STUDIES OF SUBGRADE PRESSURES UNDER FLEXIBLE ROAD SURFACES

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SYNOPSIS

This paper shows the results of pressure measurements taken under 4 in., 6 in. and 8 in. of stone screenings placed on a subgrade and subjected to 4,000, 8,000 and 12,000-lb. wheel loads, in the laboratory of the National Crushed Stone Association.

Load-indentation tests were also made on the subgrade in place as well as on the surfacing material, in an effort to tie in the present tests with subsequent investigations. This report is merely one of progress, but it is felt that the results may be useful in the later formulation of a theory for flexible road design.

It is the purpose of this paper to present the results of some preliminary tests made to determine the subgrade pressures under flexible road surfaces of different thicknesses. The results have not reached the stage which will permit of generalizing them into a theory for flexible road design, but, none the less, light is thrown on distribution of pressure to the subgrade and on the effect of differences in thickness and rigidity of the flexible surface on subgrade pressure distribution.

METHOD FOR MEASURING PRESSURES

The tests were conducted in the laboratory making use of a bin constructed of heavy timber backed with I-beam supports. The base of the bin was designed for rigidity. The soil pressure measurements were made by the use of a soil pressure cell such as described by the author before the last annual meeting of the Highway Research Board.[1]

In the bin was first placed a sand-clay mixture which had previously been mixed with the desired amount of water to give it the necessary degree of stability. If a soft subgrade was desired, additional water was used in the mix. The subgrade was rolled in 3-in. layers by the use of a sheep's foot roller made with concrete disks alternating with disks having a toothed circumference. This roller was followed by a heavy hand concrete roller of cylindrical form. The characteristics of the subgrade materials used in these tests are shown in Table 1 by a series of laboratory tests made through the courtesy of the American Bitumuls Company.

It was decided that the most convenient surfacing material to use in these preliminary tests would be stone screenings, for they could be very readily mixed with water and laid in a homogeneous layer and could be well compacted in the laboratory bin with the method just described. The present tests were all made with stone screenings as the surfacing layer, laid to different thicknesses and allowed to dry to different amounts depending upon the rigidity desired. When first laid and rolled, the wet screenings did not have a great deal of stability, but, as they dried they attained high stability and apparently even had bending resistance until cracks were formed under the test load.

The method of installing the soil pressure cell and its location were subject to change as experience was obtained during the progress of the tests. It is recognized that the soil pressure cell, having a thickness of about $1\frac{1}{2}$ in. and having rigidity, theoretically is not an ideal device for this particular kind of pressure measure-

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[1] *Proceedings*, Highway Research Board, Vol. 18, Part II, p. 66 (1938).

ment, because it introduces a rigid element into the subgrade structure which has possibilities of producing error. These possibilities were fully recognized before the tests were begun but it is believed that with the methods used, an accuracy has been attained which is in keeping with the kind of measurements taken and the use for which they are intended.

The soil pressure cell was installed in the center of the bin, in all cases with the weighing face down in contact with the subgrade. In some cases the cell was first laid on the subgrade before applying the screenings and rolling them. In other cases, especially where unstable screenings were used in the test, the cell was placed with its weighing face $1\frac{1}{2}$ in. below the surface of the subgrade. In this type of installation, however, the cell was surrounded with a brass collar loosely filled with a graphited gland packing so as to eliminate friction between the sides of the cell and the surrounding collar. See Figure 2. In theory the unit pressure on the weighing face of the cell would be the unit pressure at the base of the cell which was set level with the surface of the subgrade.

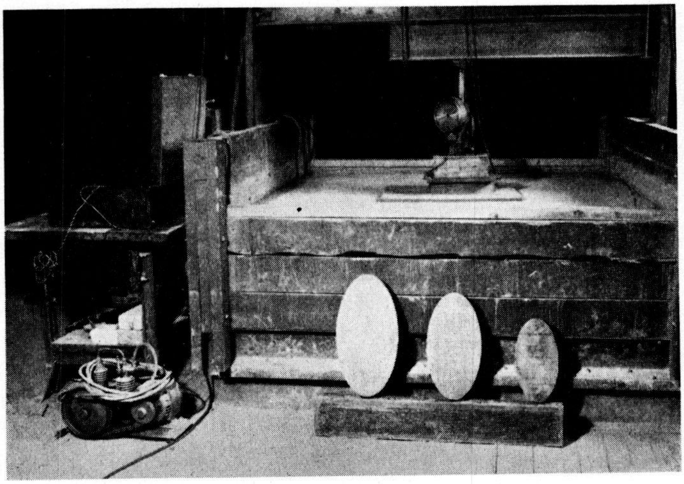


Figure 1. Apparatus for Measuring Subgrade Pressure

Here is shown the 6 ft. square by 3 ft. high bin with the hydraulic jack mounted for applying load. The different size elliptical bearing blocks correspond with the contact areas produced by 4,000, 8,000 and 12,000 lb. wheel loads. On the left is the pressure gauge box to which is connected a soil pressure cell mounted on the subgrade under the stable surfacing material.

METHOD OF LOAD-APPLICATION AND LOAD MEASUREMENT

Loads were applied through elliptical bearing blocks designed to have an area equal to the area of contact of tires suitable for 4,000, 8,000 and 12,000 lb. loads respectively. The dimensions of these blocks and of the unit pressures equal to the appropriate tire pressures and the areas of contact are given in Table 2.

In all cases the bearing block was first set on a $\frac{1}{2}$-in. rubber pad placed on the wearing surface. A hydraulic jack was used for applying the load. This jack was calibrated frequently to insure continued accuracy.

The procedure in taking measurements

TABLE 1

Characteristics of Screenings Surface

MATERIAL

Limestone screenings

GRADATION

Sieve	Percentage passing
¼-in.	100
No. 10	82.4
No. 200	23.9

STABILITY (PUNCHING SHEAR TESTS)

Moisture, %	1.9	3.4	6.5	9.68
Punching shear	5300	4500	2700	3400

Screenings were compressed at moisture content of 6.5 per cent, then air dried to respective moisture contents.

Characteristics of Subgrade

MATERIAL

Sand-clay mixture

GRADATION

Sieve	Percentage passing
¼-in.	100
No. 10	99
No. 200	36.2

STABILITY TEST

Moisture, %	3	5	6	7	9	10	12
Stability (½-in. bottom layer)	40,000+	40,000+	29,000−	15,500	7500	2900	0

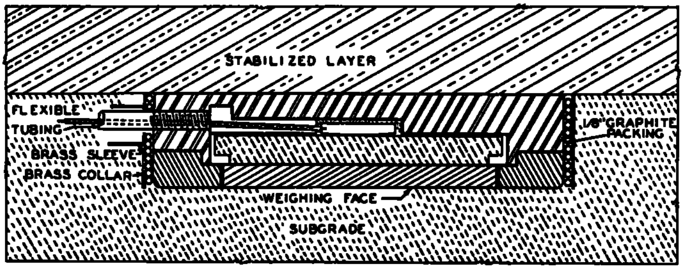


Figure 2. Soil Pressure Cell

was to place the bearing block at the side of the bin and pointing toward the cell; load was applied and pressure readings taken on the cell. Zero load subgrade pressure readings were made before and after each load application. The block was then advanced a short distance and was again loaded and the pressure readings taken. This procedure of loading and advancing the block was repeated until the block was centered over the cell. In this manner an influence line for subgrade pressure was obtained and the pressures would thus represent the increase in pressure at any given spot on the subgrade as the load was advancing toward that spot. This is the condition of loading which actually exists as a truck wheel operates on a road surface. It would seem reasonable to believe that this influence line for pressure likewise very closely represents the actual distribution of longitudinal pressure. It is believed that substantially the same results are obtained by this method of loading by the use of a single cell as would be obtained were a number of cells installed to determine the pressure distribution.

TABLE 2

Data on Bearing Blocks

Long diameter, 2 A (in.)	Short diameter, 2 B (in.)	Area, sq. in.	Total load, lb.	Unit load, lb. per sq. in.
12-1/8	6-1/16	58	4,000	69.0
15-3/4	7-7/8	97	8,000	82.5
18-1/8	9-1/16	130	12,000	92.3

The method used has the advantage of subjecting the subgrade to advancing pressures such as would obtain under actual loading conditions. From our tests we know that the mere fact of having loaded the surface in a given zone, results in the compaction of the subgrade in that zone. This compaction increases the subgrade resistance in the zone which has been loaded as compared with the unloaded zone.

In a manner similar to that just described, lateral distribution of pressure was obtained, the bearing block in this case being advanced laterally, rather than longitudinally.

LOAD INDENTATION CHARACTERISTICS OF SUBGRADE AND OF SURFACING MATERIAL

A series of subgrade pressure-distribution tests would not be complete unless they were supplemented by tests to determine the respective bearing values of the subgrade and of the surfacing material. It seems reasonable to assume that if the maximum pressure on the subgrade exceeds the load-supporting value of the subgrade when the load is applied, then that particular combination of surfacing material and subgrade is in danger of failure. It becomes highly important, therefore, to determine the load-supporting value of the subgrade in order to determine if the maximum subgrade pressure is approaching or even exceeding the subgrade supporting value. Undoubtedly, the surfacing material gives some degree of confinement to the subgrade and, furthermore, it would seem desirable to make a load-supporting value test on the subgrade in its undisturbed condition. Having these two points in mind it was decided to make load-indentation tests on the subgrade in the following manner.

The design of the apparatus and its load-carrying capacity as a whole was such that a bearing block of 100 sq. in.

area seemed appropriate. A hole approximately ½ in. greater in diameter than the diameter of the block was very carefully formed in the surfacing material and after very carefully scraping the subgrade material to a level, flat surface, the steel bearing block was mounted on it and load was applied very slowly by the hydraulic jack. Simultaneously, indentation readings of the bearing block into the subgrade were taken. The first tests were performed by the continuous application of load and by the measurement of indentation through the use of a steel scale. But as refinements were developed in the method, load was applied in increments and after each increment of application, a period of one minute was allowed to elapse and indentation readings were taken by the use of two Ames dials reading to 0.001 in. In this way a load-indentation curve was obtained and since the time intervals are alike the respective curves on different subgrades should be comparable.

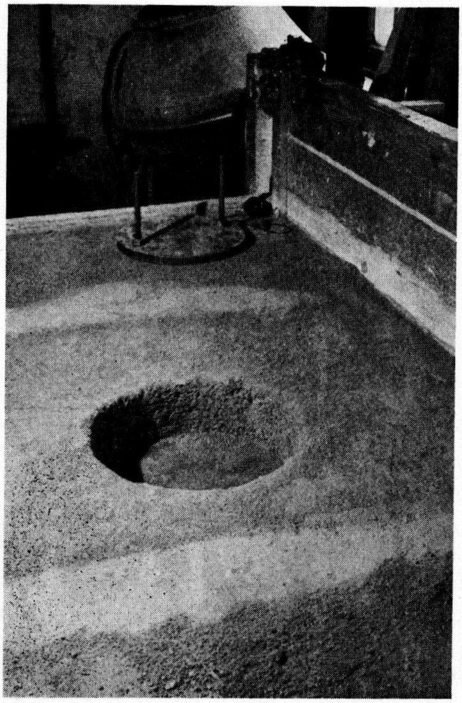


Figure 3. Hole dug through screenings layer preparatory to making load-indentation or bearing value test on subgrade.

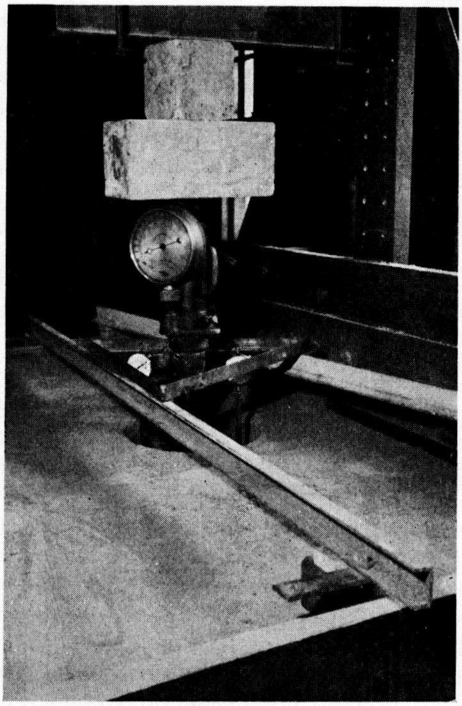


Figure 4. Making load-indentation (bearing value) test on subgrade. Bearing block, circular, with 100 sq. in. of area. Indentation is determined with two dials reading to 0.001 in.

In a similar manner load-indentation tests were made on the surfacing material and these tests may be taken as a measure of the physical properties of this material. In the case of the surfacing materials, however, a bearing block having only 10 sq. in. was employed, because were a large block to be used, the subgrade would contribute to the indentation. In this test it was desired that the indentation be confined entirely to the surfacing material if possible. By the use of this 10-in. bearing block, this objective was in large measure accomplished.

It no doubt would be desirable if additional tests could be made in the nature of an extrusion or punching shear test, especially if the samples could be taken from the subgrade and surfacing materials respectively in their undisturbed condition. In the absence of these, however, it is felt that the present load-indentation tests will serve a very useful purpose in identifying and relating subsequent tests to those at present described. All of the pressure readings will not be given at the present time, but merely typical curves to show some of the extremes of pressure obtained.

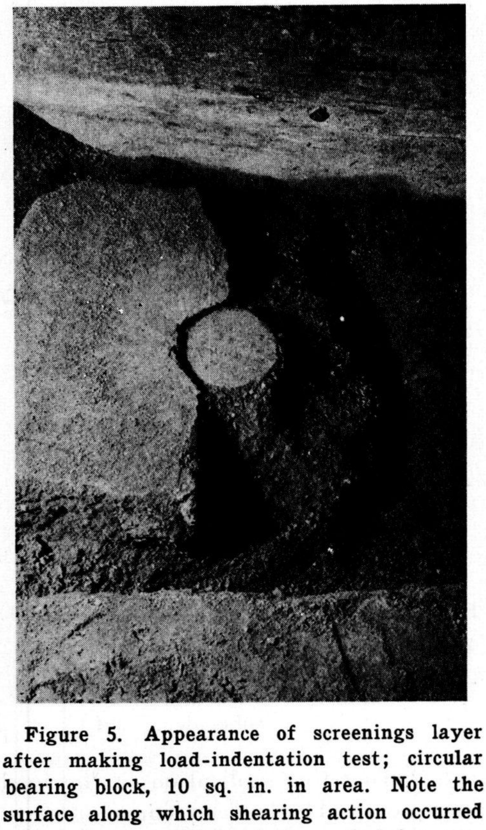


Figure 5. Appearance of screenings layer after making load-indentation test; circular bearing block, 10 sq. in. in area. Note the surface along which shearing action occurred during the test. Through the underlying cone the load is carried to the subgrade.

CURVES SHOWING TEST DATA

The following curves of test data have been selected from the tests thus far made in order to bring out the influence on maximum pressure and pressure distribution of variables in the thickness and rigidity of subgrade and wearing surface. Also, they show the influence of the magnitude of load applied.

In this test shown in Figure 6 the screenings were 4 in. thick, had only 3.4 per cent moisture and were very stable. The subgrade had 9.4 per cent moisture and it likewise was quite stable. Four thousand and 8,000 lb. wheel loads were applied on their respective bearing blocks with the resulting pressure distribution shown. Roughly, 48 lb. per sq. in. was the maximum pressure on the subgrade under the 8,000 lb. wheel load and 28 lb. per sq. in. under the 4,000 wheel load.

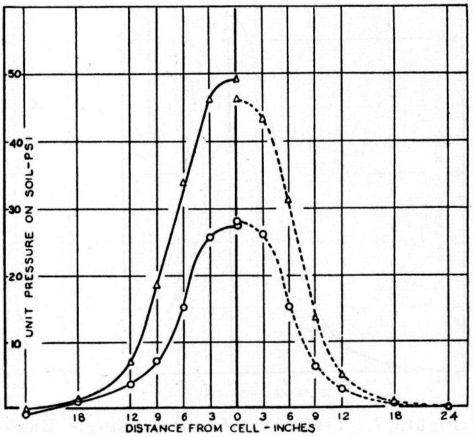


Figure 6. Longitudinal Loading, Single Block

Total load	Unit load p.s.i.
○—4,000	69
Δ—8,000	82.5

Test No. 2:
4-in. Screenings on 18-in. Subgrade
Moisture: Screenings....3.4
Subgrade.....9.4

The lateral pressure distribution for the above described conditions is shown in Figure 7. It will be recalled that the bearing block is advanced transversely in making these tests for transverse distribution and in view of the fact that a center zone of pressure is created by virtue of the prior application of the bearing block, in all probability there is a higher concentration of pressure on this center zone than in those portions of the subgrade to which direct application of pressure has not been applied. It has been noted time and again that in those spots in the subgrade which have received prior compression in excess of that received in other spots, there is a tendency for higher pressure concentration in the compressed portion. This fact makes it extremely difficult to obtain closely concordant check readings, but at the same time it demonstrates the lack of necessity for extreme accuracy in making tests of this character. We are dealing with a plastic material in both the subgrade and the wearing surface, or at least an inelastic material, and pressure conditions are changing rapidly during the making of the test. In Figure 7 it will be noted that the highest lateral pressures are spread out less than the high longitudinal pressures in the vicinity of the bearing block where most of the pressures are concentrated.

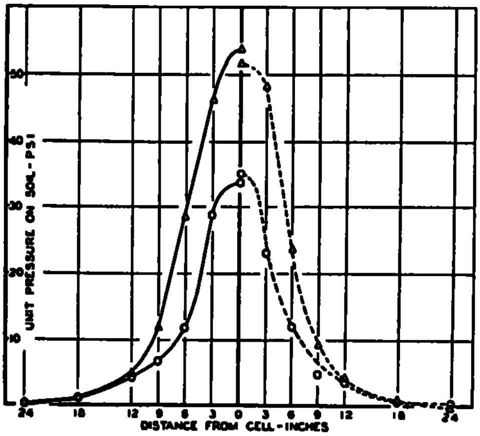


Figure 7. Transverse Loading, Single Block

Total load	Unit load p.s.i.
○—4,000	69
△—8,000	82.5

Test No. 2:
4-in. Screenings on 18-in. Subgrade
Moisture: Screenings....3.4
Subgrade.....9.4

In Figure 8 are shown typical load-indentation tests on the subgrade. The stepped shape of the curve is due to the interval of one minute after applying the load, during which indentation of the bearing block is taking place. The slant portions of the curve represent the intervals during the application of the load increments. The load increments are applied in a fraction of a minute, but not in a definite time interval. Curves B and C were obtained on those portions of the subgrade which had not been loaded by the bearing block while tests A and A′ were made on the central portion of the bin where the bearing block had been previously applied in making the load-distribution tests. Thus, the mere fact of loading the surface has increased the

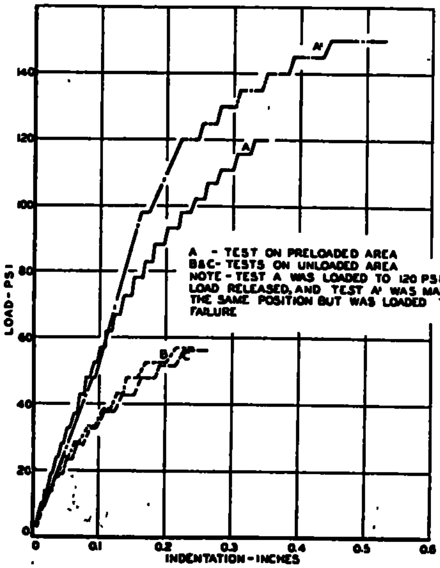


Figure 8. Load Indentation Test on Subgrade

Test No. 2:
4-in. Screenings on 18-in. Subgrade
Moisture: Screenings....3.4
Subgrade.....9.4

resistance of the subgrade to a very great extent. This test indicates that the subgrade is improved by the action of traffic, due no doubt to its greater compaction. This compacting action of traffic has of course been observed also in practice.

Note that there is a more or less definite yield point beyond which the subgrade yields at a higher rate. It would seem reasonable to use curve A as the curve which represents the significant pressure-indentation characteristics of the subgrade, for it probably would more nearly approach the condition of a subgrade in service after having been subjected to traffic. If this assumption is valid, then it would seem that the bearing value of this particular subgrade might be taken at around 65 lb. per sq. in., this point being that beyond which the curve deviates rather rapidly from the straight line.

In Figure 9 are shown typical load-indentation tests on the screenings surface. Since this particular surface contained only 3.4 per cent of water, the screenings were very stable as shown by the fact that rapid yielding did not take place until after a load of approximately 350 lb. per sq. in. was applied. It is of course somewhat indefinite as to what point on the load-indentation curve may be considered as the bearing value of the material. The selection of this point needs discussion and clarification. Perhaps it should be selected at a definite indentation, such as 0.1 in.

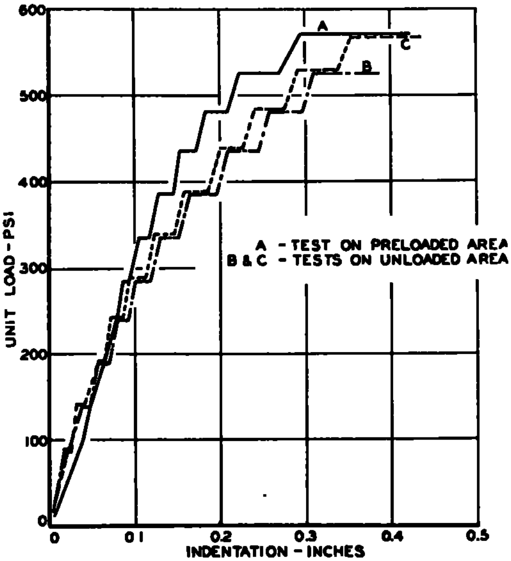


Figure 9. Load-Indentation Test on Screenings

Test No 2:
4-in. Screenings on 18-in. Subgrade
Moisture: Screenings....3.4
Subgrade.....9.4

Figure 10 is to be compared with Figure 6. The moisture conditions in the screenings and subgrade are not exactly alike, but they are closely comparable. Here, the surfacing material was 6 in. thick instead of 4 in. as in Figure 6. It will be noted that the maximum subgrade pressures are reduced. It was found possible to apply a 12,000 lb. wheel load on the 6-in. material without failure, whereas only 8,000 lb. could be applied in the case of the 4-in. layer.

In Figure 11, 8 in. of stabilized screenings were used instead of 6 in. as in Figure 10 and 4 in. as in Figure 6. Here, again, a very great reduction in the subgrade pressures is noted. The pressure under the 12,000 lb. wheel load in Figure 11 is no greater than that due to the 8,000 lb. wheel load in Figure 2.

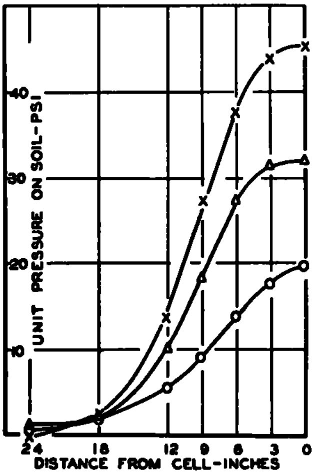


Figure 10. Longitudinal Loading, Single Block

Total load	Unit load p.s.i.
O—4,000	69
Δ—8,000	82.5
X—12,000	92.5

Test No. 1:
6-in. Screenings on 18-in. Subgrade
Moisture: Screenings....3.8
Subgrade.....9.2

In contrast with the prior results, the tests shown in Figure 12 indicate the high pressures which are possible when the surfacing layer is unstable. Here, the screenings layer has 6 per cent of moisture and it will be noted that under the 8,000 lb. wheel load, something over 70 lb. per sq. in. maximum pressure was attained.

The influence of the high per cent of moisture on the stability of the screenings is well shown in Figure 13. Note that the bearing value of these screenings is only about 100 lb. per sq. in. as con-

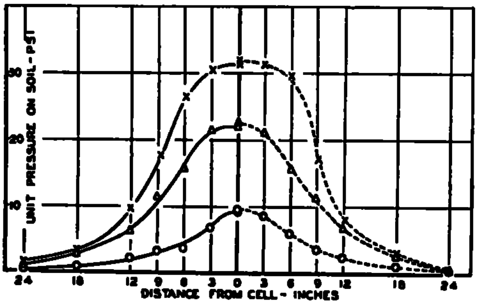


Figure 11. Longitudinal Loading, Single Block

Total load	Unit load p.s.i.
O—4,000	69
Δ—8,000	82.5
X—12,000	92.5

Test No. 6:
8-in. Screenings on 18-in. Subgrade
Moisture: Screenings....3.5
Subgrade.....8.3

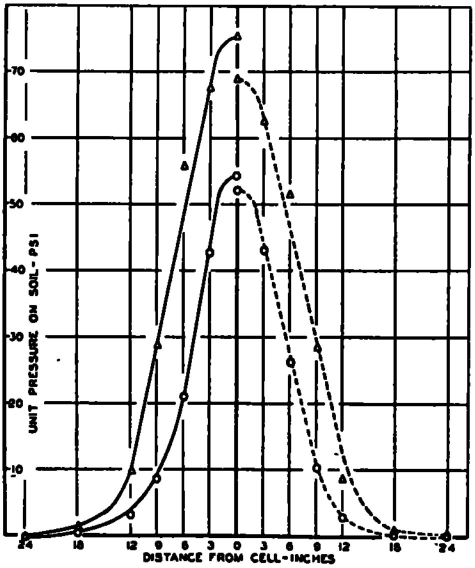


Figure 12. Longitudinal Loading, Single Block

Total load	Unit load p.s.i.
O—4,000	69
Δ—8,000	82.5

Test No. 9:
6-in. Screenings on 18-in. Subgrade
Moisture: Screenings....6.0
Subgrade....10.0

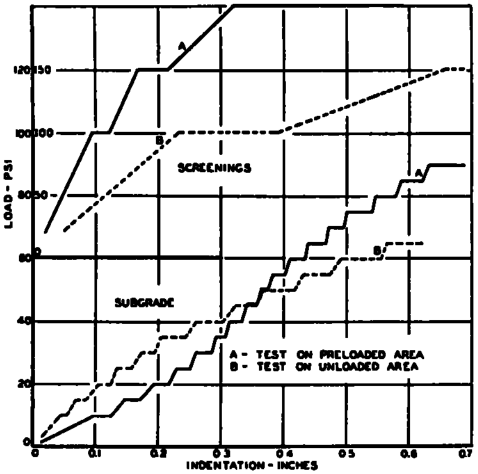
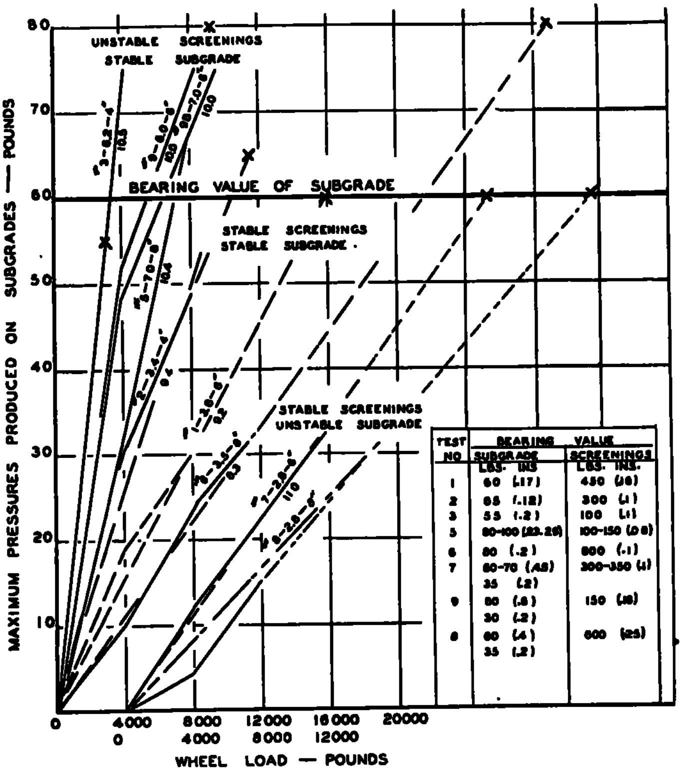


Figure 13. Load-Indentation Tests

Test No. 9:
6-in. Screenings on 18-in. Subgrade
Moisture: Screenings....6.0
Subgrade....10.0

trasted with 350 lb. per sq. in. with a low percentage of moisture. It is also seen that the subgrade in this particular case was none too stable. At least it showed a high indentation under the application of load.

The results, as far as maximum pressure intensities under different wheel loads are concerned, are summed up in Figure 14. The ordinates are the maximum pressures obtained on the subgrade under the center of the wheel load. A very great contrast in these pressure intensities is evident. For illustration, in test No. 3, made with 4 in. of screenings having a high percentage of moisture, a 4,000 lb. wheel load shows a maximum pressure intensity of well over 70 lb. per sq. in. This probably is in excess of the bearing capacity of the subgrade. When



TEST NO	BEARING VALUE SUBGRADE LBS. INS	BEARING VALUE SCREENINGS LBS. INS.
1	60 (.17)	450 (.16)
2	65 (.12)	300 (.1)
3	55 (.2)	100 (.1)
5	80-100 (.23-.28)	100-150 (.08)
6	80 (.2)	600 (.1)
7	60-70 (.45) 35 (.2)	300-350 (.1)
9	80 (.8) 30 (.2)	150 (.16)
8	60 (.4) 35 (.2)	600 (.25)

Figure 14. Maximum Subgrade Pressure Obtained Under Various Conditions

the screenings layer was stabilized by drying it out to only 3.4 per cent moisture, the pressure intensity on the subgrade due to a 4,000 lb. load was reduced to only 30 lb. per sq. in., well within the bearing capacity of the subgrade. It is indicated that this layer, with an 8,000 lb. wheel load had a maximum subgrade pressure of only 49 lb. per sq. in., apparently also well within the bearing capacity of the subgrade. The effects of other combinations of wheel load, surfacing, thickness and condition of the subgrade are shown in Figure 14.

CONCLUSIONS

Most of the theories for the design of the flexible road have assumed that the subgrade pressure is uniform in intensity and that it occupies an area which is confined within lines sloping outward from the area of surface contact, generally at 45°. Some of the older theories even ignore the fact that there is an area of contact between the tire and the road. It is quite evident that these theories are fallacious for the pressure intensity is not uniform.

No attempt is made at the present time to formulate a theory of design. It is too early for that, but rather are the present tests aimed at obtaining results which may later be of value in the formulation of a theory. It is hoped that ultimately the tests will be made to include different thicknesses of typical flexible surfaces and typical subgrade materials. It is also proposed to pursue them in the field if possible.

The present measurements take no account of impact and field tests should be made to determine to what extent, if any, impact is an important factor. For this purpose different apparatus or a modification of the present apparatus will be necessary. The whole project of flexible road design is important enough to warrant cooperative tests to the end that more rapid progress might be made.