	27.3		26.4	22.2	27 3	5.1	25.4
8-in. base section	22	22.8	24.0	24.4	21.8	25.6	25.4	23.8	23.9	27.2	24.1	21.8	27.2	5.4	24.4
12-in. base section	22	23 5	26.2	24.6	24.5		29.2	25.7	27 0	25.0	23.8	23.5	29.2	5.7	26.6

[a] Natural subgrade refers to an undisturbed subgrade location adjacent to the auxiliary test pavement.

the spring season, auger holes gradually filled with free water even though no rain fell during the period between making the auger holes and the observation of the free water. In the area in which the auxiliary pavement was constructed, there was a definite relation between periods of heavy rainfall and the elevation of free water in the test pits dug in the construction area.

Such a condition may be present in the area under the auxiliary test pavement since the natural soil structure below the 9-in. compacted layer was not disturbed by construction operations. This condition should not be found beneath the 800-ft. test pavement because the subgrade is on a fill section composed of soils that were uniformly mixed and compacted to a depth of 5 ft. to minimize moisture variations resulting from the change in texture or structure.

A 16-point automatic temperature recorder will be installed in the subgrade, base course, and bituminous pavement of the oval test track to measure the variations in temperature at various elevations below the surface of the pavement. These continuous records of temperature will be used to study the insulation effect of the various thicknesses of pavement as well as furnish temperature data for assisting in the correlation of the pavement evaluation work.

LOAD BEARING SURFACES

In connection with the load testing of nonrigid pavements it was recognized that the use of rigid plates would cause stresses in the structure radically different in character from those produced by pneumatic tires. The reason for this is that the material beneath a rigid plate must displace equally at all points even though the resistance offered to displacement is not uniform. In a cohesive material such as a bituminous pavement the resistance to displacement will be greater at the boundaries of the load bearing surfaces and less in the central portion. Consequently the contact pressure which will develop beneath the peripheral area of a rigid plate as it is forced into a bituminous pavement may exceed greatly that beneath the interior of the plate. Under a pneumatic tire the situation is quite different. Here, because the tire can undergo a change in shape without a significant change in its pressure distribution pattern, the material being loaded will tend to deform in a natural manner.

The use of tires themselves as static load bearing surfaces was not considered feasible: (1) because the contact area does not remain constant but increases with load; (2) because of the physical difficulty of measuring the deflection of the material being tested; and (3) because tests are to be made on the base course and subgrade components of the pavement and the opening to accommodate the tire would have to be larger and of a more irregular shape than desired.

Thus, one of the important instrumental problems was the development of a type of load bearing surface that would simulate the action of a tire and yet have none of its undesirable physical characteristics.

In the development work on this problem it was necessary to study the pressure distribution characteristics of a variety of materials. A special pressure indicating apparatus was constructed with which the contact pressure at any point beneath a particular loaded material could be determined.

The fact that sponge rubber mats had been used to reduce high peripheral pressures beneath rigid plates in concrete pavement loading tests prompted a series of initial studies with this material. The effect of the type and thickness of the rubber cushion both when confined and nonconfined laterally was studied. It was found that in either case the pattern of pressure distribution was extremely irregular. When unconfined they displaced laterally under load, thus reducing the normal intensity of the pressure beneath the peripheral area and increasing the pressure beneath the central area of contact. When confined, an edge or perimeter effect was created resulting in a high concentration of pressure at the outer limits of the area of contact.

Considerable time was spent in a study of the pressure distribution characteristics of a specially built rubber bag. This was composed of gum rubber, molded in a cylindrical shape, containing a vertical hole through its center which was to be used for deflection measurements of the material under test. It was tested in a number of ways with and without lateral confinement both when inflated with air and when filled with water. The distribution of pressure beneath the bag was erratic. When confined laterally and overinflated with either air or water, the pressure was concentrated largely over an annular section between its perimeter and center opening. When confined laterally and underinflated a high concentration of pressure developed beneath the side wall and around the center opening. When unconfined, the bag compressed vertically under load to the extent of creating abnormal pressure beneath the side walls and around the center opening. There appeared to be no way in which the bag could be used so that the carcass or vertical walls of the unit did not adversely influence the pattern of pressure distribution.

Many other types of material were studied from the standpoint of their potential ability to transmit load and give the desired pattern of pressure distribution. Among other things the pressure transmitting characteristics of thin rubber membranes were investigated in considerable detail. The fact that the pressure transmitted by such a material was invariably found to be equal to the pressure imposed upon it led to the decision that the ultimate design of the bearing surface should embody the use of such an elastic membrane as the primary pressure transmitting medium. The problem resolved itself into one of determining how to attach the membrane to a chamber that could be inflated with air so that: (1) the membrane would not blow out; (2) the contact area would not vary to any appreciable extent with load; and (3) the intensity of the transmitted pressure over the entire facial area of the bearing surface would be reasonably uniform.

Three types of bearing cells were developed employing an elastic membrane as described above. They are shown schematically in Figure 10. The cell on the left consists simply of an air chamber with intact side walls. The cell in the center consists of two cylindrical sections, the lower one of which telescopes into the upper. The cell on the right is similar to that on the left except that a section of flexible metal bellows is installed in the cylindrical section. The performance characteristics of all three cells were studied both with the elastic diaphragm attached to the inside and to the outside of their respective base sections.

From a standpoint of the forces of action and reaction all three cells are basically the same when the diaphragm is on the inside. A given internal air pressure will produce an upward reaction R equal to the area of the diaphragm times the prevailing pressure ($R = AP$). To develop the same unit intensity of pressure beneath the rim or end projection of the cylinder as that acting through the diaphragm, a supplemental load L of a magnitude such that L = rim area times inflation pressure, can be applied by external means to the top of the cell.

Thus it appears that any one of the three cells could be used in such a way that the contact pressure would be uniform over its entire facial area, that is, beneath both the diaphragm and end projection of the rim section. In this case the rim section would be a part of and constitute the peripheral area of the bearing surface. However, in tests with the cell having intact side walls, extreme difficulty was encountered in manually controlling its operation so that load L at all times was in balance with load R. There appeared to be no way of mechanically or automatically maintaining the desired balance between the two components of the load as the internal air pressure is increased or decreased during the progress of a test.

The telescopic cell was developed in an attempt to overcome the operational difficulties of the cell described above. It was reasoned that in a cell of this design the internal air pressure would bear against the upper projection of the lower section and that this pressure, less the effects of friction which may be present or may develop as the sections move with respect to one another, would be transmitted downward to the material under test. In other words, the pressure transmitted automatically by the end projection of the rim section would be approximately equal to that of the internally existing air pressure. In order, however, to prevent undue leakage of air from the space between the sections it was necessary to use a leather gasket seal that had a relatively high coefficient of friction. This seal served to reduce the pressure transmitted by the rim about 30 percent when the sections were in the process of opening and to increase this pressure about the same amount when the sections were closing.

It is possible that a bearing surface of the telescopic type, having the diaphragm attached to the inside of the base section, could be used in a manner that would tend to promote continuous and progressive opening of the movable sections during the course of a test. This would result in a reasonably constant deficiency of pressure beneath the rim section, a situation which, if the ratio of the rim to the diaphragm area is low, might not be considered objectionable. However, if it is considered essential to have the same intensity of pressure transmitted through the rim section as that acting through the diaphragm, the total reaction load must be controlled or made to equal the total facial area of the cell times While the bellows section, designed to withstand an internal pressure of 100 lb per sq in., exhibited a higher spring rate than desired it did serve to impart a much greater degree of vertical flexibility to the cell than when the side walls were intact. Because of this vertical flexibility the load may be applied and released more uniformly and with less likeli-

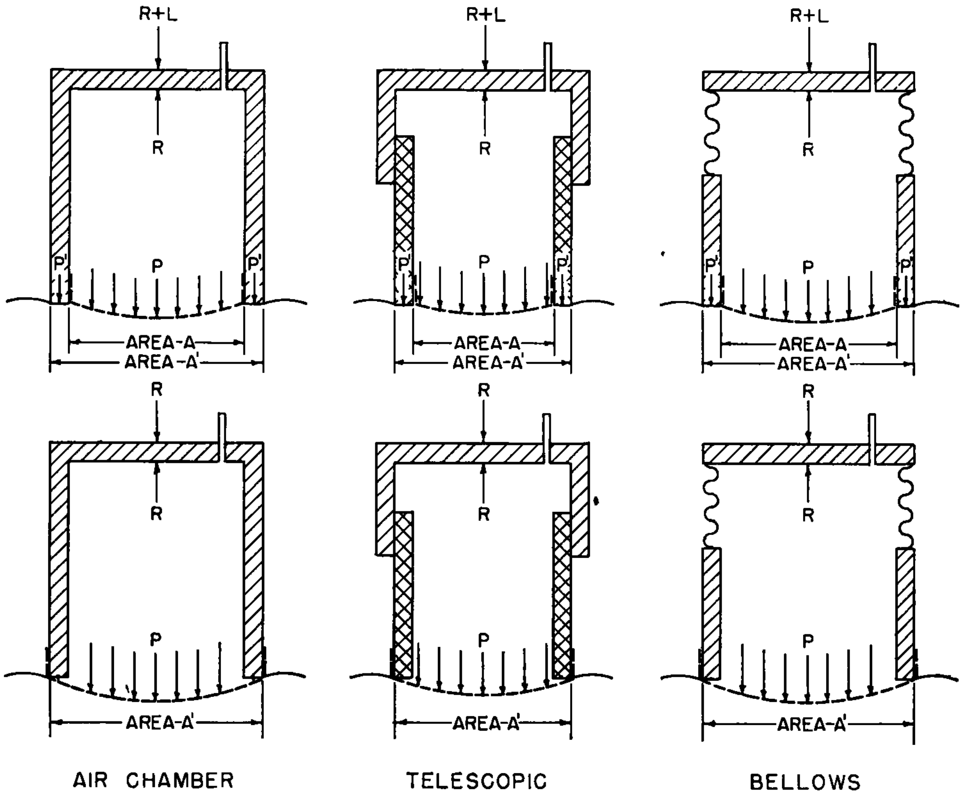

Figure 10. Schematic Views of Flexible Load Bearing Surfaces

the internally existing air pressure. In contrast to a cell having intact side walls, this can be accomplished without serious danger of overloading or underloading the rim section.

The bearing cell shown on the right of Figure 10 was conceived in an effort to overcome the undesirable features of those described above. It was reasoned that the bellows convolutions installed in the cylindrical section would allow a certain amount of vertical movement without altering the distribution of pressure over its contact face. A considerable amount of work has been done with a cell of this type.

hood of rupturing the membrane than was experienced with the rigid walled cell.

The foregoing discussion has concerned the three flexible bearing surfaces with the diaphragm attached to the inside of the lower cylindrical section. In some of the preliminary tests with these surfaces it was found that the peripheral rim section left what appeared to be an abnormal cut or sharp impression in the material tested. This was in marked contrast to the impression left by a loaded tire on the same material. Here the impression around the edge of the imprint area was relatively smooth.

As a result of these observations the possibility of attaching the diaphragm to the outside rather than to the inside of the unit was considered. It was realized that in this event the contact face of the unit would vary depending upon the magnitude of the applied load, the carcass stiffness of the diaphragm, and the amount of clearance between the end projection of the rim and the diaphragm or material on which it rests. As a result it is not possible to formulate the forces of action and reaction to the same degree of accuracy as when the diaphragm is attached to the inside. It has been found, however, that by controlling the amount of clearance between the rim and diaphragm the variations in size of contact area are of negligible proportions. In tests with this type of diaphragm attachment the tendency toward the development of a shearing or cutting action at the perimeter of the contact area is greatly reduced.

LOAD TESTING PROCEDURES

One of the purposes of the auxiliary test pavement was to develop a procedure for conducting the load bearing tests on the oval track pavement, a procedure which could be relied upon to give the best possible results. Methods for making such tests have never been standardized, particularly those having to do with the load supporting capacity of pavements.

Three procedures of load testing using rigid plates were studied. The first involved the application of five or more load increments, each increment being applied and released five times. Each increment produced a net deflection of the medium under test of 0.1 in., thus five increments produced a gross deflection of 0.5 in. In tests using this procedure the applied load was not released nor was the load reapplied until the rate of vertical movement had slowed down to 0.002 in. per min. Tests were made according to this procedure on the pavement surface, base course, and subgrade of the three sections of the auxiliary pavement (see Fig. 3) using plates 9 and 18 in. in diameter. Duplicate tests were made in all cases and where the results of the two tests were not in reasonably good agreement a third test was run.

The second procedure differed from the first in that the load was applied rapidly and without interruption until visible rupture of the

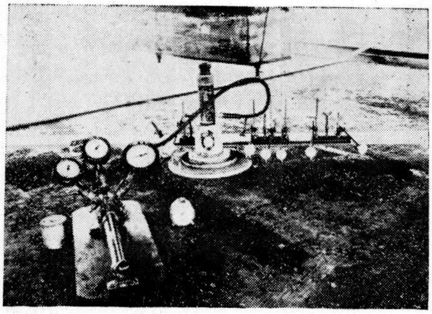

Figure 11. Load Test Assembly—Rigid Plates

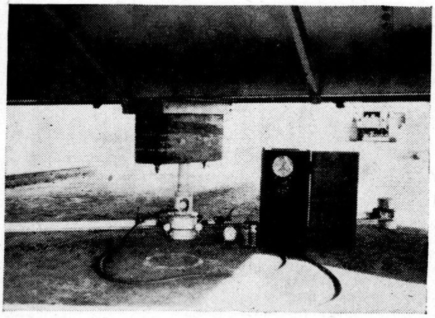

Figure 12. Load Test Assembly—Telescopic Cell

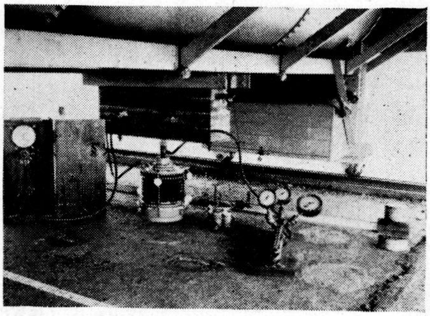

Figure 13. Load Test Assembly—Bellows Cell

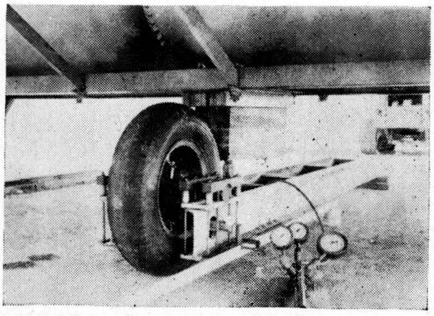

Figure 14. Load Test Assembly—Pneumatic Tire

material occurred or until its resistance was overcome. The application of the load was such as to produce a reasonably constant rate of deflection of 1.2 in. per min. Tests were conducted according to this procedure on the pavement surface, base course, and subgrade of the auxiliary pavement sections with four rigid plates, 6, 9, 12, and 18 in. in diameter. In addition a special series of tests was made, using this procedure, in an effort to develop some preliminary information relative to the effect of the temperature of the bituminous surface upon the load supporting capacity of the pavement structure. Tests were run with the same group of rigid plates upon the 2-, 4-, and 6-in. thicknesses of bituminous surface over the 4-in. base section of pavement when the temperature of the surface was about 68, 85, and 105 F.

The third procedure was that of repetitional loading in which from 15 to 100 load applications were applied and released. Tests were made on the top of the base of all three auxiliary pavement sections with the 9- and 18-in. diameter plates. The series of tests was planned specifically for the purpose of studying the elastic action of the base course-subgrade component of the pavement.

In addition to the various tests described above a great number of tests was conducted upon the sections of the auxiliary pavement in connection with the problem of the development of a flexible type of bearing surface. Photographs of the several load test assemblies are shown in Figures 11, 12, 13, and 14. That in Figure 11 is a view of a rigid plate assembly. The plates are arranged in typical pyramid fashion to insure rigidity. Vertical movement readings are made with dial gages bearing against the center and edges of the base plate and against the surface of the pavement at distances of 3, 6, 12, and 24 in. from the plate. Load is applied by means of a retractable hydraulic jack. In this as well as in all the other load assemblies used, an electric buzzer is clamped to the dial supporting beam for the purpose of freeing the dial stems when readings are made. It has been found that the use of such a buzzer not only serves to facilitate reading the gages but tends to give more accurate results.

Figure 12 shows a load assembly employing one of the telescopic types of bearing surfaces described previously. The deflection of the pavement surface in this case is measured at the center of the unit on the top of a rod extending downward through the cell to the diaphragm. The deflection of the rim of the cell or the material beneath the end projection of the rim is measured by means of three dial gages operating against brackets attached to the rim. The air pressure in the cell is controlled by means of the pressure regulating valve assembly shown. The hydraulic jack superimposed on the cell is used to determine or control the reaction load. In Figure 13 a view of another load test assembly is shown employing one of the bellows type of bearing surface. This cell is operated and the deflections measured in much the same manner as described for the telescopic cell.

In Figure 14 a view of still another load assembly is shown that utilizes a pneumatic tire as the load bearing surface. Here the vertical movement of the pavement surface beneath the center of the tire contact area is measured by means of a specially designed deflection rod unit that is installed in the tire. Lack of clearance beneath the water tank that was being used to provide the necessary load reactions made it necessary to mount the tire on the end of the beam assembly shown and apply the load in the manner indicated.

SUMMARY

A great deal of pertinent and useful information has been obtained from the tests made to date on the sections of the auxiliary pavement. This information has been particularly helpful in the formulation of the testing program for the sections of pavement on the oval test track.

As mentioned before, the investigation has been planned in a way such that it should be possible to compare and correlate all existing proposed methods of thickness design. This means that in the course of the investigation such tests as the North Dakota cone, the California bearing ratio, and triaxial shear will be made on the component materials of the pavement at the majority of the locations where the bearing tests are made. In addition, samples of these components will be obtained for moisture content and density determinations.

The completion of the planned program of tests should throw considerably additional light on many questions as yet, to a great extent, unanswered. One important question, on which comprehensive information will be obtained, is that of the relative effect of transient versus statically applied loads.