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LABORATORY STUDIES OF SOIL BEDDING REQUIREMENTS FOR FLEXIBLE MEMBRANE LINERS

by

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16. ABSTRACT

This study was conducted in two phases. Phase I consisted of a series of full-scale tests conducted to determine a method of protecting flexible membranes from damage during the construction of landfills. Subgrade soils were selected that were considered to be representative of those which would be found in areas where landfills are constructed. Four membranes were tested. The membranes were placed on top of the subgrades and covered with various thicknesses of a sand material. The test items were trafficked using three different vehicles representative of the type of loadings that could be applied during landfill construction. Performance of the membrane was judged by its resistance to puncture and wear. The lean clay bedding provided the best protection for the liner and was effective in preventing puncture by the subgrade.

In Phase II of this study, three laboratory tests were developed to simulate field loading conditions on flexible membrane liners during construction of hazardous waste landfills. One test method used a moving pneumatic-tire loading, another used a rotating gyratory load, and the third used a cyclic vertical plate load. Loading conditions and thickness of cover material over the membrane varied using Boussinesq equations to produce vertical stresses on the membrane similar to those encountered under field conditions.

Test results showed that the moving pneumatic-tire load test would be the most useful for determining cover and bedding criteria using available site soils and candidate membranes. Also, a layer of clay soil was effective in preventing puncture of the membrane by the subgrade.

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FOREWORD

The study described herein was sponsored by the Environmental Protection Agency as part of Interagency Agreement EPA-80-R-X0937 entitled "Soil Bedding Requirements for Flexible Membranes."

The study was conducted by personnel of the Geotechnical Laboratory, U. S. Army Engineer Waterways Experiment Station (WES), under the general supervision of Mr. J. P. Sale, retired Chief, Geotechnical Laboratory, and Dr. W. F. Marcuson III, Chief, Geotechnical Laboratory. Personnel actively engaged in the planning and conducting of the study were Messrs. R. L. Hutchinson, retired, S. G. Tucker, D. M. Ladd, R. W. Grau, G. L. Carr, R. C. Gunkel, and Dr. W. R. Barker. This report was prepared by Messrs. Carr and Gunkel.

Commanders and Directors of WES during the conduct of the study and preparation of this report were COL N. P. Conover, CE, and COL T. C. Creel, CE. Technical Director was Mr. F. R. Brown.

ABSTRACT

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FIGURES

TABLES

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurements used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
feet	0.3048	meters
gallons (U. S. liquid)	3.785412	cubic decimeters
gallons (U. S. liquid) per square yard	4.5273	cubic decimeters per square meter
inches	25.4	millimeters
miles (U. S. statute) per hour	1.609347	kilometers per hour
mils	0.0254	millimeters
ounces (mass)	28.34952	grams
ounces (mass) per square yard	33.90575	grams per square meter
pounds (force) per square inch	6894.757	pascals
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
pounds (mass) per square yard	0.542492	kilograms per square meter
square feet	0.09290304	square meters
square inches	6.4516	square centimeters
tons (2000 pounds, mass)	907.1847	kilograms
yards	0.9144	meters

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: C = (5/9) (F - 32). To obtain Kelvin (K) readings, use: K = (5/9) (F - 32) + 273.15.

ABBREVIATIONS AND SYMBOLS

ASTM	American Society for Testing and Materials
CBR	California bearing ratio
CE	Corps of Engineers, U. S. Army
cm	Centimeters
CPE	Chlorinated polyethylene
CSPE	Chlorosulfated polyethylene
EPA	U. S. Environmental Protection Agency
ft	Feet
GP	Poorly graded gravels, USCS symbol
in.	Inches
lb	Pound
max.	Maximum
ml	Milliliter
ML	Inorganic silts with slight plasticity, USCS symbol
No.	Number
oz	Ounces
pcf	Pounds per cubic foot
psi	Pounds per square inch
PVC	Polyvinyl chloride
SC	Clayey sands, USCS symbol
SP	Poorly graded sands, USCS symbol
sq ft	Square feet
sq in.	Square inches
sq yd	Square yard
USCS	Unified Soil Classification System
WES	U. S. Army Engineer Waterways Experiment Station

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to Dr. Walter R. Barker and Mr. Donald M. Ladd, Geotechnical Laboratory, WES, for providing guidance for the project and for the analysis and discussions of test results.

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The authors also wish to thank Mr. Robert E. Landreth for his guidance, encouragement, and support during the conduct of this project.

SECTION 1

INTRODUCTION

BACKGROUND

Today, many industrial wastes may be highly toxic to the environment if their disposal is not properly controlled. A common method for disposal is the use of landfills, but improperly designed landfills could result in contamination of ground and surface water by toxic waste material. This condition exists because of various physical, chemical, and biological processes occurring when water or fluids percolate through the wastes, resulting in a leachate which contaminates the soil and ground water. The placement of impervious flexible membrane over the subgrade material in hazardous waste landfills could be one solution to controlling the leachate. One problem associated with this approach is potential damage to the membrane caused by earthmoving equipment during construction. Not only does the heavy equipment tend to damage the liner material, but puncture of the flexible membrane by underlying angular rock and soil particles in the natural soil also presents a source of damage. To study the problem, the U. S. Environmental Protection Agency (EPA) requested the U. S. Army Engineer Waterways Experiment Station (WES) to conduct an investigation to determine the requirements needed to protect flexible membrane from damage.

TEST OBJECTIVE

The initial objective of this study was to investigate the performance of membrane liners during construction of hazardous waste landfills and develop a means for protecting the liners from damage. This objective included the development of laboratory tests that could be used to determine bedding and cover requirements for protecting the membranes from puncture.

SCOPE

This study was conducted in two phases. In Phase I the performance of flexible membranes was investigated through the construction and testing of full-scale test sections. A test section containing 12 test items was constructed and subjected to three types of vehicle traffic (tracked, pneumatic-tired, and cleated). During this phase of the study, four flexible membranes, six selected subgrades, three thicknesses of a protective sand layer, and two bedding materials were investigated.

In Phase II three laboratory tests were developed to simulate field loading conditions on flexible liners during construction of hazardous waste landfills. One test utilized a moving pneumatic tire loading, another used a rotating gyratory load, and the third used a cyclic vertical plate load. Tests were conducted using a gravelly sand or limestone subgrade under the membrane liner and a gravelly sand cover. In some tests, a lean clay or a fabric was placed between the liner and subgrade to serve as a protection for the membrane liner. One type and thickness of cover and three membrane liners were used in the tests. Other special tests were conducted to develop a test that could possibly be used as a screening test for membrane liners.

DEFINITIONS

1. Subgrade - Soil used in these tests to represent natural material upon which a landfill may be constructed.

2. Bedding Material - That material placed between the membrane liner and the subgrade to protect the liner from puncture.

3. Cover Material - That material placed on top of a membrane liner to protect it from puncture during construction of a landfill.

SECTION 2

CONCLUSIONS

Based upon the results of this study, the following conclusions are considered warranted:

a. The three traffic vehicles used in the full-scale tests produced similar amounts of damage to each membrane.

b. The 6 in.* of bedding material placed in the full-scale test section reduced the number of punctures in the membranes.

c. The pneumatic-wheel load tests would be the most useful laboratory test for determining cover and bedding criteria using available site soils and candidate membranes.

d. The cover material placed above a liner as well as the bedding material should be a soil classified as a clay, silt, or sand, and having a gradation similar to the clay or concrete sand used herein. Material should have no particles larger than 3/8 in.

e. The 1 in. of lean clay bedding material was effective in preventing puncture of the liner material by the gravel subgrade during laboratory tests.

f. Use of the geotextile as a bedding material reduced the number of punctures, and the use of a thicker geotextile may prevent punctures from occurring.

* A table of factors for converting U. S. customary units of measurement to metric SI units is presented on page ix.

SECTION 3

RECOMMENDATIONS

The tests reported herein show strong trends in the performance of liner materials placed in landfills and need to be continued to develop a complete range of design criteria. It is therefore recommended that:

a. Additional laboratory tests be conducted using other subgrade materials and methods for protecting the liners.

b. Further analytical work be accomplished on the field and laboratory data to extend criteria.

c. Criteria obtained from laboratory tests be validated by conducting full-scale field tests.

d. Additional series of tests be performed with the laboratory gyratory equipment and the artificial rocks (barbs) to develop a laboratory method of test for screening membranes.

e. Compaction requirements be established for bedding and cover materials.

SECTION 4

FULL-SCALE TEST SECTION STUDIES (PHASE I)

CONSTRUCTION OF TEST SECTIONS

A test section was constructed under shelter at the WES. The test section was 16 ft wide, 240 ft long, and consisted of 12 test items, each 20 ft long and 16 ft wide. A plan and profile of the test section are shown in Figure 1. Construction started by excavating an area of the subgrade floor of the shelter, where the test section had been staked out, to a depth of 6 in. and a width of 16 ft as shown in Figure 2a. The last 40 ft, at the north end of the test section, was excavated to a depth of 12 in. to accomodate a 6-in. layer of coarse gravel that was overlaid with 6 in. of sandy silt. This fine-grained sandy silt was used as a bedding material to protect the flexible membranes from puncture during traffic tests. The remainder of the test section was backfilled, as shown in Figures 2b-2c, with the selected subgrades. The subgrades were compacted with pneumatic-tire and vibratory rollers as shown in Figures 2d and 2e. Figure 2f illustrates the test section with the selected subgrades in place. The texture of the compacted subgrade materials used in the 12 items of the test section before traffic is depicted by Figures 2g-2l. After the six subgrades had been placed, each of the 12 test items in the test section was covered with flexible membranes. Shoulders were then constructed on both sides of the test sections using material that had been excavated previously from the floor of the shelter. The height of the shoulders depended on the thickness of the protective layers of sand that were placed over the membrane liners for each test program. For the first test program, the shoulders were 6 in. in height so as to contain that depth of sand (see Figure 2m). The sand was dumped between the shoulders at each end of the test section. Then a bulldozer pushed the sand toward the center of the test section. Care was taken to maintain at least 6 in. of sand between bulldozer's tracks and the flexible membranes at all times during placement operations. Figure 2n shows the complete test section with a protective sand layer of 6 in.

SUBGRADE SOILS

Six subgrade materials were selected and used for the 12 items of the test section. These materials were classified according to the Unified Soil Classification System (USCS) as follows:

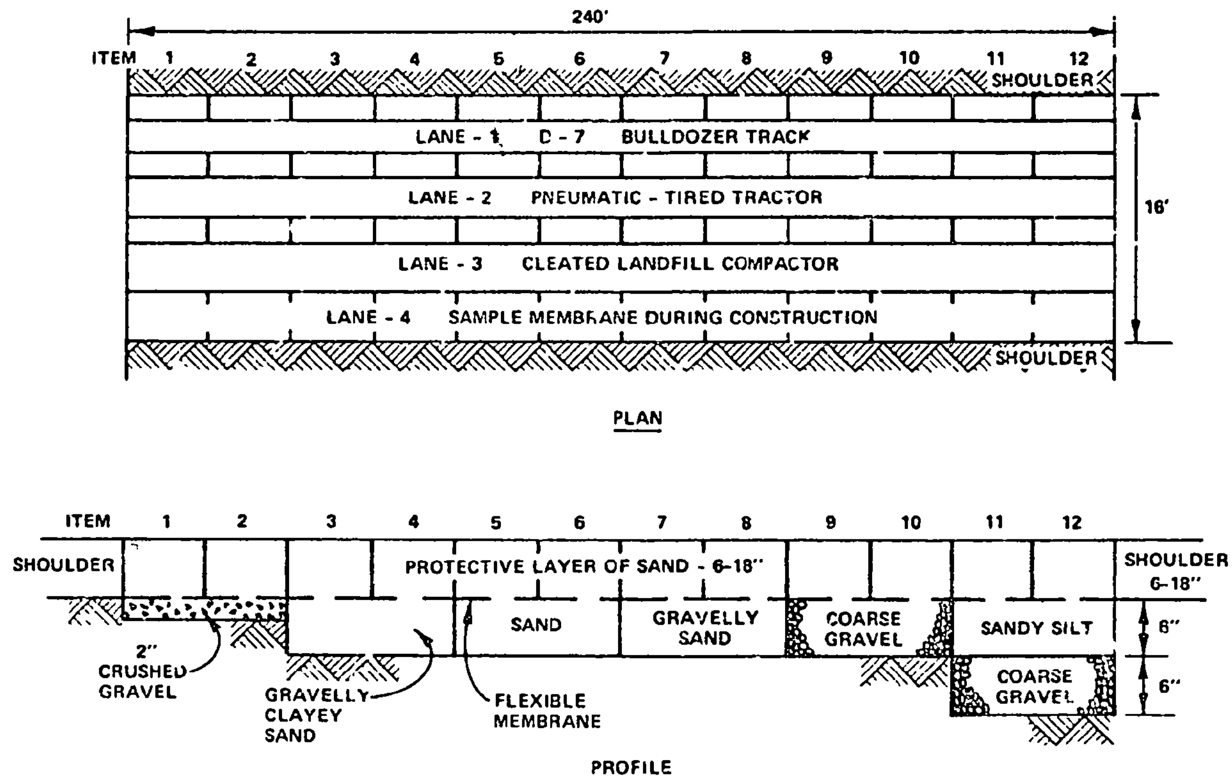
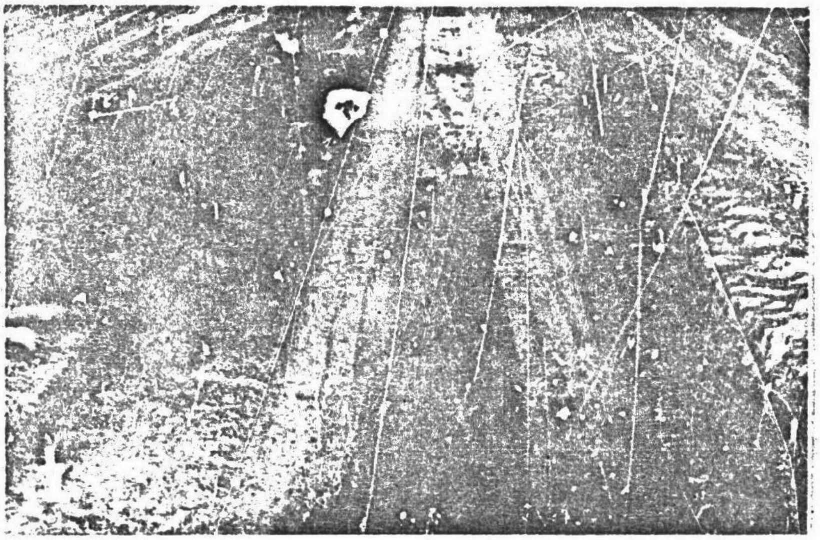
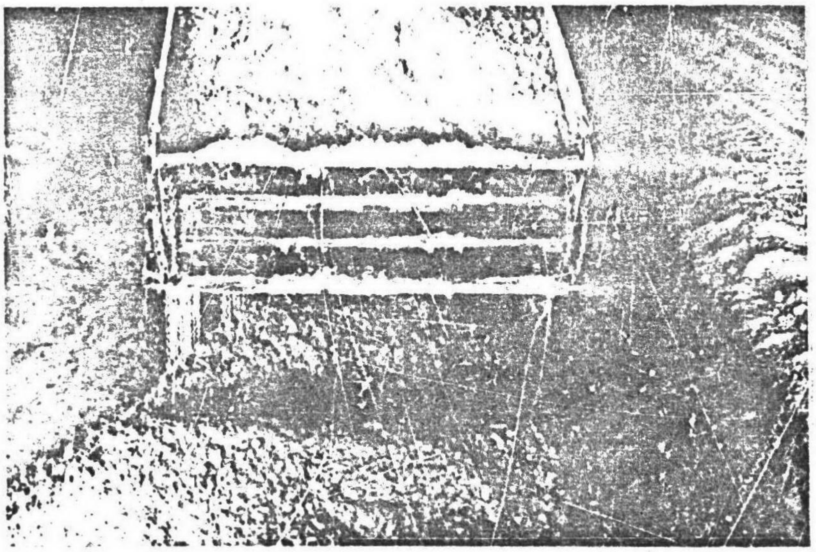


Figure 1. Plan and profile of test section.

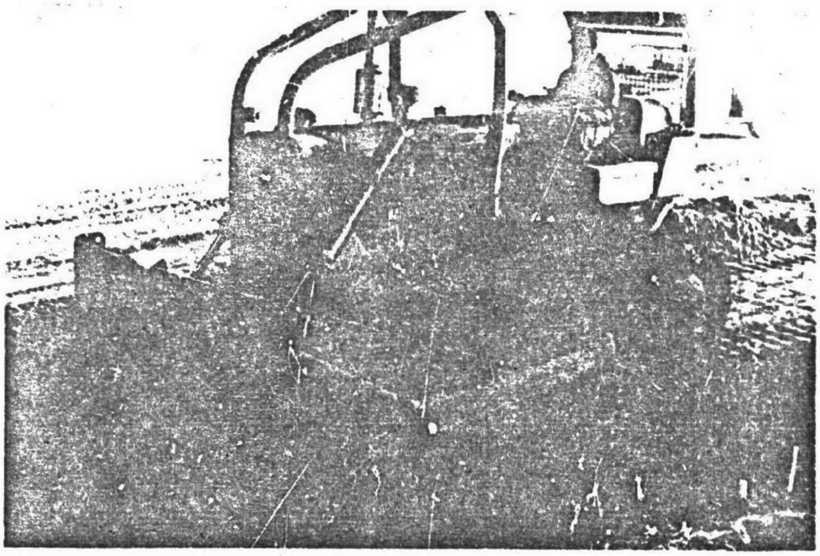


a. Test section prior to placement of selected subgrades.

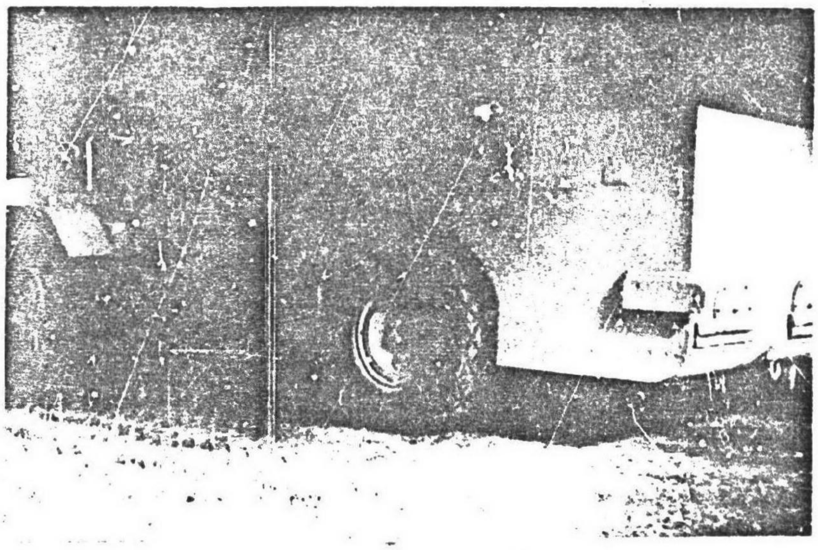


b. Subgrade being placed in Items 3 and 4.

Figure 2. Construction of the test section.

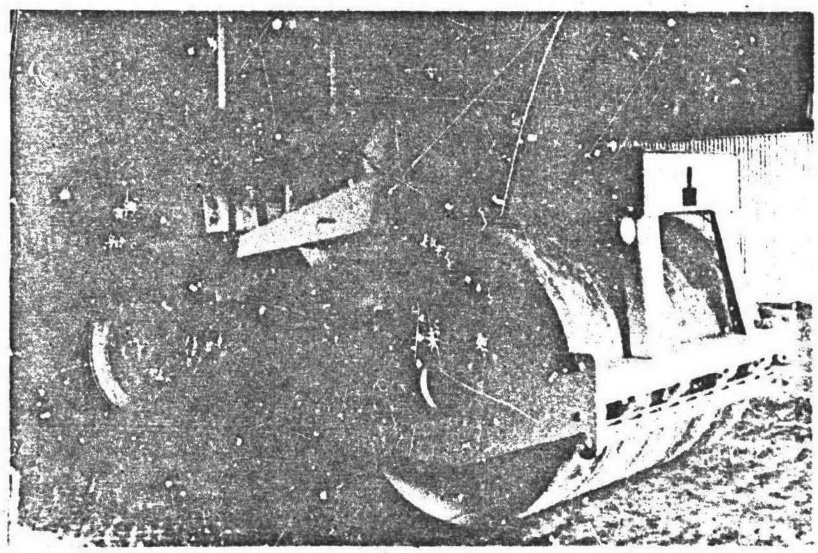


c. Spreading subgrade material.

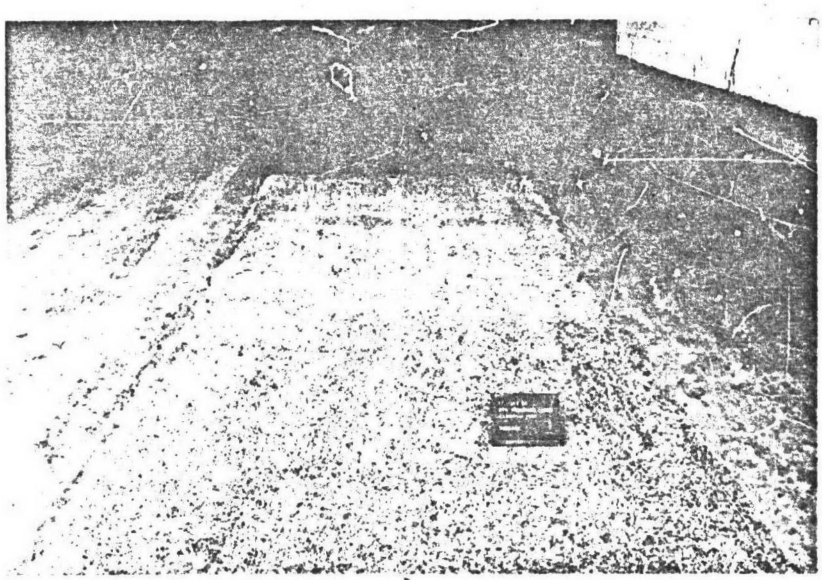


d. Pneumatic-tire roller used for compaction of subgrade.

Figure 2. (Continued).

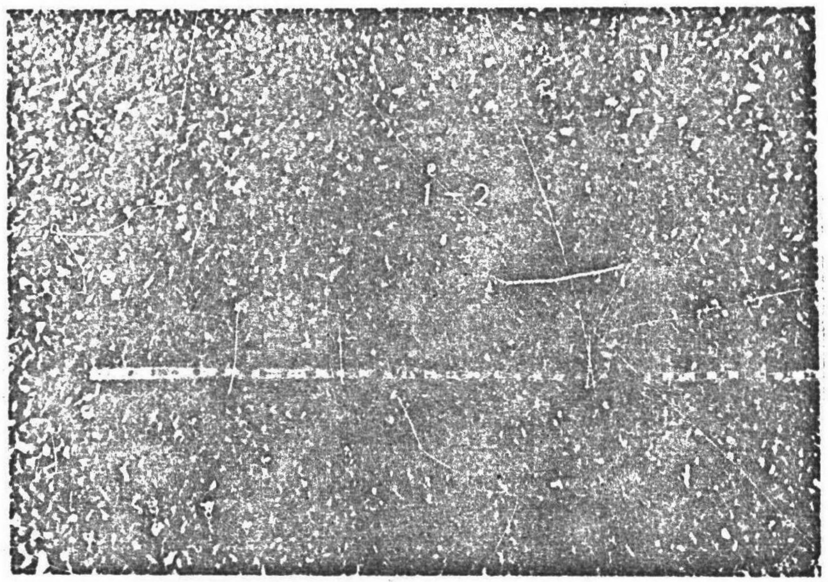


e. Vibratory roller used for compaction of subgrade.

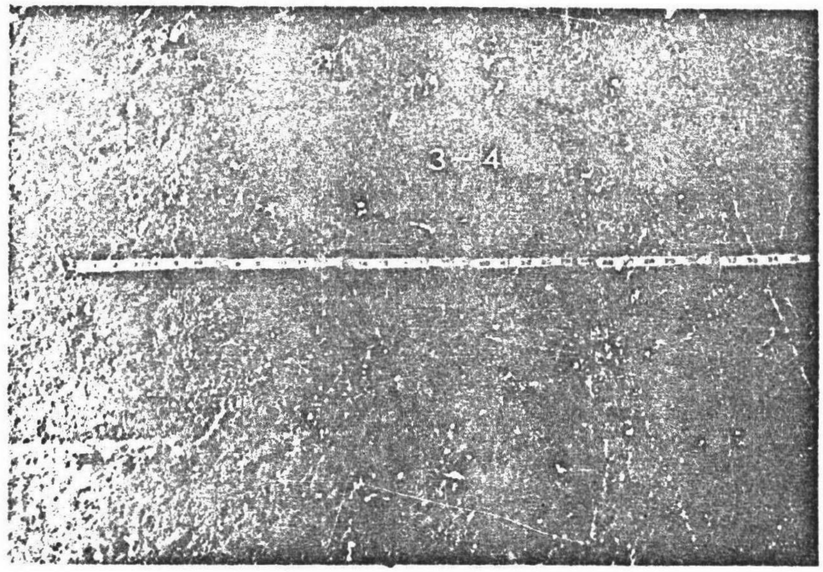


f. Overall view of test section with subgrades in place.

Figure 2. (Continued).

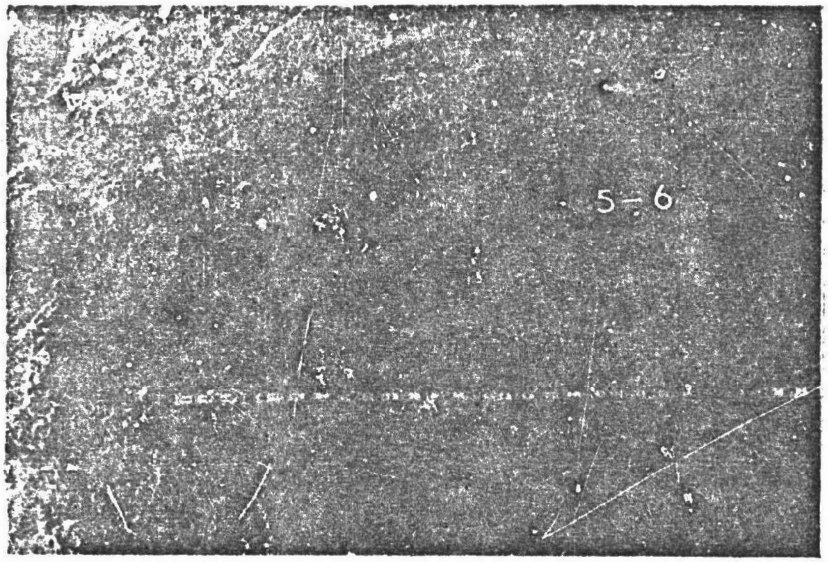


g. Close-up of material in Items 1-2.

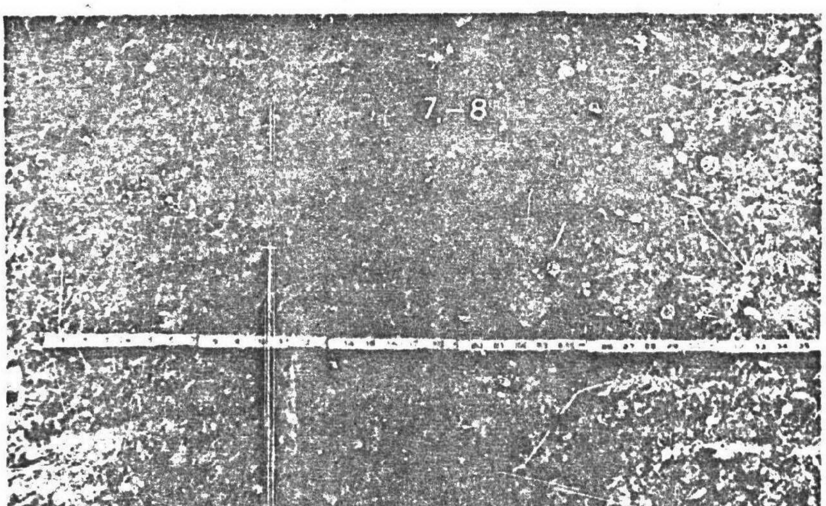


h. Close-up of material in Items 3-4.

Figure 2. (Continued).



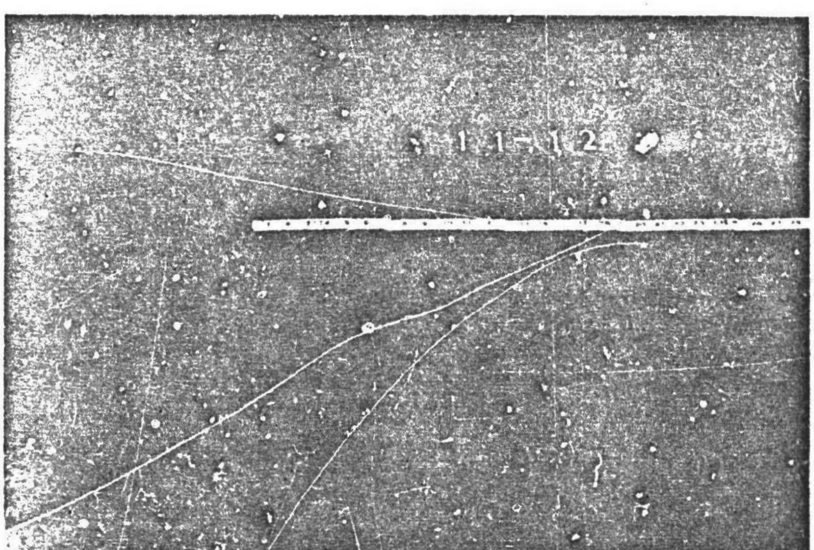
i. Close-up of material in Items 5-6.



j. Close-up of material in Items 7-8.

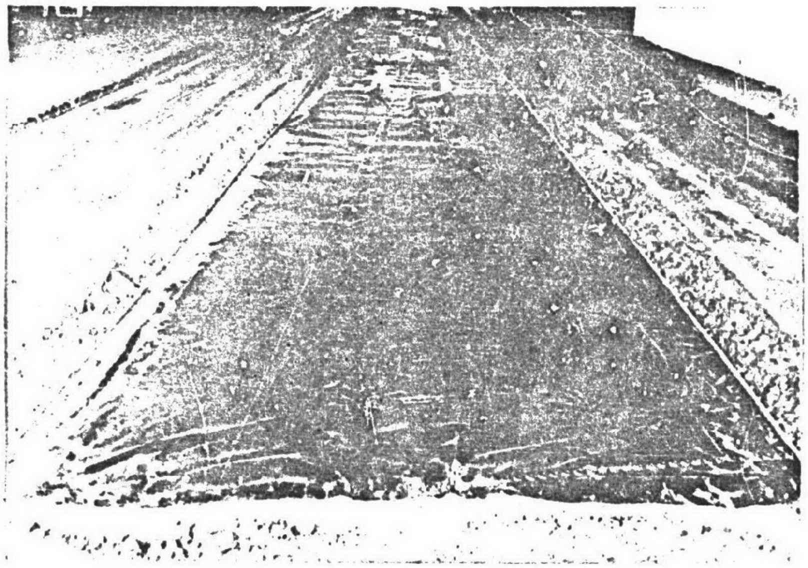
Figure 2. (Continued).

k. Close-up of material in Items 9-10.

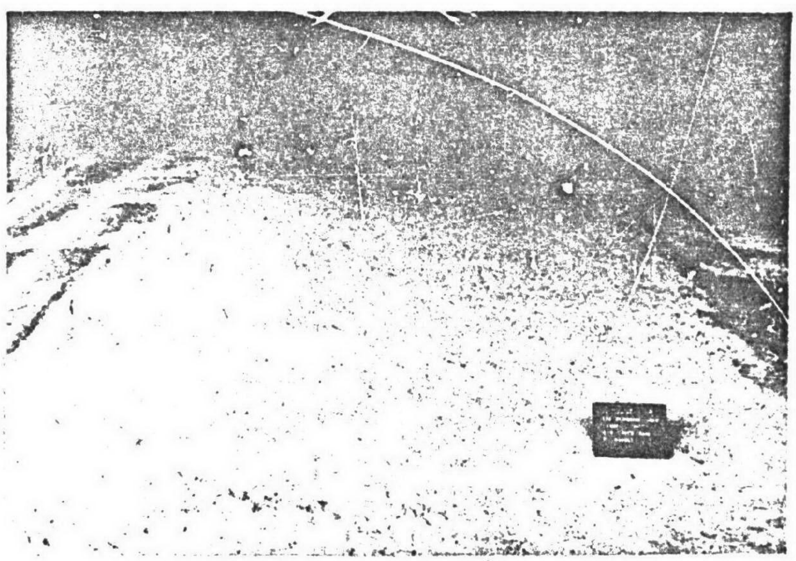


L. Close-up of material in Items 11-12.

Figure 2. (Continued).



m. Membranes in place; note 6-in. shoulders on both sides of test section.



n. Completed test section with 6 in. of protective sand.

Figure 2. (Concluded).

Item No.	Classification
1-2	Crushed gravel (GP)
3-4	Gravelly clayey sand (SP-SC)
5-6	Sand (SP)
7-8	Gravelly sand (SP)
9-10	Coarse gravel (GP)
11-12	Sandy silt (ML)

It should be noted that the sand in items 5 and 6 was the same type of sand that was used for the protective cover layers. The sand was a local (Vicksburg, Mississippi) sand usually used as the fine aggregate in concrete. Gradation curves for the subgrade materials are shown in Figure 3.

MEMBRANES

The four flexible membranes and one fabric material used as a bedding material were as follows:

Designation*	Thickness, mils	Type
M1	20	Elasticized polyolefin (3110)
M2	20	Polyvinyl chloride (PVC)
M3	30	Chlorinated polyethylene (CPE)
M4	36	Reinforced chlorosulfated polyethylene (CSPE-R)
F1	30	Nonwoven polypropylene and nylon

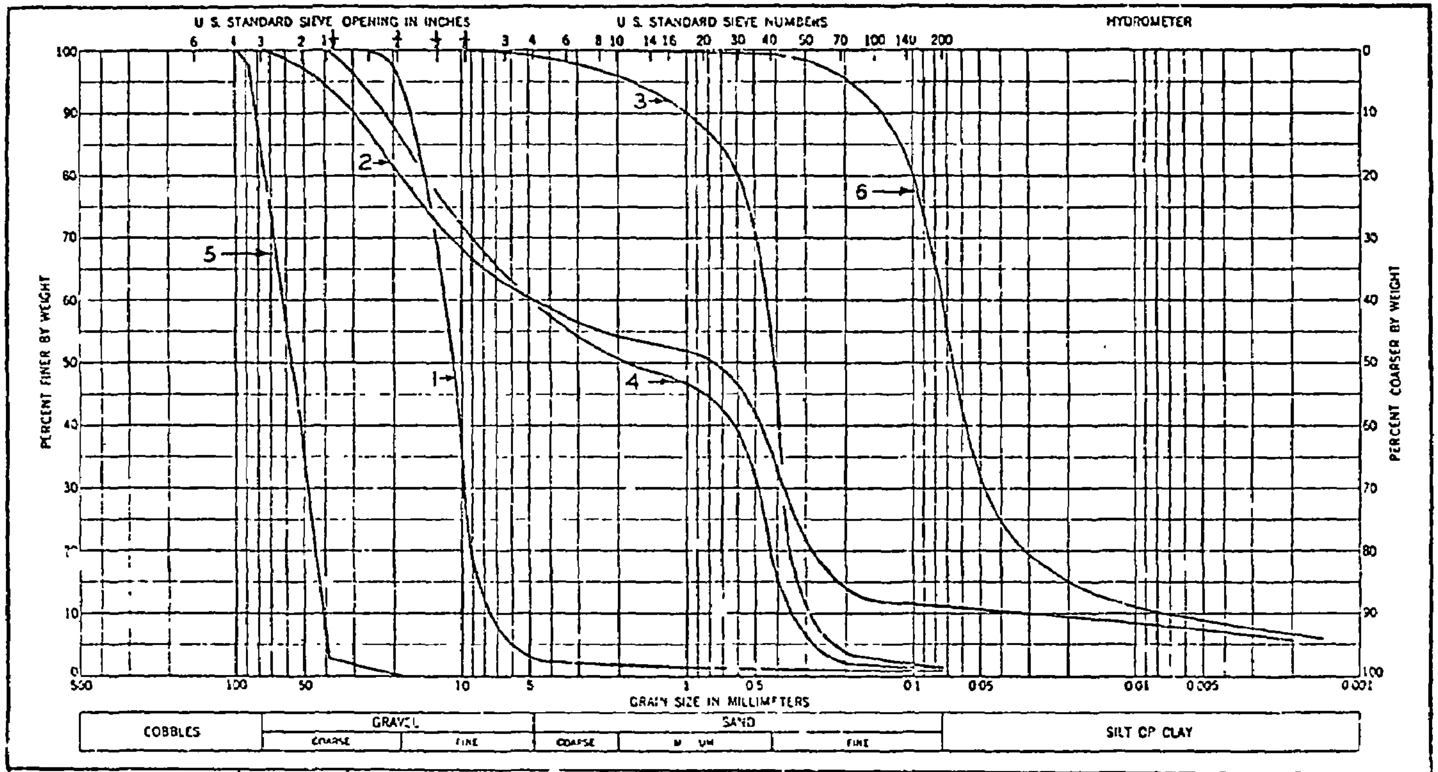
* The membranes and fabric material are referred to hereafter by the designation symbol assigned above.

TRAFFIC VEHICLES

The vehicles used to apply traffic to the various test programs were: A D-7 bulldozer equipped with 22-in.-wide tracks, weighing approximately 44,000 lb, and having a contact pressure of 9 psi; a pneumatic-tired tractor weighing 37,190 lb and equipped with two 29.5x29, 22-ply tires (each tire had a contact area of 574 sq in. which produced a contact pressure of 32 psi); and a model 816 landfill compactor, weighing 40,900 lb, equipped with four cleated steel wheels having a contact pressure of 18 psi. The traffic vehicles are shown in Figure 4.

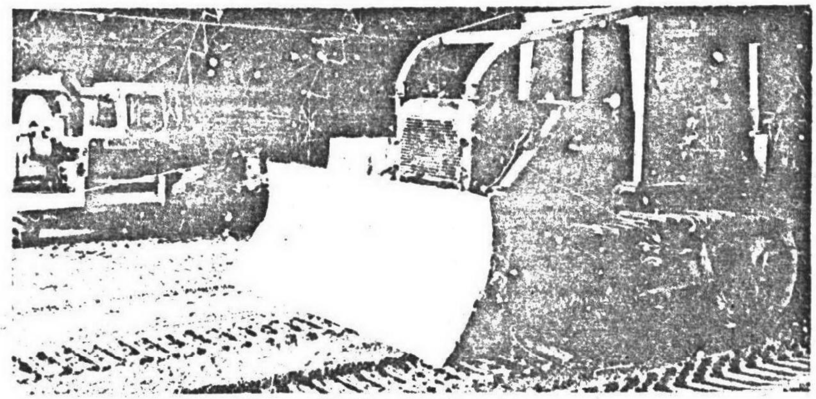
TRAFFIC PATTERN

Traffic tests were conducted on each test item to simulate actual heavy equipment operations during the construction of landfills. Traffic was applied with both the tracked bulldozer and cleated landfill compactor in the



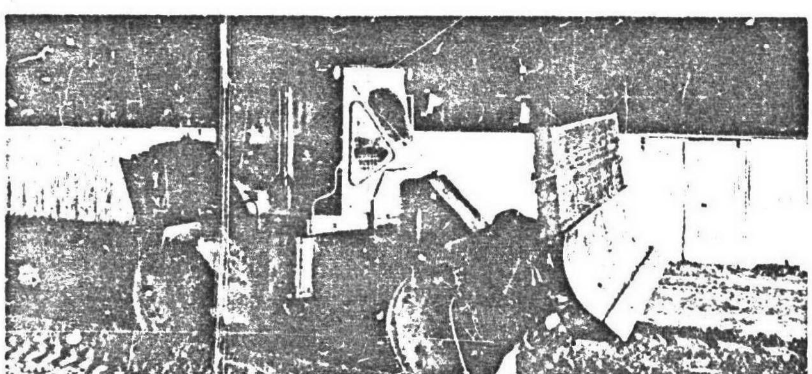
SAMPLE NO	ITEM	CLASSIFICATION
1	1-2	GRAVEL (GP)
2	3-4	GRAVELLY CLAYEY SAND (SP-SC)
3	5-6	SAND (SP)
4	7-8	GRAVELLY SAND (SP)
5	9-10	COARSE GRAVEL (GP)
6	11-12	SANDY SILT (ML)

Figure 3. Gradation curves for selected subgrades.



a. D-7 Bulldozer.

b. Pneumatic-tired tractor.



c. Cleated landfill compactor.

Figure 4. Vehicles used to traffic test sections.

same manner. These vehicles were operated in one direction until they had traveled the entire length of the test section where they were stopped and then returned in the same track or wheel path in reverse. The pneumatic-tired tractor was operated in the same direction and in the same wheel path as it had traveled in the preceding pass. One pass of the bulldozer and pneumatic-tired tractor resulted in one coverage within their respective traffic lanes, while one pass of the landfill compactor resulted in two coverages within the traffic lane.

SOIL DATA

Except for the crushed and coarse gravel material, laboratory compaction tests and unsoaked California bearing ratio's (CBR's) were performed on the selected subgrades. Field tests to determine moisture content, density, and CBR value on the in-place material of the test section were also performed. The results of the soil data obtained from these tests are presented in Table 1.

TABLE 1. SOILS DATA FOR MATERIALS USED IN FIELD TEST SECTIONS

		Field Tests			Laboratory Tests		
Item No.	Soil Classification	Dry Density pcf	Moisture Content	CBR	Max. Density* pcf	Optimum Moisture	Unsoaked CBR
3-4	Gravelly clayey sand	125.3	9.8	7.0	131.8	7.4	20.4
5-6	Sand	104.1	8.1	4.0	105.6	14.0	30.5
7-8	Gravelly sand	118.6	6.0	8.3	126.6	8.0	21.3
11-12	Sandy silt	98.5	18.7	7.0	105.5	14.8	24.4

* CE-12 compactive effort (12 blows of a 10-lb hammer and 18-in. drop).

MEMBRANE EVALUATION

In evaluating the performance of the flexible membranes, only the after-traffic condition was considered. After 10 passes of the traffic vehicles, a trench was excavated across each traffic lane in all 12 items. A sample of the membrane was removed from each traffic lane in each item, marked for identification, and inspected. After patching the membrane and replacing the protective layer of sand in the trenches, traffic was continued on the items in which the membranes showed only a few or no punctures. After 30 passes, traffic was stopped and a final inspection was made.

FAILURE CRITERIA

Each sample of membrane was placed over a light table and inspected for punctures. A 5-sq-ft area, within the wheel path, was marked on the membranes and from this area the number of punctures noted were recorded. A membrane was considered "failed" if any punctures were noted.

RESULTS OF TRAFFIC TESTS

Test Program 1

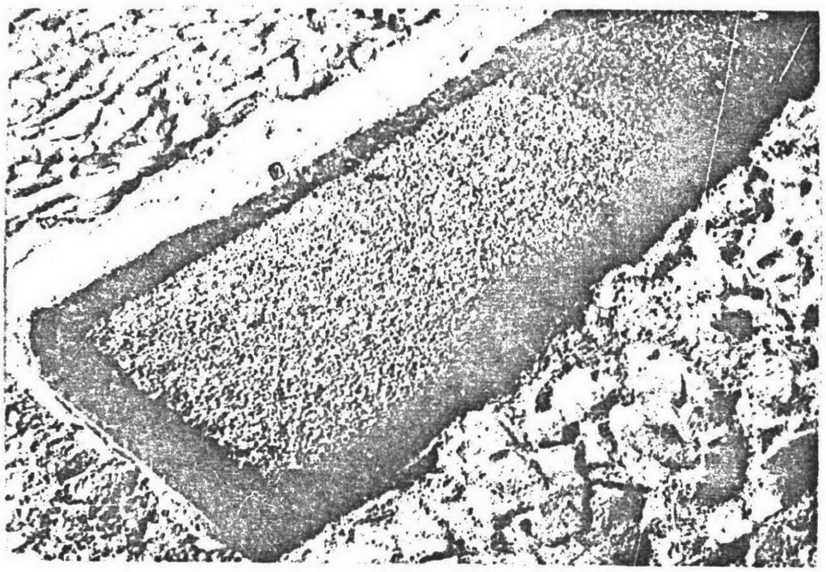
In test program 1, two types of membranes (M1 and M2) were placed over the six subgrade materials. The M1 and M2 membranes were placed on the odd and even numbered items, respectively. A 6-in.-thick sand cover was placed over the membranes to act as a protective layer. Traffic was applied to the test section with the D-7 tracked bulldozer and the pneumatic-tired tractor. After 10 passes, traffic was stopped and trenches were dug across the traffic lanes in each of the 12 items. Samples of the membrane from each traffic lane and each item were removed for inspection. Figures 5, 6, and 7 show several of the inspection trenches and the condition of membrane samples after removal. After patching the void in the membrane and replacing the protective layer of sand in the trenches, traffic was continued on 4 items (5-6 and 11-12) which showed only a few or no punctures in the membranes. After 30 passes were completed, traffic was again stopped and a final inspection was made. The final results for test program 1 are graphically displayed in Figure 8.

Test Program 2

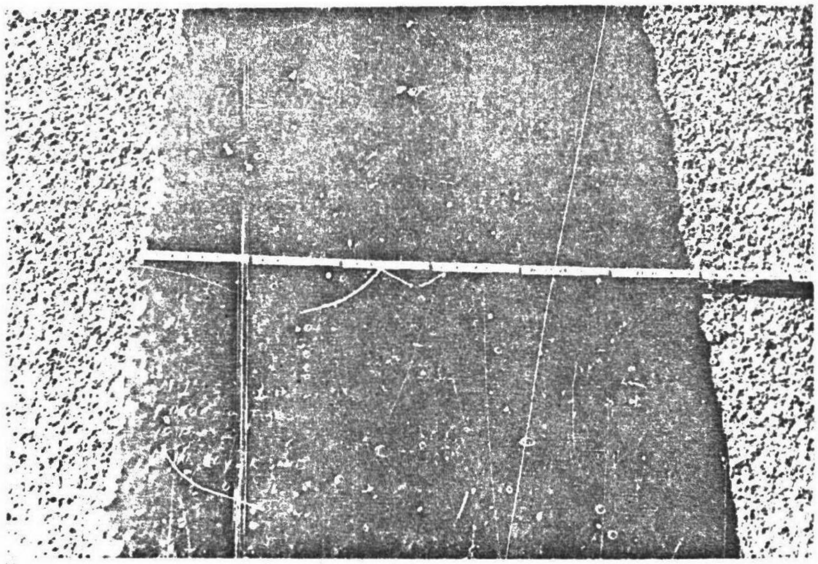
Test program 2 was identical to the first test program with the exception of the thickness of the sand protective layer which was increased from 6 in. to 18 in. In trafficking test program 2, three types of vehicles were used (track-tire-cleated). The cleated vehicle was a Model 816 Landfill Compactor which was owned by Bolivar County, Mississippi, and was operated at one of their landfill sites. The 816 landfill compactor was leased for test program 2. After traffic, the sampling of the membrane was accomplished in the same manner as in test program 1. A typical view of rutting that occurred in the sand protective layer during traffic operations is shown in Figure 9. Figure 10 shows the trenches that were excavated prior to removal and inspection of the membrane. The final test results of test program 2 are shown in Figure 11.

Test Program 3

After trafficking and obtaining the final data in test program 2, the sand protective layer and membranes were removed and preparation of test program 3 was started. Test program 3 contained the same selected subgrades and 18 in. of sand was placed as the protective layer. However, the existing

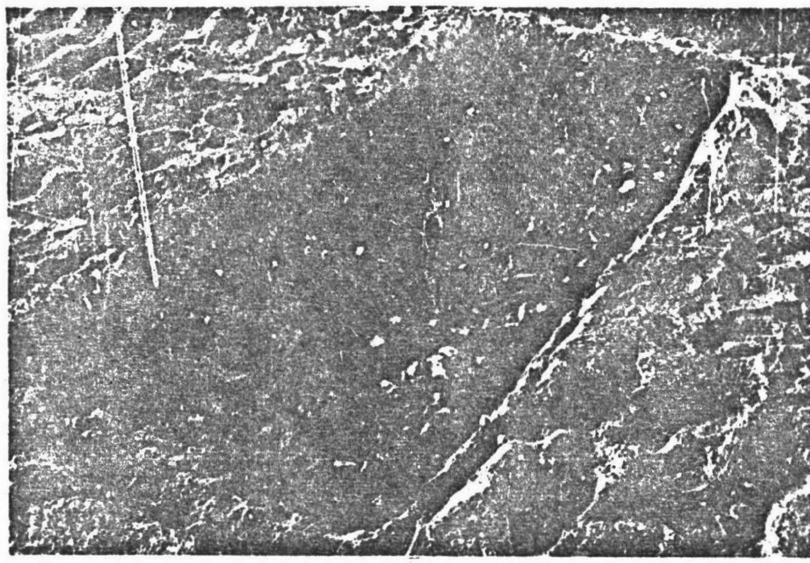


a. Inspection trench after removal of membrane.

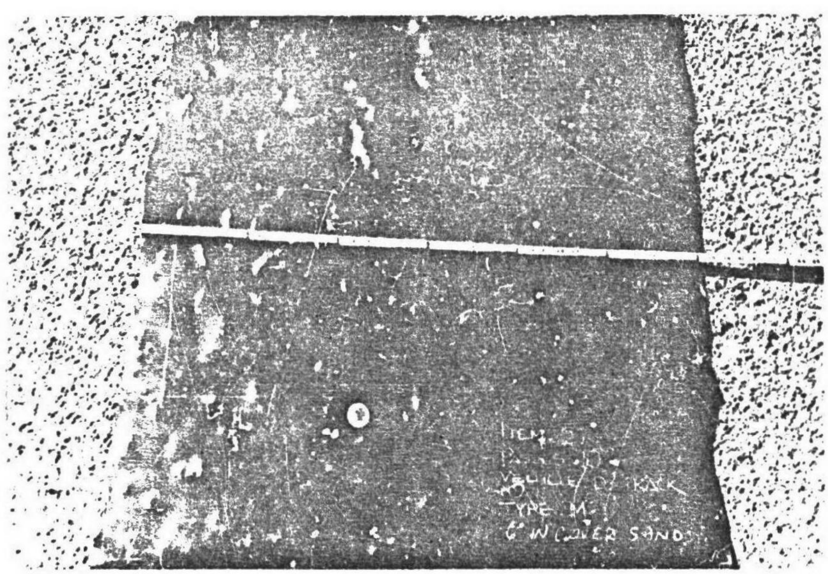


b. Holes in membrane after 10 passes of the pneumatic-tired tractor.

Figure 5. Excavated trench and membrane, test program 1.

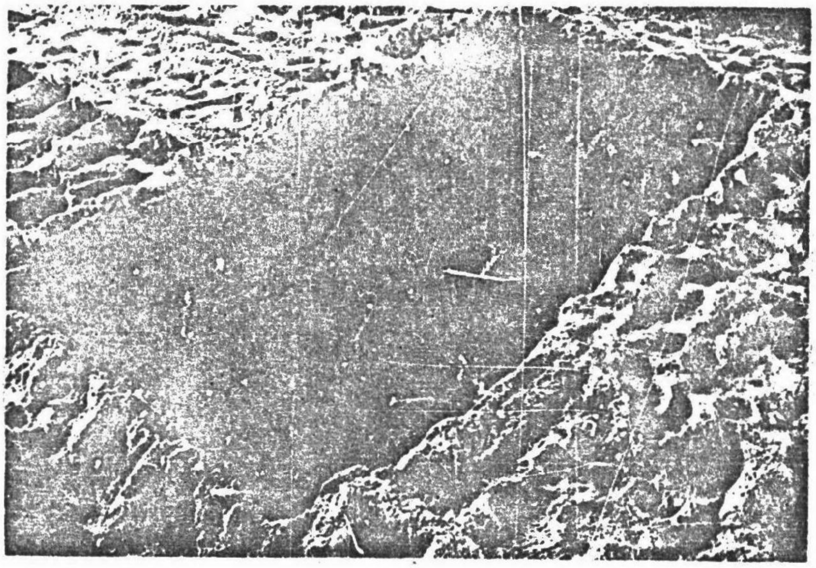


a. Excavated trench in item 10, No. 1 and 2 designate track and tire traffic lanes.

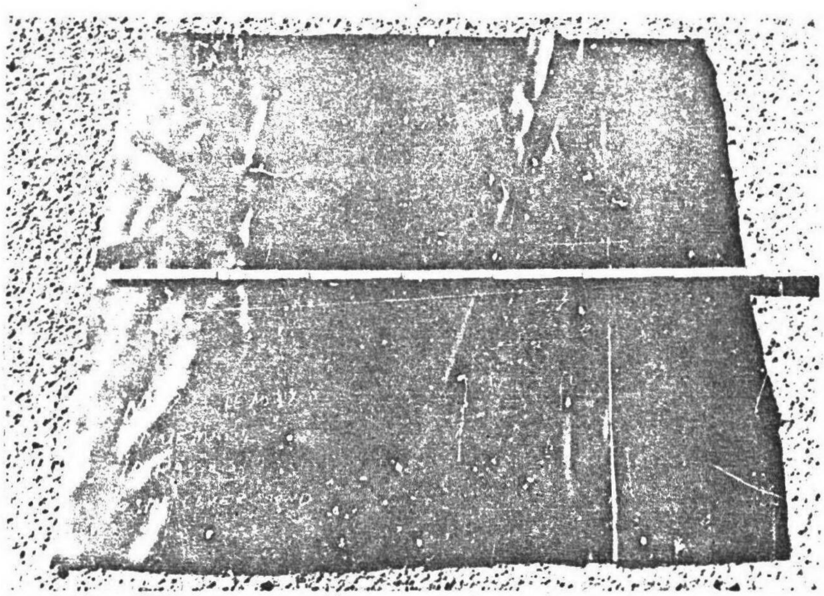


b. Inspected membrane; note identification markings.

Figure 6. Inspection trench and membrane after traffic, test program 1.



a. Trench in item 11 after 10 passes of traffic.



b. Membrane after 10 passes of pneumatic-tired tractor, no punctures.

Figure 7. Trench and membrane from items 11 and 12, test program 1.

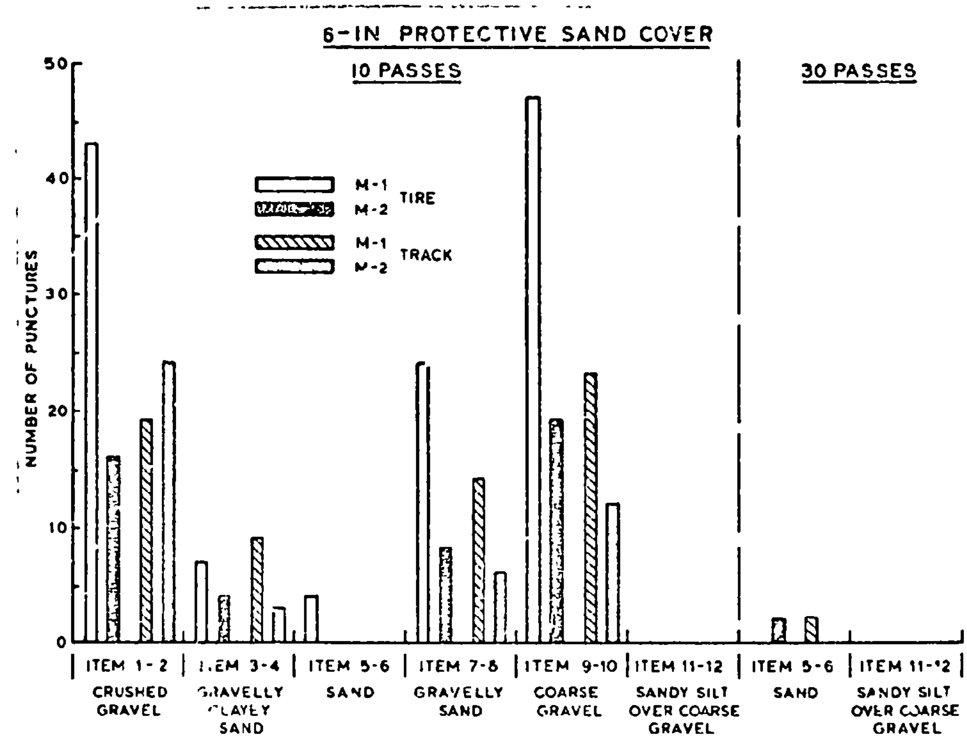
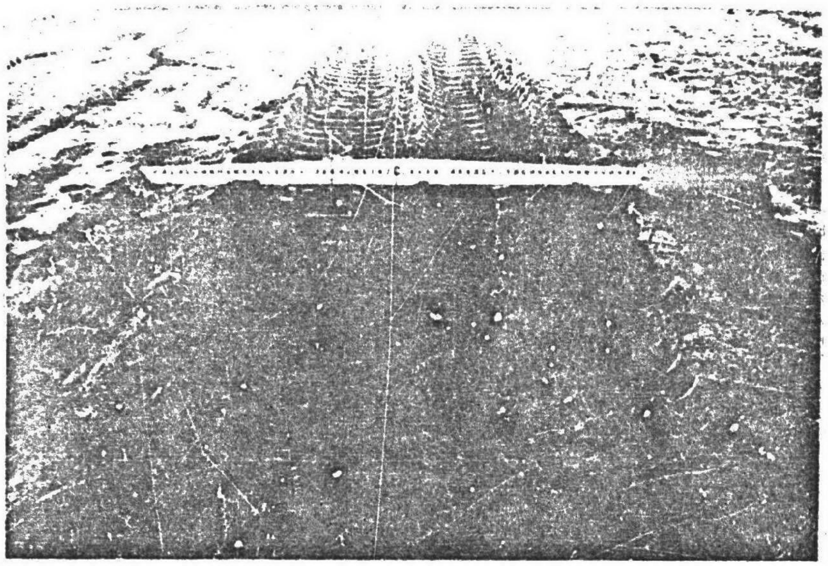
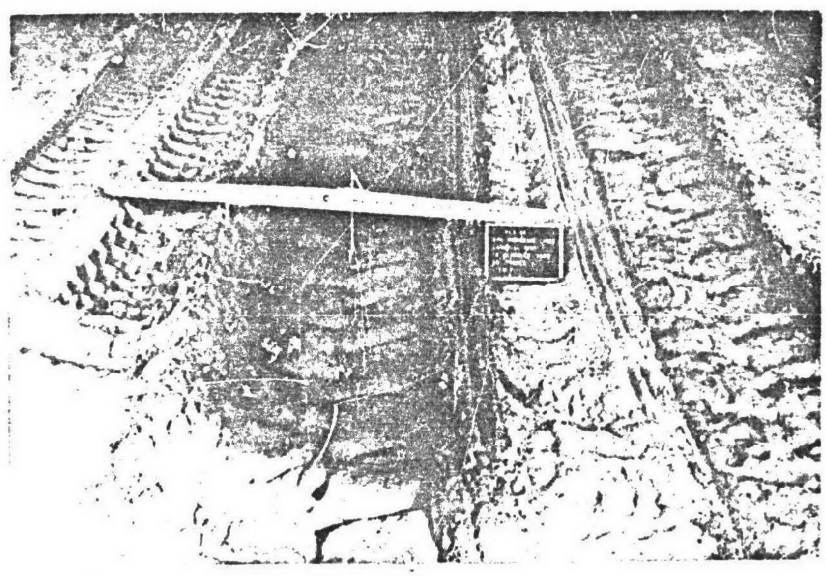


Figure 8. Results of test program 1.

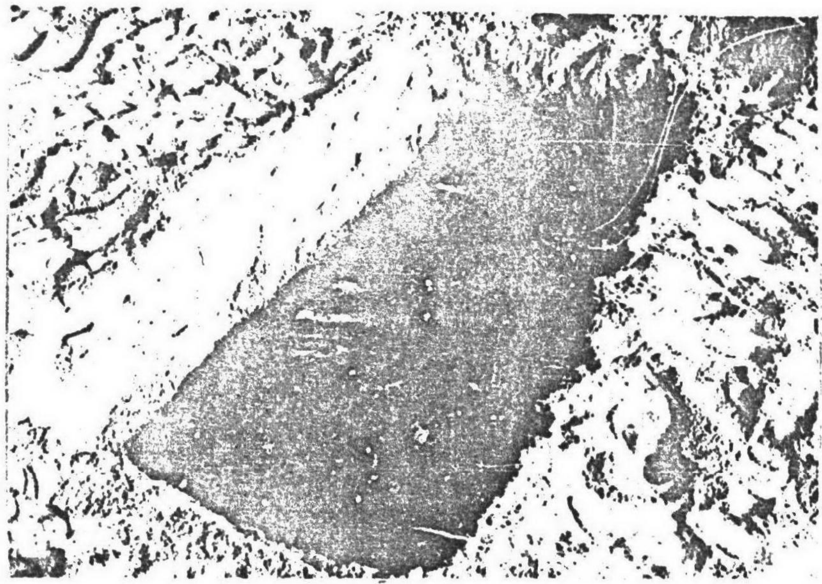


a. Lane 1 (track), lane 2 (tire) rutting after 30 passes.

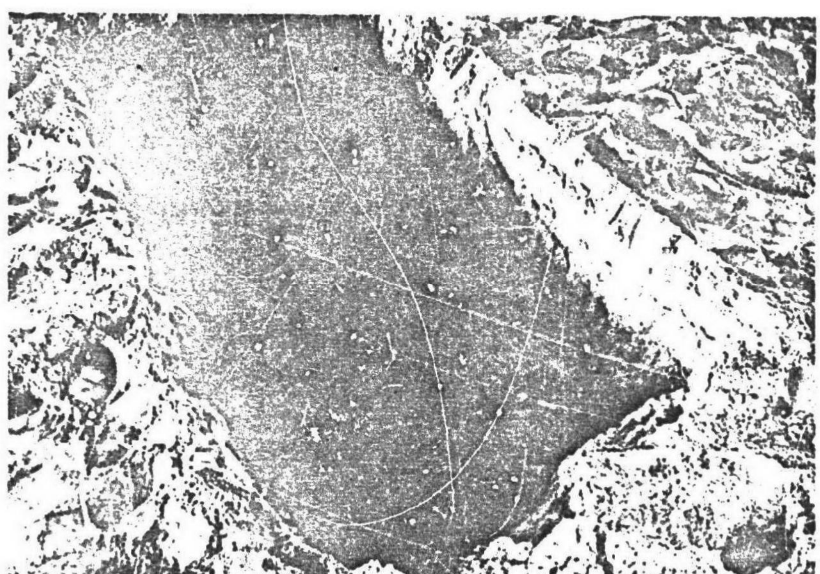


b. Rut pattern of cleated landfill compactor.

Figure 9. Rutting in 18-in. sand protective layer.



a. Membrane in item 3 after 10 passes.



b. Membrane in item 10 after 10 passes.

Figure 10. Membrane in trenches before removal and inspection, test program 2.

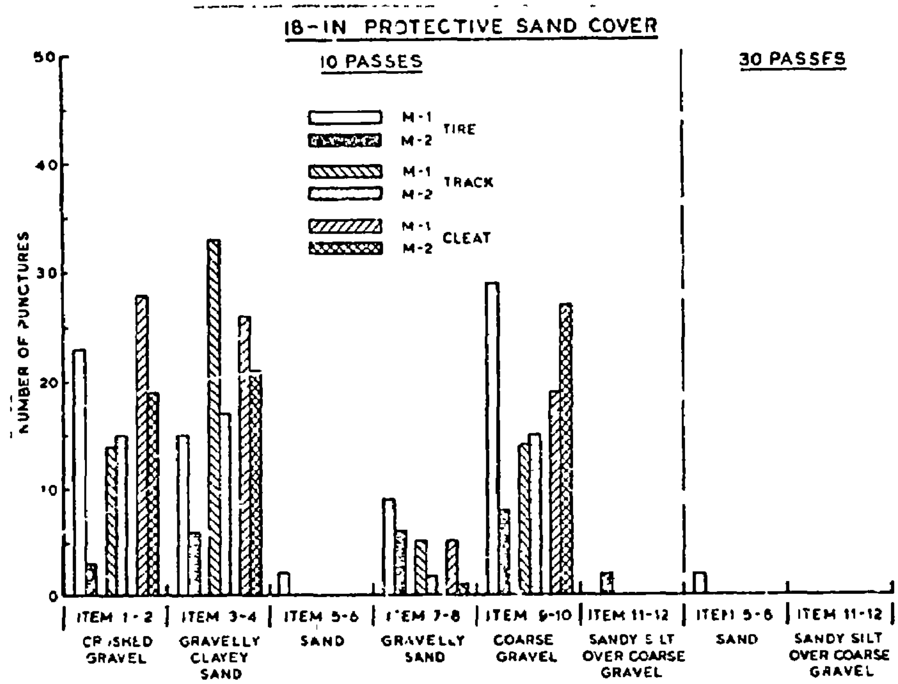
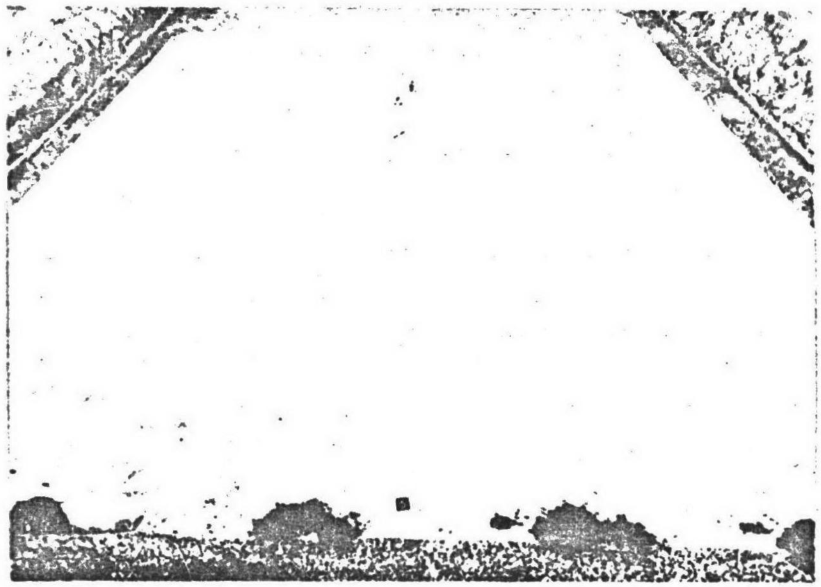


Figure 11. Results of test program 2.

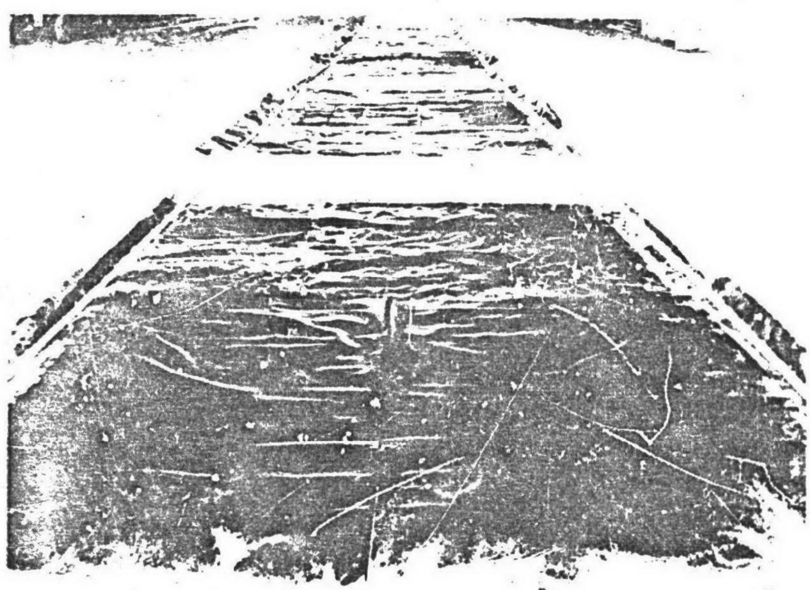
20-ft-long items were subdivided into two 10-ft-long subitems which resulted in four separate test items in each of the six types of subgrade materials. The four test subitems per subgrade material were overlaid with membranes M1, M2, and M4, respectively. A nonwoven fabric material (F1), used as a separation barrier or a bedding material, was placed between the M1 and M2 membranes and the subgrade. Photographs showing both the fabric material and the four membranes in place in test program 3 are shown in Figure 12. Test results for test program 3 after trafficking both the D-7 bulldozer and the pneumatic-tired tractor are presented in Figure 13.

Test Program 4

After completion of test program 3, 6 in. of the protective sand layer and 6 in. of the shoulders were removed from the entire test section. With the protective layer of sand now 12 in. in thickness, another series of traffic tests was performed using the same two vehicles. During this test program, traffic was applied to the various test items by moving the test vehicles to lanes 3 and 4 of the test section. Results from this series of tests are shown in Figure 14.



a. Nonwoven fabric placed on subgrade.



b. Four membranes in place; M3 is the gray membrane.

Figure 12. Fabric and four membranes tested in test programs 3 and 4.

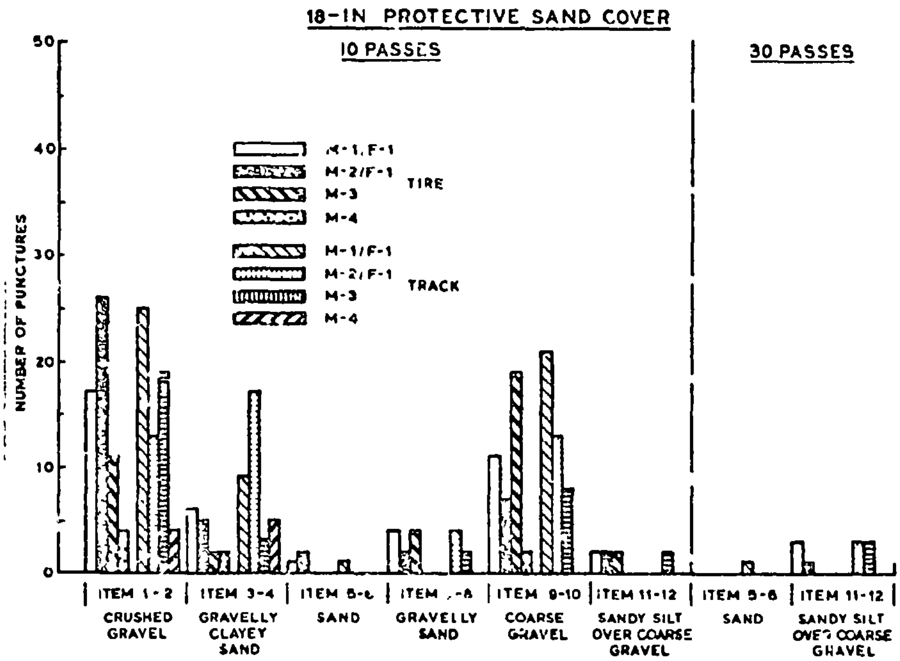


Figure 13. Results of test program 3.

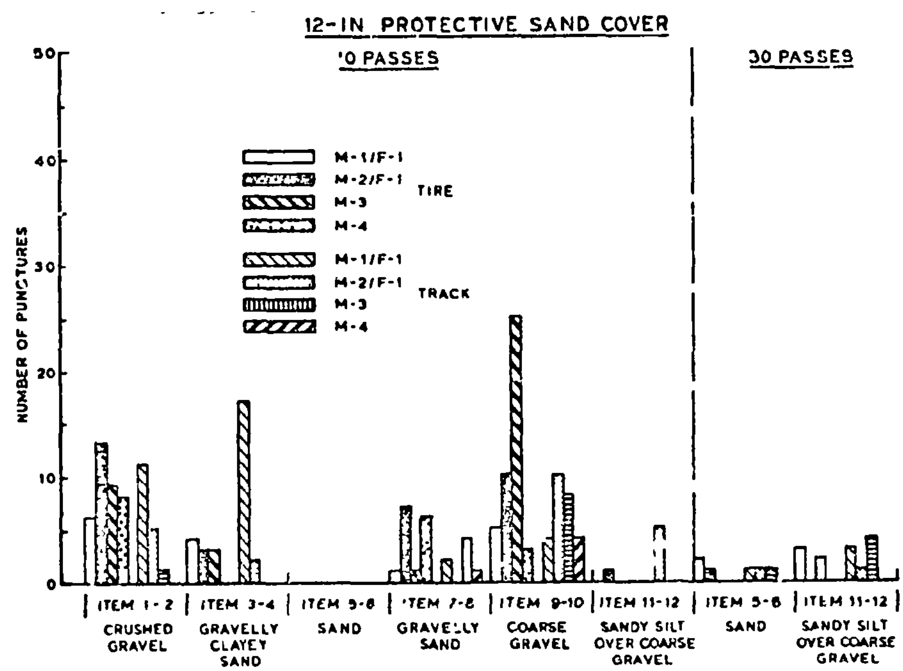


Figure 14. Results of test program 4.

DISCUSSION OF TEST SECTION RESULTS

The large number of punctures that were noted in the four flexible membranes tested during this study was attributed to the selected subgrades used in the construction of the test section. Five of the six subgrades used contained large percentages of sand and gravel with only a small amount of fines. The one remaining soil that was used in the test section was classified as a sandy silt. This fine-grained sandy silt soil was used as a bedding material, and 6 in. were placed over the coarse gravel in items 11 and 12. The purpose of the bedding was to act as a protective barrier between the coarse gravel and the flexible membrane. For comparison purposes, items 9 and 10 contained the same coarse gravel subgrade but were not covered with the sandy silt bedding material. Final results indicated that the bedding material used in items 11 and 12 aided in the protection of the flexible membrane by reducing the number of punctures. During test programs 3 and 4, another type of bedding material was used. A nonwoven polypropylene and nylon-type material (F1) was placed under membranes M1 and M2 during traffic testing. After final inspection of the membranes and a comparison of results from test program 2, a small reduction in the number of punctures was noted when the geotextile was placed under the M2 membrane but not when placed under the M1 membrane.

It was also observed during the inspection of the trafficked membrane that most of the punctures detected occurred from the bottom in an upward direction. Because of these observations, it is assumed that for subgrades containing angular gravel and coarse soil particles, a bedding and/or cushioning material would be required to prevent punctures.

The four membranes investigated during this study received numerous punctures when subjected to the subgrades containing gravel-size material. However, a considerable decrease in the number of punctures was observed when the membranes were trafficked on the items containing the sand and sandy silt subgrades. After completion of some traffic operations on these test items, no punctures were detected in several of the membranes.

It was also observed that the three types of vehicle loadings (tracked, pneumatic-tired, and cleated) used to apply traffic to the membranes produced similar degrees of damage.

SECTION 5

LABORATORY STUDIES (PHASE II)

APPROACH

Following completion of the full-scale tests, it was decided that efforts should be directed toward developing laboratory tests for use in determining bedding and cover requirements for protecting membrane liners from punctures. Three test procedures were selected for laboratory testing of the membranes. These procedures involved the use of the gyratory compactor, a plate-loading device, and a moving pneumatic-tired wheel. In all laboratory tests, selected parameters were adjusted to approximate field conditions by modeling the stress on the membrane.

DEVELOPMENT OF MODEL PARAMETER

The vertical stress on the membrane was selected as the key modeling parameter in the laboratory test. It was felt that this was an important parameter affecting the behavior of the membrane and one that could be translated from the field to the laboratory. The stress on the membrane is basically dictated by the type and magnitude of the load, surface contact pressure, and thickness of the cover over the membrane. In the field tests three types of loadings were applied to the landfill: a pneumatic-tired roller, a tracked tractor, and a steel-wheel cleated roller. Based upon the number of punctures produced in the membrane liner during the field tests, the rubber-tired roller was as severe as or more severe than either of the other two loadings. In addition, the stress under the rubber tire could be more easily estimated; therefore, the rubber-tire loading was chosen as the loading to be simulated in the laboratory tests. The load applied in the field test by the rubber-tired roller had a contact area of 574 sq in. at approximately 32 psi inflation pressure. Using Boussinesq's stress equations for a uniformly loaded circular area, the stress on the membrane can be estimated for each of the cover thicknesses used in the field test. The estimated stress on the membrane for cover thickness of 6, 12, and 18 in. used in the field tests could be reproduced as 30-, 23-, and 16 psi, respectively, in the laboratory tests. However, in the laboratory tests only the stress at 6 in. was used.

DESCRIPTION OF EQUIPMENT AND TESTS

Three types of test equipment were selected for testing the membranes.

One consideration was that the equipment be readily available to most commercial-type laboratories, or be easily obtained, and that it be adaptable for testing membrane materials. The test equipment selected were: a gyratory compactor, a plate-loading machine, and a moving pneumatic-tired wheel. The initial tests were conducted using the plate-loading equipment since this method has been used to test fabrics used as reinforcement in pavements. The gyratory tests were conducted next since they required a small sample and were easy to conduct. The pneumatic-tire tests were conducted last and required the development of test equipment to simulate the effects of a moving tire load. The various types of equipment are described below.

Pneumatic-Tire Load

The model load cart and soil test box are shown in Figure 15. The load cart was moved for tracking purposes by the force generated by an air cylinder on a ram that moved through a maximum travel distance of 24 in. The load wheel was capable of being maneuvered into three different positions in the soil box for traffic test purposes. A total load of 800 lb was positioned on the load cart and the 5.00-5, 4-ply tire inflated to 32 psi. To determine the contact pressure of the loaded wheel, the tire was placed on a hard rigid surface, paint sprayed around the tire surface that interfaced a flat steel plate, and the contact area determined by the tire print produced on the steel plate. The elliptical tire print measured 6.5 by 4 in. and this produced a contact area of approximately 20.7 sq in. A side view of the lower portion of the load tire is shown in the background in Figure 16 along with the soil box in the foreground. The dry weight and water content were determined for the soil used for each of four lifts. Each lift was compacted by hand tamping to produce the density desired. After compaction, the water content and density were determined by using the Troxler Nuclear Densitometer (Figure 17). Following this, the membrane was placed taut over the subgrade and the 1-1/4-in deep collar was C-clamped in position to confine the cover soil. The tracking lanes were 4 in. wide by 24 in. long; however, only the center 14 in. of the lanes were used for comparison purposes (Figure 18). The ends of the tracking lanes were not used for evaluating punctures as the load was shifted in this area when the cart direction was reversed. The cover material was placed, compacted, and leveled in the box collar and on top of the membrane as a cushion (Figure 19). Three tracking lanes (three tests) were available for traffic tests each time the soil box was filled with soil. After three tests were conducted, the top 6 in. of subgrade material was reworked and/or replaced, and recompacted for additional traffic tests. In some tests, the top 1 in. of the subgrade was replaced with a lean clay to protect the membrane from puncture.

Gyratory Shear

The gyratory shear test was conducted in the gyratory testing machine shown in Figure 20. Figure 21 gives a schematic drawing of the gyratory machine. In this test a vertical load is applied by a piston to a material sample contained in a tilted mold. By applying a rotating load to the mold, shear strain is induced through the sample. The combined action of the vertical stress and shear strain is similar to the kneading action of a

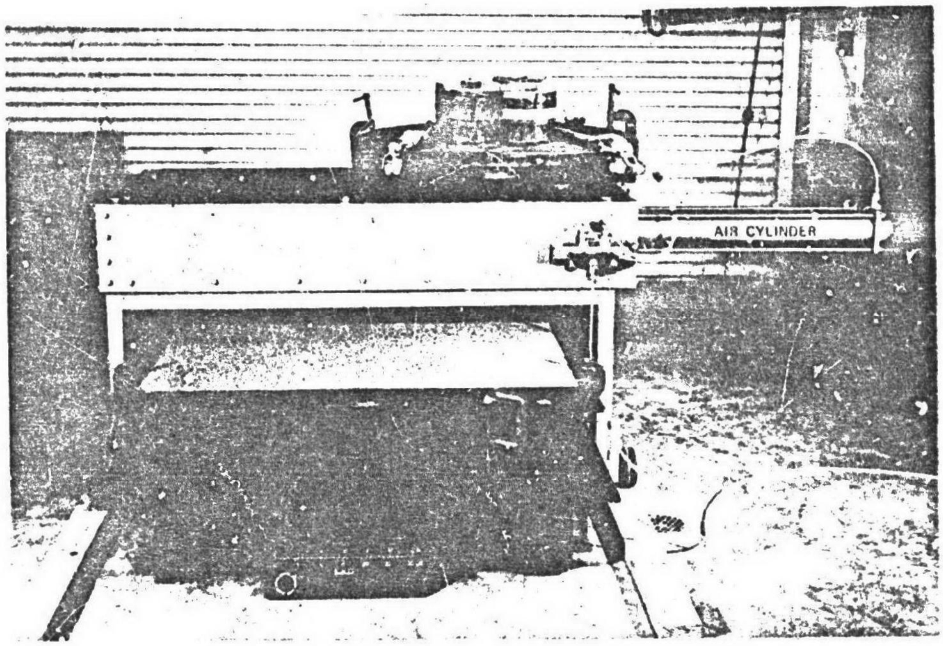


Figure 15. Model load cart and soil box.

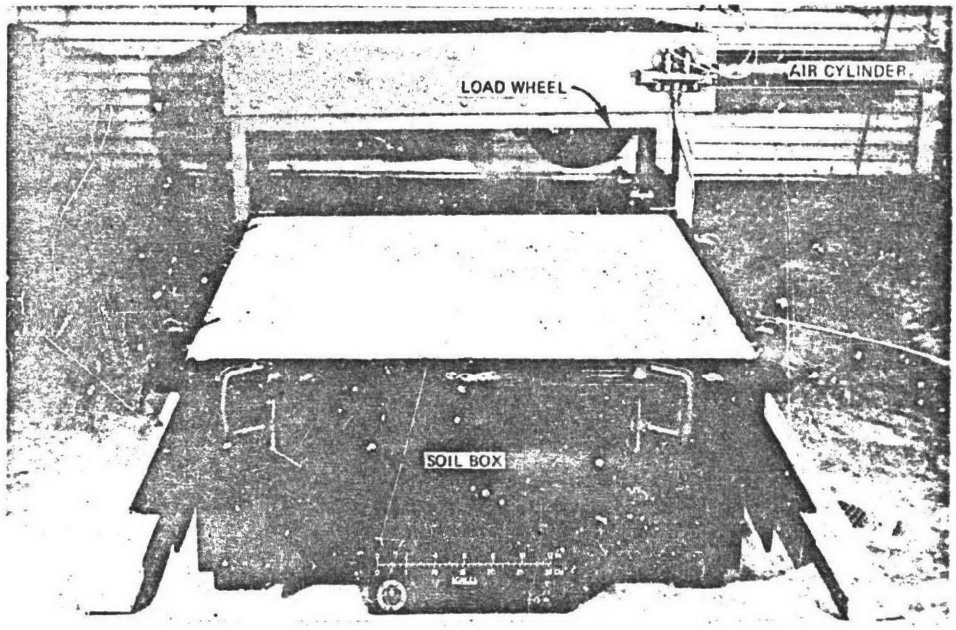


Figure 16. Lower portion of the load wheel in background, soil box in the foreground.

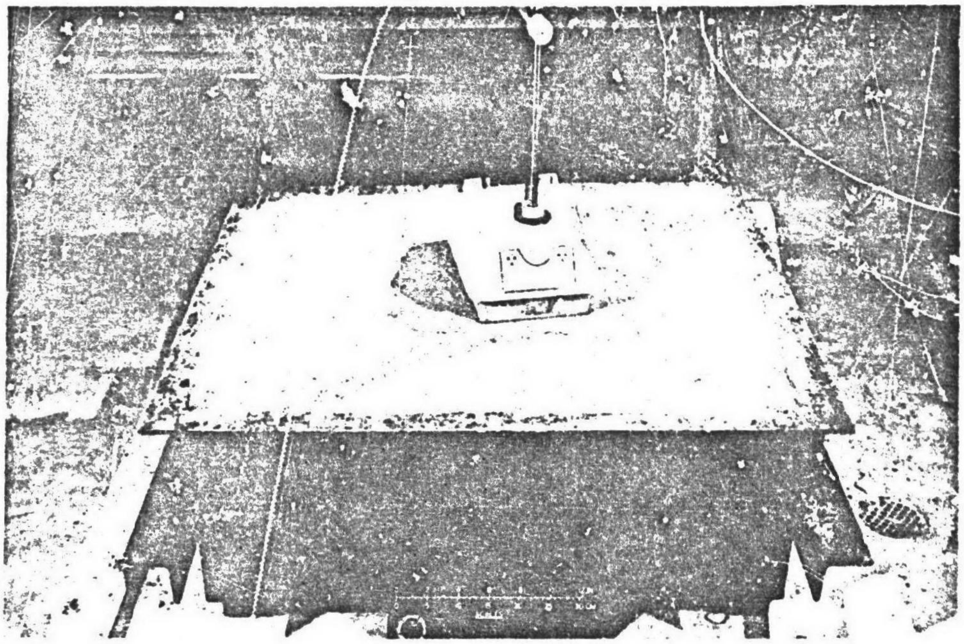


Figure 17. Troxler Nuclear Densitometer used to measure density and water content.

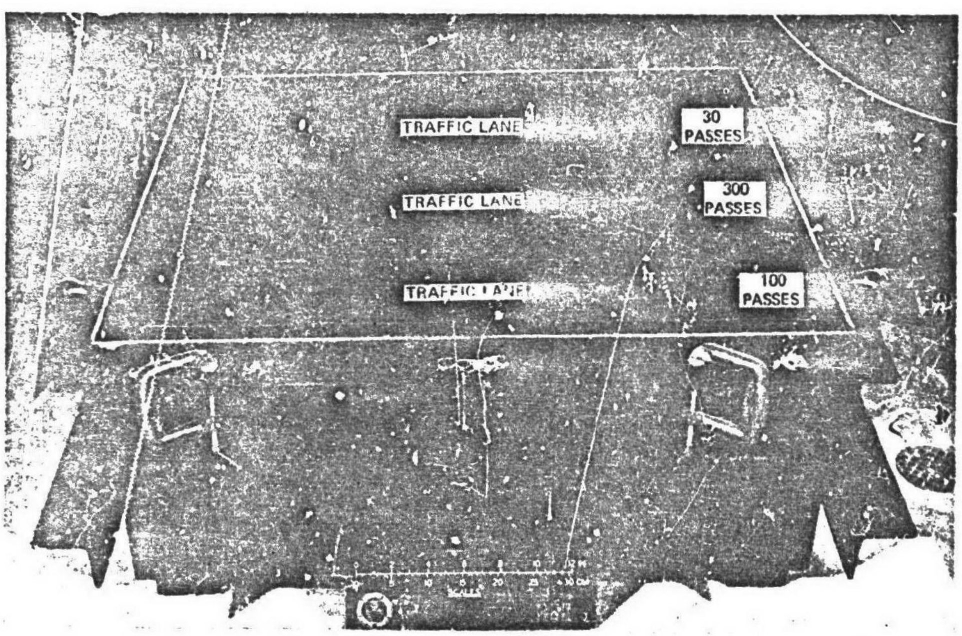


Figure 18. Membrane placed over compacted soil with collar for sand clamped in place and tracking lanes marked.

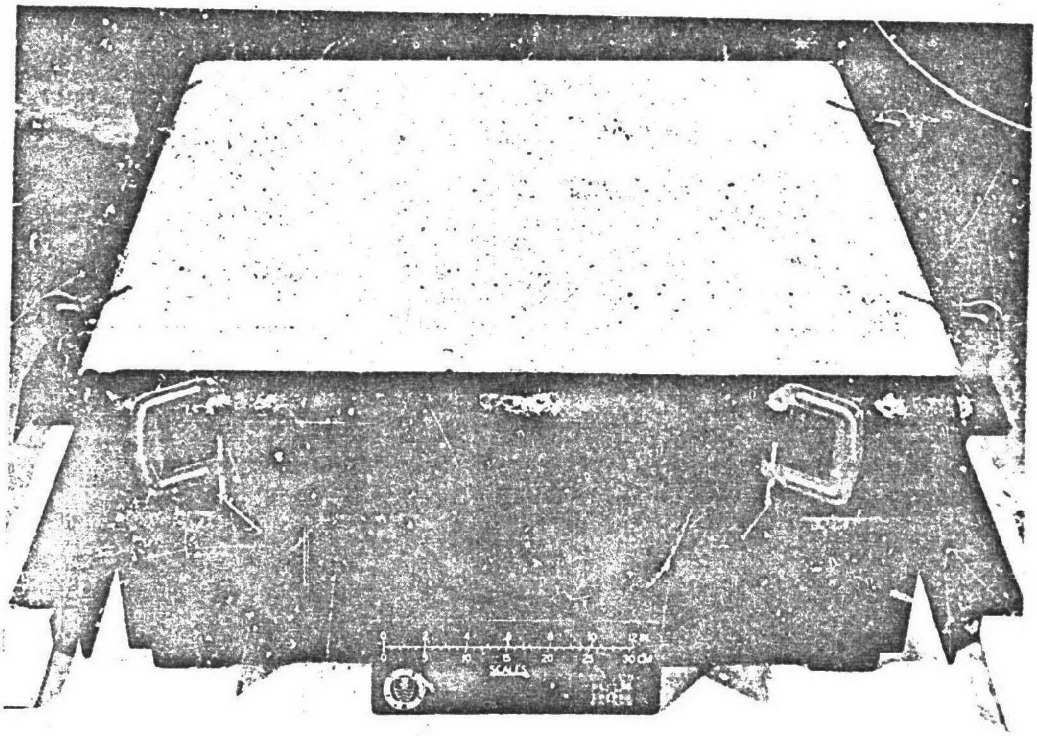


Figure 19. Soil box ready for traffic.

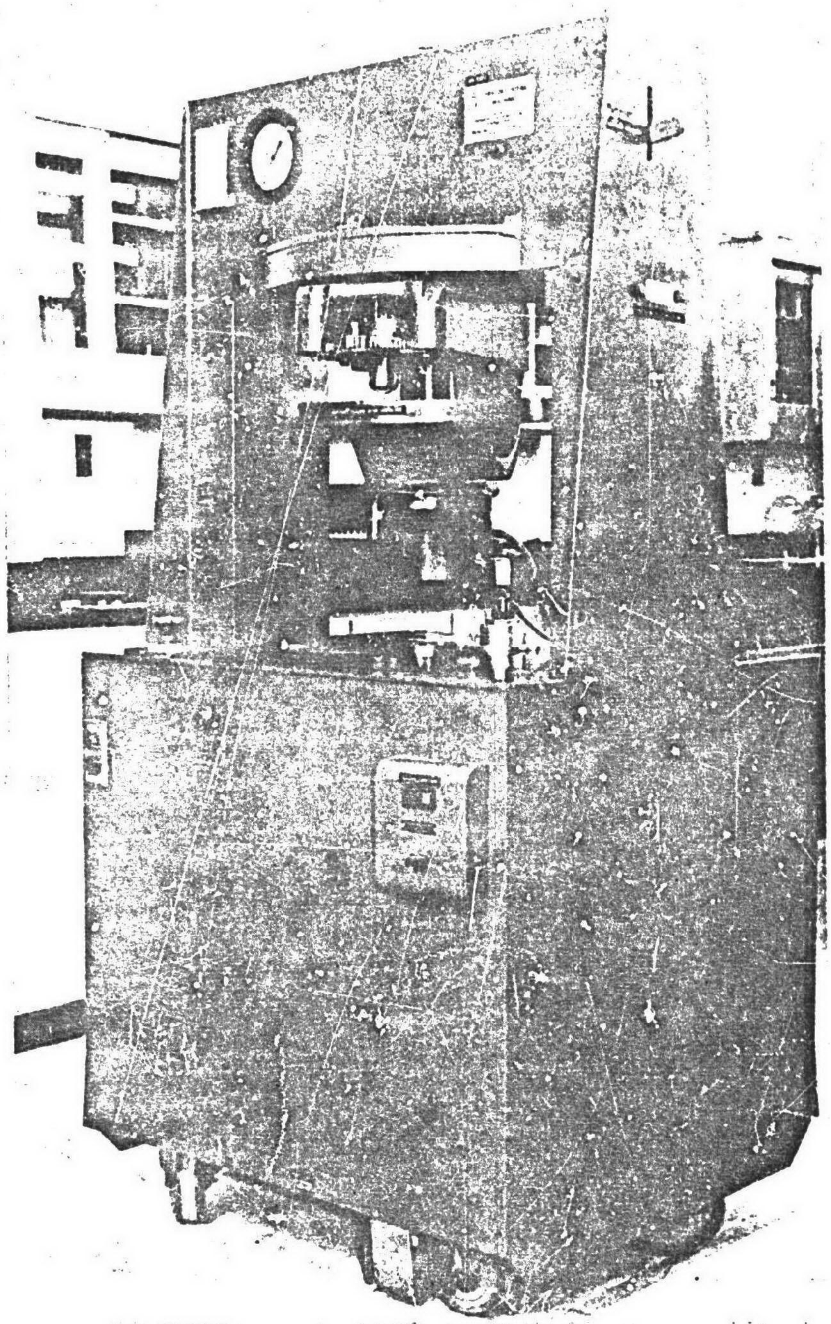


Figure 20. Gyratory compactor.

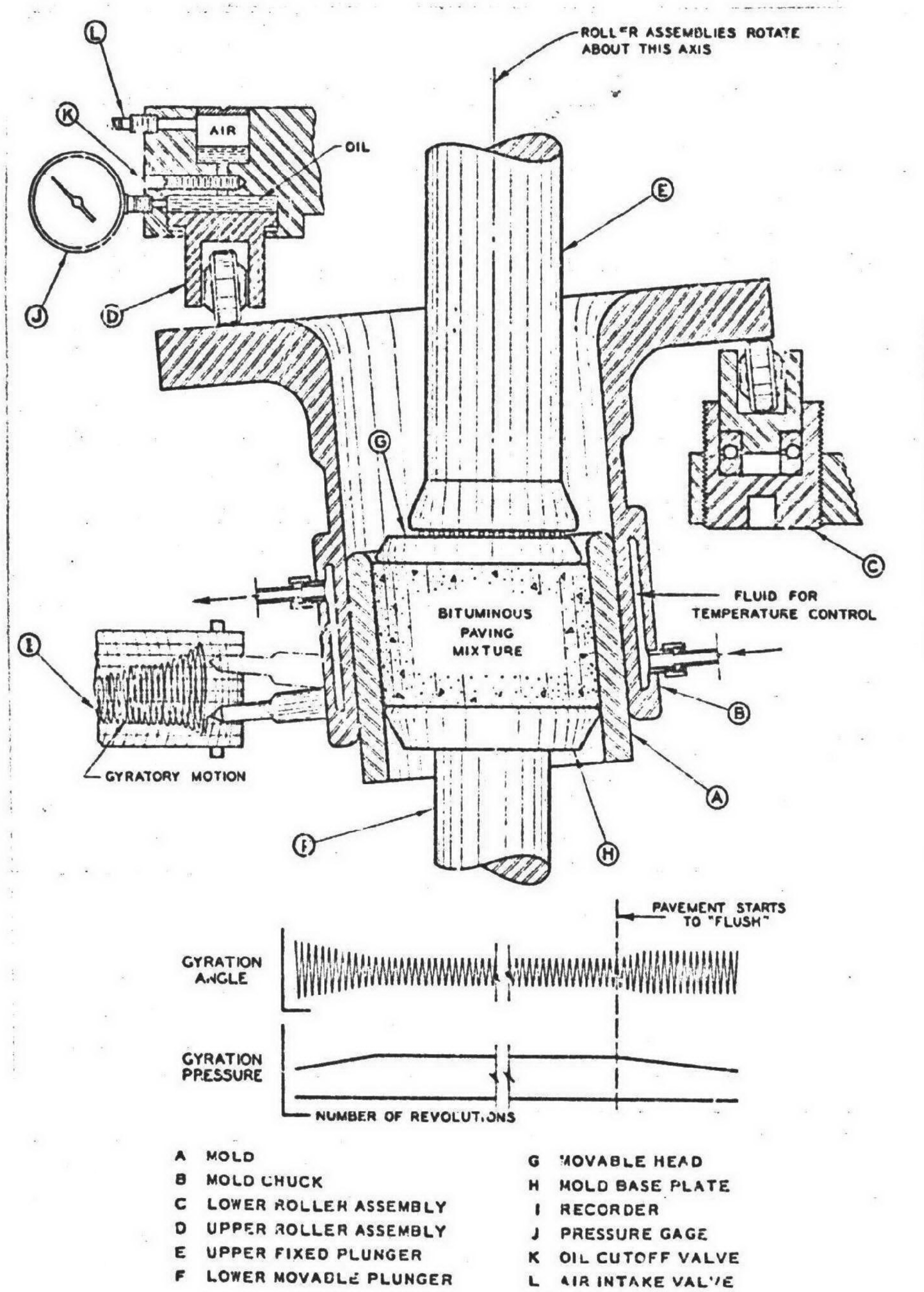


Figure 21. Schematic illustration of gyratory machine.

rolling tire load. During the test, the applied load (pressure), tilt or angle of gyration (usually 1 degree), and number of revolutions are controlled.

Two types of subgrade were used in these tests. One was a crushed limestone similar to that used with the model load cart and in full-scale test section tests. The other subgrade was a 2-in. thick rubber block with a CBR value of 16 percent. The rubber subgrade contained steel barbs at the surface to simulate rocks. The dimensions of the barbs were: 1/4, 1/2, and 3/8 in. high with a conical angle of 60 degrees. The radius of the apex angle of the above three barbs was 1/64 in. Another 1/4-in.-high barb had a 1/32-in. radius at the apex angle; one had a 1/16-in. radius, and the last one was a half sphere with a 1/4-in. radius referred to as smooth. The dimension of a typical barb is given in Figure 22. The test membranes with a sand cover were placed above the subgrades of both types of samples. In some tests 1 in. of the subgrade was replaced with a lean clay as a bedding to protect the membrane from puncture.

<u>Plate Loading</u>

The plate-loading tests were performed using the Instron equipment (Figure 23). The load was applied to an 11-1/2-in.-diam steel plate, 1 in. thick. A load of 3324 lb was applied cyclically to the 103.9-sq-in. plate to achieve 32 psi pressure to the sand-covered membrane. The soil box 2 ft by 2 ft by 1-1/2 ft deep (Figure 24) was filled with gravelly sand and compacted in four layers. Each layer of soil was weighed and compacted in a known volume to produce the desired density. The water content was controlled prior to compaction and the density and water content measured with the Troxler Nuclear Densitometer (Figure 17) after compaction. The membrane and collar (2-1/2 in. deep to confine the concrete sand) were clamped in place (Figure 25) followed by the addition of the concrete sand which was tamped and leveled (Figure 26).

A 3324-lb cyclic load was applied at a rate of 10-12 cycles per minute to a maximum of 1000 cycles. After a varied number of cycles had been applied (300, 400, or 500 cycles), the membrane was removed, inspected, the punctures marked. The membrane was then replaced as nearly as possible in its original test position with the collar and sand cover replaced and the test continued. The subgrade after these cyclic loads were applied was not disturbed or replaced. As additional tests were conducted, only the top 6 in. of the subgrade was scarified and recompacted.

<u>Standard Tests</u>

Standard tests for physical properties of the membranes were conducted using test equipment as required by the American Society for Testing and Materials (ASTM) D 751. These tests were conducted to determine thickness, weight, bursting strength, tensile strength and percent elongation before and after weathering and hydrostatic resistance before and after abrasion. Results of these tests are shown in Table 2.

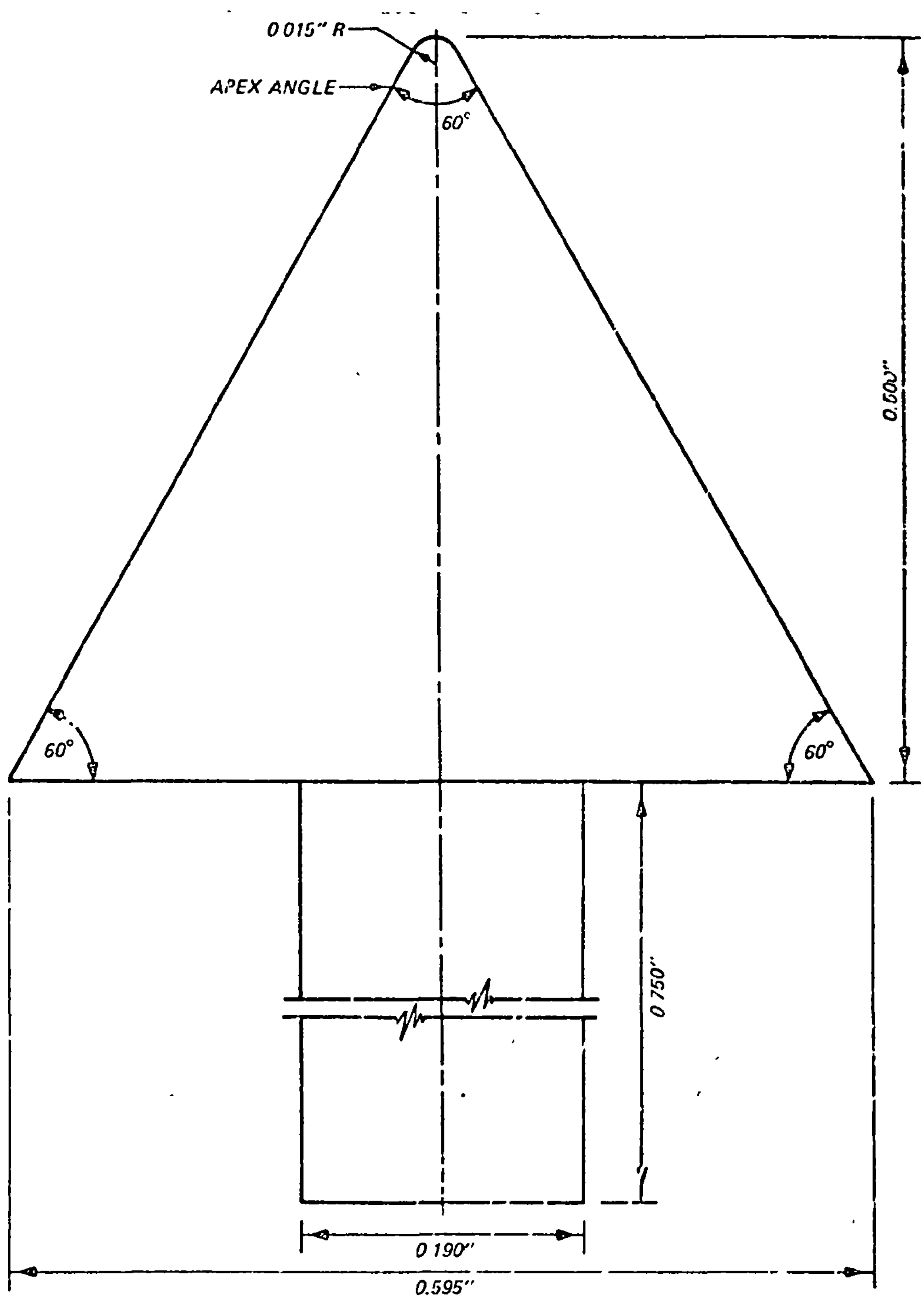


Figure 22. Dimensions of a typical barb.

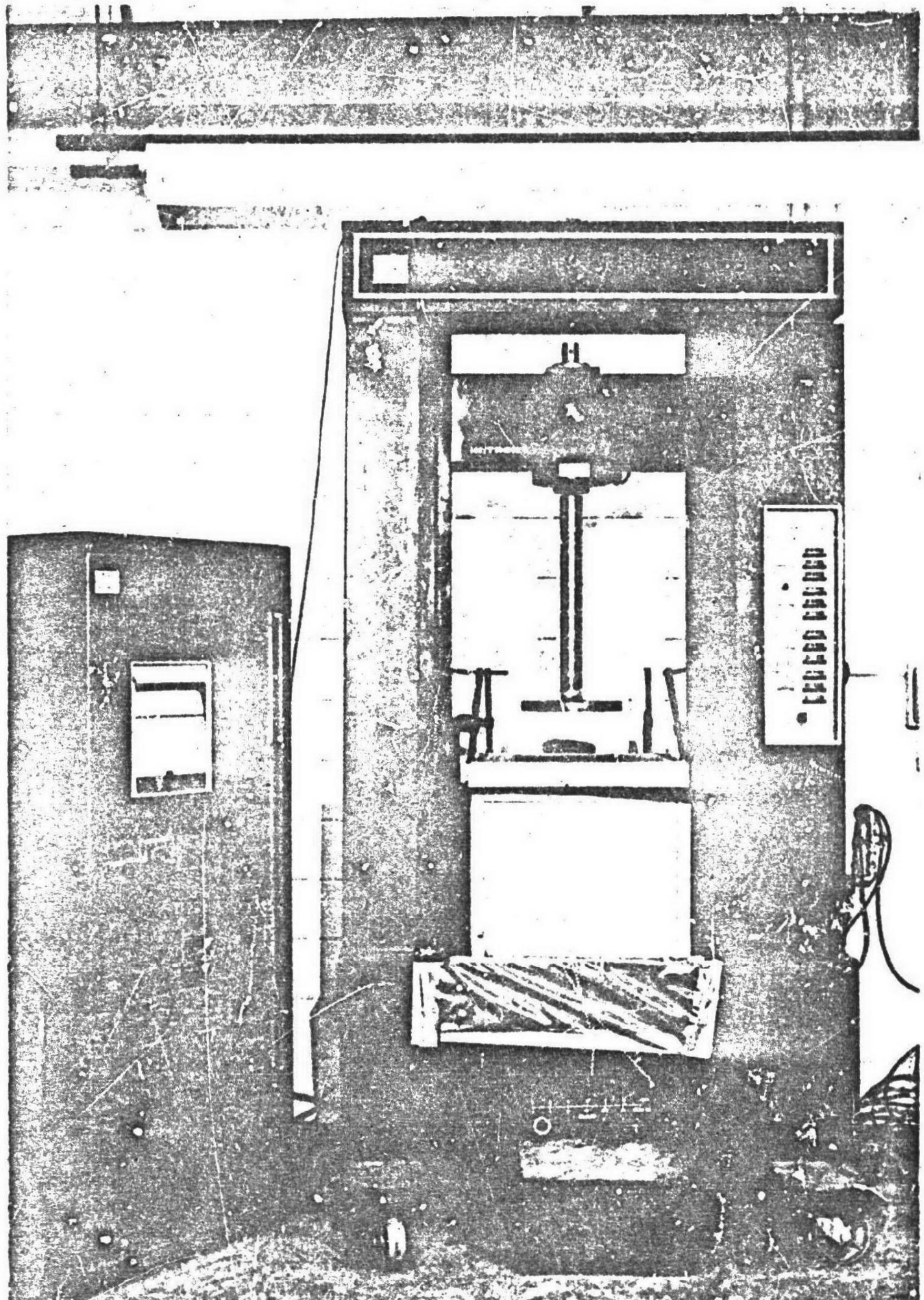


Figure 23. Instron machine, recorder, and soil membrane test setup.

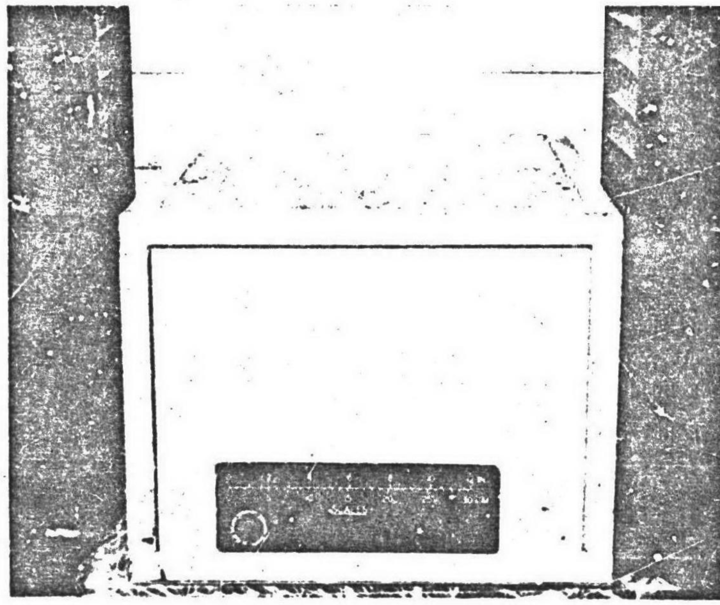


Figure 24. Soil box filled with compacted gravelly sand.

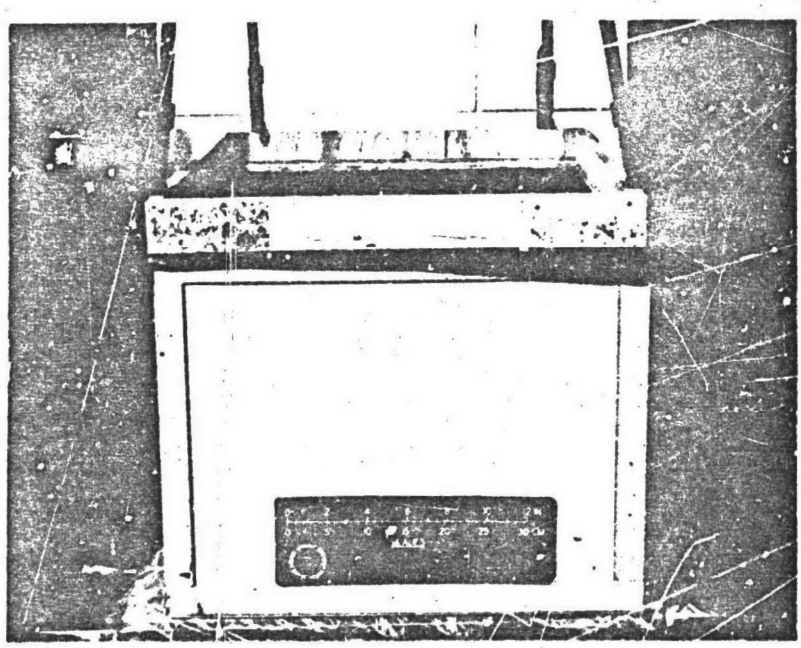


Figure 25. Membrane and 2-1/2-in.-deep collar clamped in position for sand cover.

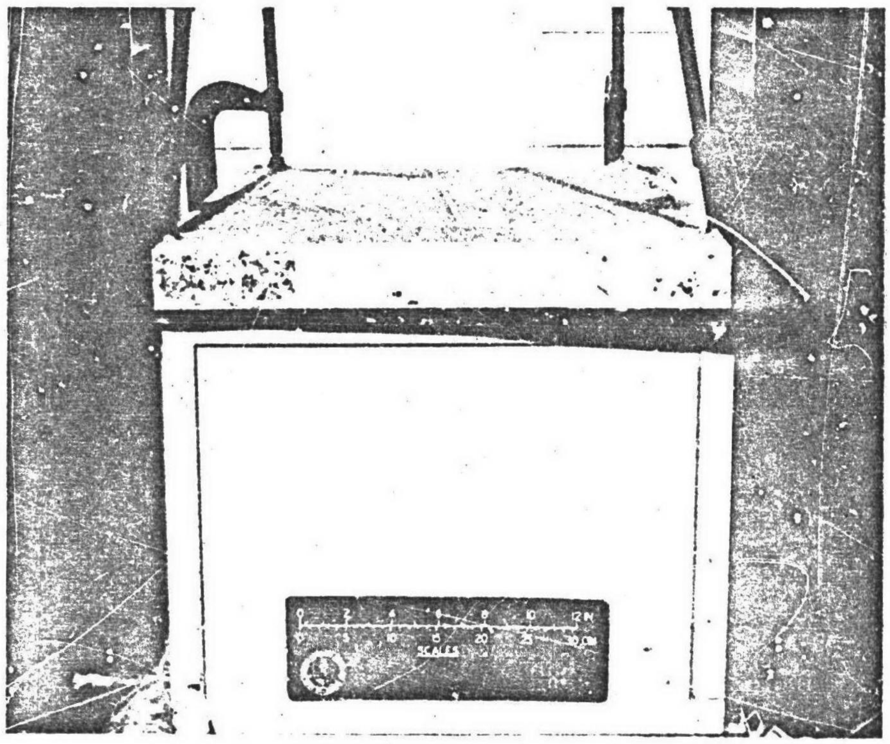


Figure 26. Cover sand compacted and leveled for test.

TABLE 2. PHYSICAL PROPERTIES OF MEMBRANE LINER MATERIALS*

Test Conducted	Test Results		
	M2	M3	M4
Thickness, mils	19.5	29.6	37.2
Mass, oz/sq yd	18.1	34.0	33.5
Tensile strength at fabric break, lb - warp	N/A†	N/A	286.2
fill	N/A	N/A	306.4
Elongation at fabric break, percent - warp	N/A	N/A	20.7
fill	N/A	N/A	25.6
Tensile strength at polymer break, lb	123.9	73.0	NOT TESTED
Elongation at polymer break, percent	259.3	363.2	NOT TESTED
Burst strength, lb	102.5	69.3	348.4
Hydrostatic resistance, ml/24 hr	0	0	0
Hydrostatic resistance after 5000 cycles of abrasion (ASTM D 1175), ml/24 hr	0-947††	0	0
Tensile strength at fabric break,** lb - warp	N/A	N/A	271.2
fill	N/A	N/A	292.2
Elongation at fabric break,** percent - warp	N/A	N/A	19.2
fill	N/A	N/A	24.6
Tensile strength at polymer break,** lb	129.2	85.4	NOT TESTED
Elongation at polymer break,** percent	234.2	364.0	NOT TESTED

* All properties determined in accordance with ASTM D 751 with the exception of hydrostatic resistance after 5000 cycles of abrasion (ASTM D 1175).
** After accelerated weathering for 160 hours.
† 1 of 3 specimens leaked 947 ml.
†† N/A = not applicable.

DESCRIPTION OF MATERIALS

Soils

The soils selected for use in testing the membrane liners were similar to those used in the initial full-scale tests. Two gravelly sands (SP) were used. One gravelly sand commonly found in concrete mixes was used as a cover material to protect the membrane liner during tests. This material was sieved and only that portion passing the 3/8-in. sieve was utilized for test purposes. The other gravelly sand was used as a subgrade material. The gradation curves for these soils are shown in Figure 27.

A lean clay (CL) was used in several tests to serve as a bedding material placed between the subgrade and the liner. The liquid limit of the clay was 31 and the plastic limit was 23. The gradation curve for the lean clay is shown on Figure 27. A 60 percent compaction effort was selected for these tests because this approximates the density normally achieved during construction of a hazardous landfill.

A crushed limestone material was also used as a subgrade material. This material had approximately 85 percent of the aggregate between the 3/4- and 3/8-in. sieve. The crushed limestone gradation curve is shown in Figure 27.

Soil data for the wheel load tests are shown in Table 3.

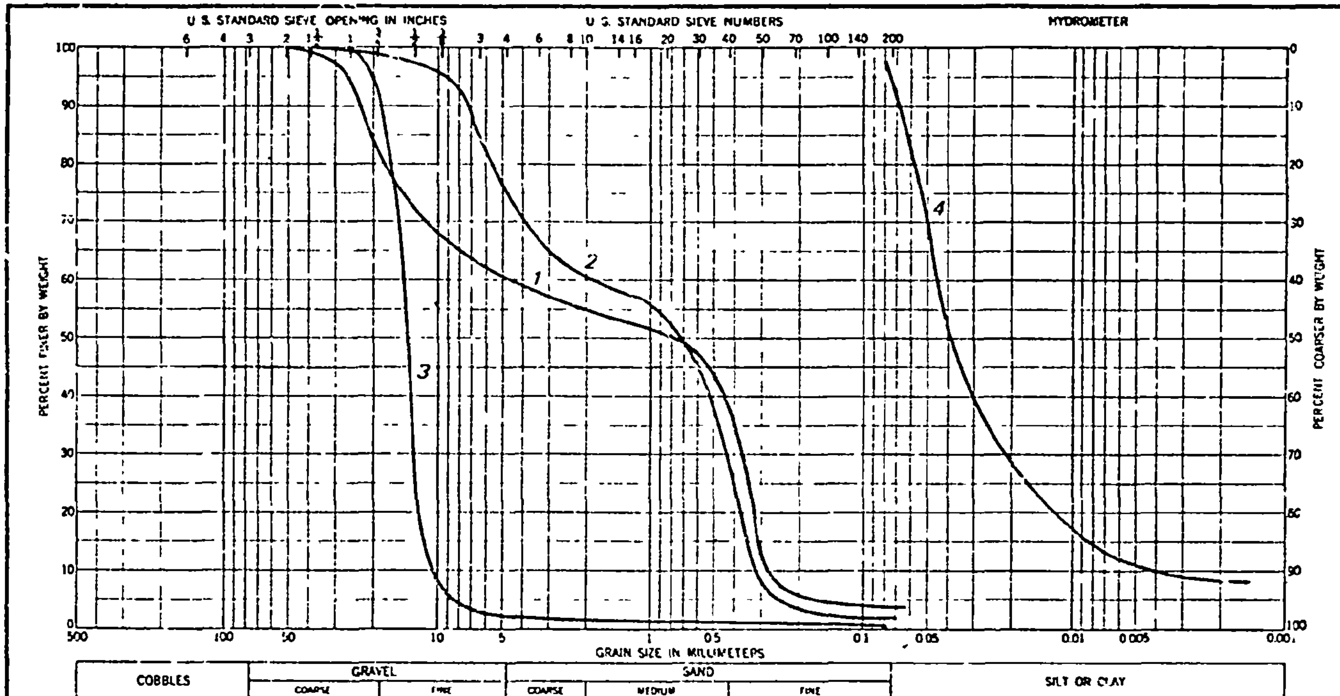
Membranes

Three of the four membranes tested during the initial field test of this investigation as well as a new fabric used as bedding material, were used in the laboratory tests and these materials are described as follows:

Designation	Polymer	Type Compound	Nominal Thickness mils	Thread Count
M2*	PVC	Thermoplastic	20	N/A
M3*	CPE	Thermoplastic	30	N/A
M4*	Chorosulfated polyethylene-reinforced (CSPE-R)	Thermoplastic	36	10x10
B1	Spunbonded continuous polyester filament, 7.7 oz/sq yd	N/A	81	N/A

* Physical test properties are given in Table 2.
N/A - Not applicable.

The M1, elasticized polyolefin (3110) membrane used during the initial full-scale tests was not used in the laboratory tests because commercial manufacturers discontinued production and processing of the material.



Sample No	Elev or Depth	Classification	Nat w %	LL	PL	PI
1		GRAVELLY SAND, SP, RED				
2		GRAVELLY SAND, SP, BROWN				
3		CRUSHED LIMESTONE				
4		LEAN CLAY				

Project EPA LINER STUDY

Area

Boring No.

Date

GRADATION CURVES

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Figure 27. Classification and gradation of gravelly sand subgrade

TABLE 3. SOIL DATA FOR WHEEL LOAD TESTS

Test No.	Soil Type	Soil Use	Oven Water Content percent	Troxler* Nuclear Test: Water Content percent	Troxler* Nuclear Test: Wet Density kilonewtons/cu m	(pcf)
W1	Concrete sand	Cover	3.5	--	--	--
	Gravelly sand	Subgrade	5.9	7.0	20.7	(131.5)
W2	Concrete sand	Cover	3.2	--	--	--
	Gravelly sand	Subgrade	--	6.8	21.0	(133.5)
W3	Concrete sand	Cover	3.7	--	--	--
	Gravelly sand	Subgrade	--	6.0	21.2	(135.0)
W4	Concrete sand	Cover	3.5	--	--	--
	Gravelly sand	Subgrade	--	6.4	20.8	(132.4)
W5	Concrete sand	Cover	4.9	--	--	--
	Gravelly sand	Subgrade	--	6.4	20.8	(132.4)
W6	Concrete sand	Cover	3.7	--	--	--
	Clay (loess)	Bedding	19.4	--	--	--
	Gravelly sand	Subgrade	--	6.5	21.0	(134.0)
W7	Concrete sand	Cover	4.6	--	--	--
	Gravelly sand	Subgrade	--	6.0	20.8	(132.1)
W8	Concrete sand	Cover	4.4	--	--	--
	Gravelly sand	Subgrade	--	6.0	20.8	(132.1)
W9	Concrete sand	Cover	4.4	--	--	--
	Gravelly sand	Subgrade	--	5.9	20.7	(132.0)
W10	Concrete sand	Cover	4.8	--	--	--
	Gravelly sand	Subgrade	--	6.2	20.8	(132.6)
W11	Concrete sand	Cover	4.2	--	--	--
	Gravelly sand	Subgrade	--	6.2	20.8	(132.6)
W12	Concrete sand	Cover	4.4	--	--	--
	Gravelly sand	Subgrade	--	6.1	20.8	(132.7)
W13	Concrete sand	Cover	4.5	--	--	--
	Gravelly sand	Subgrade	--	6.1	20.8	(132.7)

(Continued)

* Device used to expedite water content and density determinations.

TABLE 3. (CONCLUDED)

Test No.	Soil Type	Soil Use	Oven Water Content percent	Troxler Nuclear Test: Water Content percent	Troxler Nuclear Test: Wet Density Kilonewtons/cu (pcf)	
W14	Concrete sand	Cover	3.9	--	--	--
	Clay (loess)	Bedding	18.3	--	--	--
	Gravelly sand	Subgrade	6.0	5.3	20.8	(132.7)
W15	Concrete sand	Cover	3.7	--	--	--
	Clay (loess)	Bedding	19.2	--	--	--
	Gravelly sand	Subgrade	--	5.7	20.9	(133.3)
W16	Concrete sand	Cover	3.5	--	--	--
	Clay (loess)	Bedding	18.0	--	--	--
	Gravelly sand	Subgrade	5.5	6.1	21.0	(133.8)
W17	Concrete sand	Cover	3.5	--	--	--
	Limestone	Subgrade	--	--	15.7	(100.0)
W18	Concrete sand	Cover	3.5	--	--	--
	Clay (loess)	Bedding	23.2	--	--	--
	Limestone	Subgrade	--	--	15.7	(100.0)
W19	Concrete sand	Cover	3.5	--	--	--
	Clay (loess)	Bedding	18.1	--	--	--
	Limestone	Subgrade	--	--	15.7	(100.0)
W20	Clay (loess)	Bedding	18.1	--	--	--
	Limestone	Subgrade	--	--	15.7	(100.0)

FAILURE CRITERIA

The criteria used to determine liner failure consisted of the visual inspection for pinholes in the liner caused by tests and then the examination of the pinholes in accordance with ASTM Test Method D 3083. When light used in accordance with the ASTM Test Method was observed to pass through a pinhole, this was identified as failure of the liner.

DATA COLLECTED

The number of holes were recorded for selected levels of load repetitions. The general condition of the membrane was noted, such as scuffed or wrinkled, and photographs were made to illustrate these conditions. The number of loading cycles, passes, revolutions, plus the total pounds applied, and tire pressure (in pounds per square inch) also were recorded. The density and water content of the subgrade material along with the CBR of the clay bedding material were controlled. In the pneumatic-tire model test, the rut depth, soil upheaval, and cover over the membrane also were recorded at regular intervals.

SAMPLE SIZES TESTED

To check for potential membrane failures (pinholes), the full-sized gyratory sample was used. These were 6-in.-diam samples with areas of 28 sq in. each. In the pneumatic-tire load tests, the sample size was 4 in. wide (tire width) by 14 in. long, or 56 sq in. In the plate-loading test, the area under the 11-1/2-in.-diam disc was used or an area of 104 sq in. In the field test, the sample size was 24 in. (tire width) by 30 in. long, or 720 sq in. If comparison of the number of punctures from the various test methods is desired, it can be done by sample size according to the following conversion chart which presents the ratios of the sample areas:

	Gyratory	Model Tire	Load Bearing	Field Tire
Gyratory	--	x2	x3.7	x25.7
Model Tire	x0.5	--	x1.9	x12.8
Load Bearing	x0.27	x0.54	--	x6.8
Field Tire	x0.04	x0.08	x0.14	--

TEST RESULTS

Pneumatic-Tire Load

After the tire had traversed back and forth in the same path for the desired number of passes, the rut depth, shoulder upheaval, and the depth of sand over the membrane were measured. When the tire had tracked the test specimen in three separate locations, the collar and sand were removed and the membrane inspected for punctures. The test number, membrane designator, passes, rut depth, membrane depth below rut, number of holes in the membrane, and subgrade deformation are given in Table 4. Figure 28 shows typical ruts in the sand after 2 and 10 passes. The soil subgrade was controlled prior to each test and a summary of this data is presented in Table 3.

A minimum of three tests per membrane was performed on each controlled soil subgrade and cover material to determine reproducibility and reliability of test results. The results for test numbers W2, W3, and W4 for M2 membrane; W7, W8, W9, and W13 for M3 membrane; and W10, W11, and W12 for M4 membrane are averaged and summarized in Table 5. These test results indicate that punctures occurred in some of the membranes from the subgrade rocks and the membrane needed some bedding or protection from the subgrade. Hence, tests W14, W15, and W16 were repeats of the W2, W3, and W4 tests for M2 membrane, except the top 1 in. of the gravelly sand subgrade was replaced with a lean clay (loess). The clay was used as a bedding material to prevent the gravelly subgrade from puncturing the membrane during traffic tests, and the average results of these tests are shown in Table 5 for comparison with the average data on M2 in tests W2, W3, and W4. The loess reduced the number of punctures in the liner from 9 to 0 at 300 passes, and allowed an average of 1.66 punctures in three tests at 1000 passes.

Test W17 was conducted first on a crushed limestone base that readily produced holes in the membrane. Then the test was repeated using 1 in. of lean clay (loess) as the top layer of the subgrade (Table 4). The 1 in. of lean clay was used above the limestone in tests W18 and W19. Where the clay was used, no holes were observed at 150 passes; whereas, in test W17, 36 holes were recorded at 100 passes without the clay. The clay in test W18 had 22.2 percent water and a CBR of 1.8 that permitted excessive rutting, and after 300 passes, 2 holes were observed in the M2 membrane (Figure 29 and Table 4). Test W19 was conducted similar to test W16 except the water content to the clay was 18.1 and the CBR was 21. The higher CBR prevented excessive rutting and no punctures were observed in the M2 membrane after 300 passes as compared to 36 punctures recorded at 100 passes in test W17 without the clay bedding. Test W20 was conducted on the same subgrade as test W19 (not reworked) with no sand cover on the membrane (the tire was in direct contact with the M2 membrane), but only two tracking lanes were used and no punctures were observed after 500 passes.

Test W5 was conducted on the same subgrade (not reworked) as test W4. The geotextile was placed on the top of the subgrade to see how effective it was as a bedding material to prevent punctures in the membranes. The membrane was placed directly on top of the geotextile and 1-1/4 in. of protective sand was placed on top of the membrane. The geotextile reduced the number of holes at 100 and 300 passes from 3 to 1 and 8 to 6, respectively (Table 4). The lean clay loess used in test W6 produced the first laboratory test results that indicated lean clay used as bedding over coarse subgrade composed of angular particles will reduce the number of punctures or prevent pneumatic-tire traffic from producing punctures in a membrane liner.

TABLE 4. TRAFFIC DATA FOR PNEUMATIC-WHEEL LOAD TESTS

Test No.	Membrane	Number of Passes	Rut Depth* cm	Rut Depth* (in.)	Membrane Depth Below Rut cm	Membrane Depth Below Rut (in.)	Subgrade Deformation cm	Subgrade Deformation (in.)	No. of Punctures	Equivalent Number of Passes Per Square Yard	Remarks
W1	M2	10	--	--	0.63	(0.25)	--	--	0	0	
		30	3.18	(1.25)	0.46	(0.18)	--	--	0	0	
		100	3.81	(1.50)	0.63	(0.25)	--	--	4	92	1 puncture from top down
W2	M2	30	3.18	(1.25)	0.79	(0.31)	--	--	0	0	
		100	3.18	(1.25)	0.63	(0.25)	--	--	0	0	
		300	3.96	(1.56)	0.63	(0.25)	--	--	10	231	
W3	M2	30	2.39	(0.94)	0.79	(0.31)	--	--	0	0	
		100	2.84	(1.12)	0.63	(0.25)	--	--	1	23	
		300	3.33	(1.31)	0.63	(0.25)	--	--	9	208	
W4	M2	30	2.69	(1.06)	0.79	(0.31)	--	--	0	0	
		100	2.99	(1.18)	0.46	(0.18)	--	--	3	69	
		300	2.69	(1.06)	0.46	(0.18)	--	--	8	185	3 or 4 holes from top down
W5	M2	100	3.18	(1.25)	0.63	(0.25)	--	--	1	23	Undisturbed subgrade of test W4 used; geotextile under membrane
		300	3.18	(1.25)	0.63	(0.25)	--	--	6	139	
		500	2.99	(1.18)	0.46	(0.18)	--	--	2	46	
W6	M2	100	3.48	(1.37)	0.63	(0.25)	--	--	0	0	Top 2.5 cm (1 in.) of subgrade material was lean clay
		300	2.54	(1.00)	0.46	(0.18)	--	--	0	0	
		500	3.18	(1.25)	0.63	(0.25)	--	--	0	0	
W7	M3	30	2.84	(1.12)	0.90	(0.37)	--	--	0	0	
		100	2.99	(1.18)	0.46	(0.18)	--	--	1	23	
		300	3.18	(1.25)	0.63	(0.25)	--	--	5	116	
W8	M3	30	2.06	(0.81)	0.79	(0.31)	--	--	0	0	
		100	2.69	(1.06)	0.63	(0.25)	--	--	0	0	
		300	2.84	(1.12)	0.46	(0.18)	--	--	7	16[illegible]	
W9	M3	30	2.39	(0.94)	0.79	(0.31)	--	--	0	0	
		100	2.39	(0.94)	0.63	(0.25)	--	--	1	23	
		300	3.48	(1.37)	0.46	(0.18)	--	--	1	23	
W10	M4	30	2.69	(1.06)	0.79	(0.31)	--	--	0	0	
		100	2.84	(1.12)	0.46	(0.18)	--	--	0	0	
		300	2.54	(1.00)	0.46	(0.18)	--	--	0	0	
W11	M4	30	2.21	(0.87)	0.79	(0.31)	--	--	0	0	
		100	2.54	(1.00)	0.63	(0.25)	--	--	0	0	
		300	2.54	(1.00)	0.46	(0.18)	--	--	0	0	
W12	M4	30	2.84	(1.12)	0.63	(0.25)	--	--	0	0	
		100	2.54	(1.00)	0.63	(0.25)	--	--	0	0	
		300	3.18	(1.25)	0.63	(0.25)	--	--	1	23	

(Continued)

* Depth from original surface to bottom of rut.

TABLE 4. (CONCLUDED)

Test No.	Membrane	Number of Passes	Rut Depth cm	(in.)	Membrane Depth Below Rut cm	(in.)	Subgrade Deformation cm	(in.)	No. of Punctures	Equivalent Number of Passes Per Square Yard	Remarks
W13	M3	30	1.57	(0.62)	0.63	(0.25)	--	--	0	0	
		100	3.18	(1.25)	0.46	(0.18)	--	--	1	23	
		300	2.54	(1.00)	0.63	(0.25)	--	--	11	254	
W14	M2	300	3.4[illegible]	(1.37)	0.46	(0.18)	1.27	(0.50)	0	0	Clay bedding
		500	3.66	(1.44)	0.63	(0.25)	0.63	(0.25)	2	46	
		1000	3.18	(1.25)	0.46	(0.18)	0.90	(0.37)	3	69	
W15	M2	300	2.69	(1.06)	0.46	(0.18)	0.63	(0.25)	0	0	Clay bedding
		500	2.96	([illegible].56)	0.46	(0.18)	0.79	(0.31)	0	0	Membrane wrinkled in ruts
		1000	4.1[illegible]	(1.63)	0.79	(0.31)	1.27	(0.50)	0	0	
W16	M2	300	3.96	(1.56)	0.46	(0.18)	1.57	(0.62)	0	0	Clay bedding
		500	3.81	(1.50)	0.46	(0.18)	1.27	(0.50)	0	0	Rocks 0.79 cm (0.31 in.), 1.1 cm (0.44 in.), and 0.63 cm (0.25 in.) below loess at 300, 500, and 1000 passes, respectively
		1000	3.81	(1.50)	0.46	(0.18)	1.90	(0.75)	2	46	
W17	M2	10	2.84	(1.12)	1.27	(0.50)	--	--	3	69	
		30	2.54	(1.00)	0.63	(0.25)	1.57	(0.62)	19	439	
		100	4.75	(1.87)	0.63	(0.25)	1.90	(0.75)	30	837	
W18	M2	50	4.45	(1.75)	1.57	(0.62)	5.08	(2.00)	0	0	
		150	5.87	(2.31)	1.42	(0.56)	7.62	(3.00)	0	0	Clay too wet
		300	6.35	(2.50)	1.27	(0.50)	8.89	(3.50)	2	46	
W19	M2	50	3.18	(1.25)	0.63	(0.25)	--	--	0	0	
		150	3.18	(1.25)	0.63	(0.25)	--	--	0	0	
		200	2.84	(1.12)	0.15	(0.06)	--	--	0	0	
W20	M2	300	--	--	0		--	--	0	0	Same as test W19 except no concrete sand cover used
		500	--	--	0		--	--	0	0	

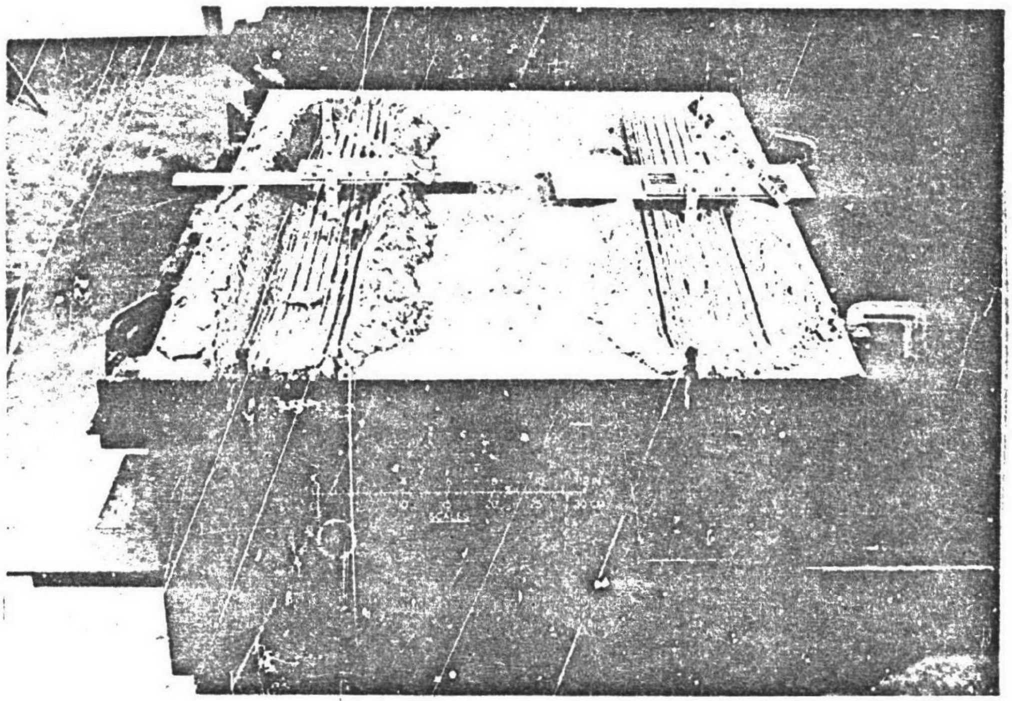

Figure 28. Typical ruts in sand cover at 10 and 2 passes.

TABLE 5. AVERAGE TEST RESULTS FOR LABORATORY WHEEL LOAD TESTS

Test No.	Membranes	Soil Cover/Subgrade	Passes	Average No. of Punctures (Per 3 Tests)
W2, W3, W4	M2	Concrete sand Gravelly sand	30	0.0
			100	1.3
			300	9.0
W7, W8, W9 W13	M3	Concrete sand Gravelly sand	30	0.0
			100	0.75
			300	6.0
W10, W11, W12	M4	Concrete sand Gravelly sand	30	0.0
			100	0 0
			300	0.33
W14, W15 W16	M2	Concrete sand Lean clay Gravelly sand	300	0.0
			500	0.66
			1000	1.66

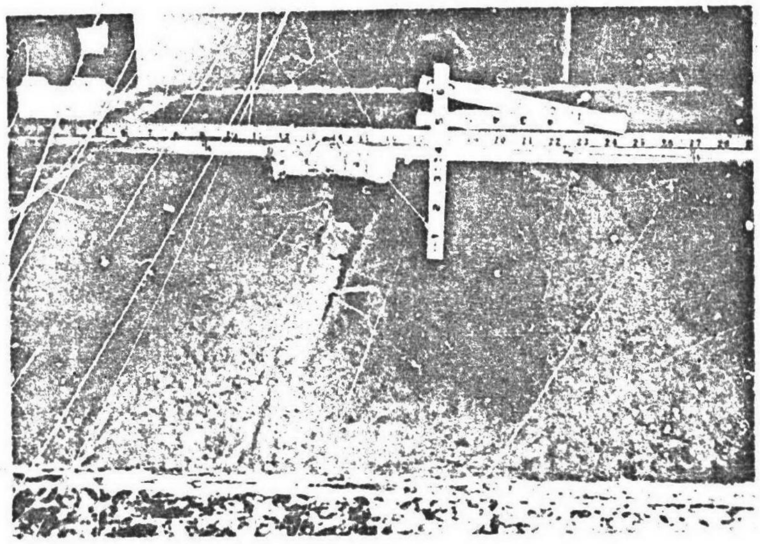

Figure 29. Rutting in clay used as bedding over subgrade.

Gyratory Shear

Using the gyratory shear equipment, tests were performed on two types of subgrades. One subgrade used was similar to that used in field tests and as used in the pneumatic-tire load wheel tests. The other was an artificially or simulated subgrade consisting of a rubber disc having a CBR value of 16, embedded with steel barbs to represent rocks. The simulated rock (barb) tests were conducted to determine the feasibility of developing a test method and procedures which may be used to compare and/or select membranes for a specified job requirement. Both types of subgrades were tested with the same membranes and sand cover as used in the laboratory and field tests. The gyratory compactor used in the design of bituminous concrete produces a kneading action on test specimens similar to that caused by pneumatic-tired traffic. During compaction of the specimen, the applied loading (pressure), angle of gyration (usually 1 degree), and number of revolutions are all controlled by the test equipment. A small simple-to-prepare sample is required for this machine, and the loading and operation are relatively easily and quickly performed. Extensive testing and previous experience with this laboratory equipment made it appropriate for use in this study.

Initial membrane test samples were prepared with a subgrade that consisted of a well-graded crushed limestone (Figure 27), except the material retained on the 3/4-in. sieve was not used. The rough irregular-shaped limestone was used with the expectation of producing holes in the membrane after a small number of revolutions, as no cushioning was used in these initial tests. Tests G1 and G5 were duplicates used to determine reproducibility of test data. These tests were found to produce reasonably close results as 20 and 17 holes were counted after 10 revolutions. The same test materials were used in test G6 except the top 1 in. of the limestone was replaced with the lean clay having a water content of 18 percent. After 500 revolutions, no holes were observed in the M2 membrane specimens; whereas, 20 and 17 holes had occurred previously after 10 revolutions in tests G1 and G5, respectively.

Tests G2, G3, and G4 were conducted on samples of the M4 membrane for comparison with test results on the M2 membrane. After 10, 30, and 100 revolutions, there were 0, 1, and 0 holes, respectively, in the M4 membrane (Table 6). Figure 30 shows from left to right the 6-in. diam by 6-in.-deep steel mold, the crushed limestone subgrade material, the M4 membrane with no holes (note scuffs and indentations) after 30 revolutions and the M2 membrane with 20 holes after 10 revolutions. Figure 31 shows the interface of the clay and the limestone in the mold after 500 revolutions in test G6. Test G7 was identical to test G6 except there was no sand cover placed over the membrane (the steel upper head of the gyratory machine was in direct contact with the membrane). After 500 revolutions, there were no holes in the M2 membrane.

After test G7 was completed, membrane samples were prepared for use with a 2-in.-thick rubber subbase disc and barbs which had been prepared for use with the gyratory machine. Barbs of three sizes (1/2-, 3/8-, and 1/4-in. high) were located equal distances from the disc's center. Figure 32 shows the steel gyratory mold in the background, the three rubber subbase discs with various sized barbs located on two of the discs. The 2-in. rubber disc with three barbs is shown in the steel mold in Figure 33 with the 4-in.-thick disc shown in the foreground. The membrane was placed on the disc and barbs, covered with 2 in. of gravelly sand (Figure 27), hand tamped, and leveled. The water content of the sand was controlled between 3.5 and 4.5 percent. Figure 34 illustrates a typical test specimen after 10 revolutions, and Figure 35 depicts indentations caused by barbs. Test C2 was used to determine the effects on the membrane caused by preparation of the specimens before exposure to the gyratory load. After the specimen was prepared, it was disassembled for inspection and found that no damage had occurred to the membrane. Specimens for tests C3 and C12 also were disassembled at zero revolutions; however, a test pressure of 30 psi was applied for 3 minutes. When inspected, the M2 (test C3) had no holes but the M4 (test C12) had ! holes. In test C12 after 3 revolutions, holes had been caused in the membrane by all 3 barbs (Table 7).

A series of tests were performed on M2 membranes for 3 revolutions to determine which barb caused the first puncture. Three tests were conducted; these tests are shown as tests C4, C7, and C8 in Table 7. The test results were not consistent as the 1/2-in. barb produced a hole in test C7, the 3/8-in. barb produced a hole in test C4, and no holes occurred in test C8. Nevertheless, 3 revolutions on the M2 membrane appeared to produce the condition that caused initial failure of the membrane.

TABLE 6. GYRATORY TEST RESULTS OF MEMBRANES PLACED ON CRUSHED LIMESTONE (3/4 in.)

Test No.	Cover Soil	Revolutions	Membrane	Number of Punctures	Equivalent Number of Punctures Per Square Yard	Remarks
G1	Concrete sand	10	M2	20	926	
G2	Concrete sand	10	M4	0	0	Numerous abrasions noted
G3	Concrete sand	30	M4	1	46.3	Numerous abrasions noted
G4	Concrete sand	100	M4	0	0	Numerous abrasions noted
G5	Concrete sand	10	M2	17	786	
G6	Concrete sand	500	M2	0	0	Layered sample from bottom to top as follows: 2 in. limestone plus 1 in. lean clay at 18 percent moisture, plus M2, plus 2 in. concrete sand at 3.5 percent moisture
G7	None	500	M2	0	0	Layered samples from bottom to top as follows: 4 in. limestone, plus 1 in. lean clay at 18 percent moisture, plus M2

NOTE: 1-degree angle of gyration, 30 psi pressure used for all tests.

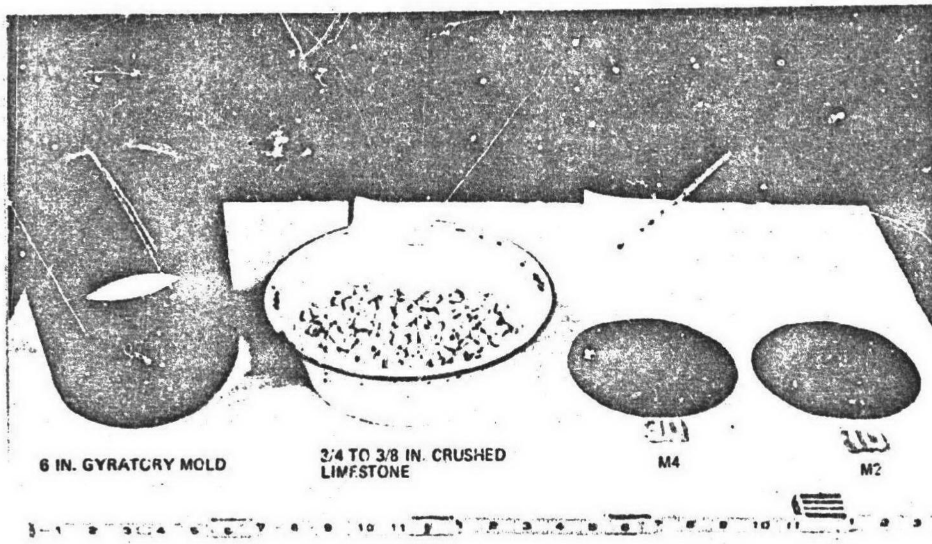

Figure 30. Six-inch gyratory mold, 3/4- to 3/8-in. crushed limestone, M4 after 30 revolutions (note scuff marks), and M2 with 20 punctures after 10 revolutions.

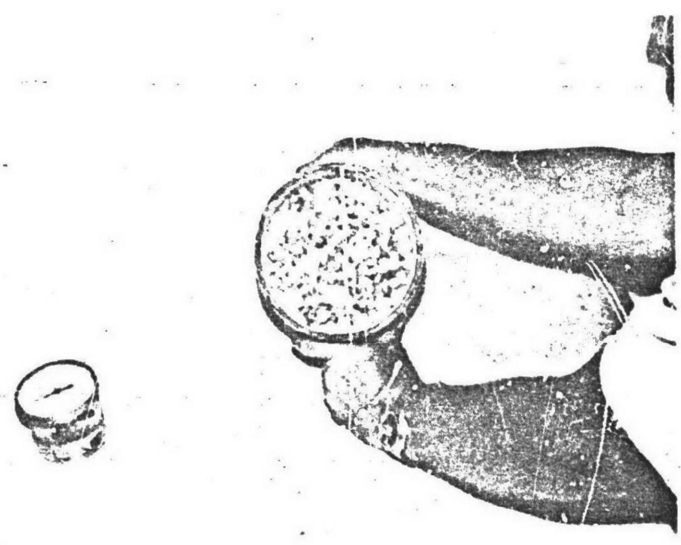

Figure 31. Interface of clay and limestone after 500 revolutions.

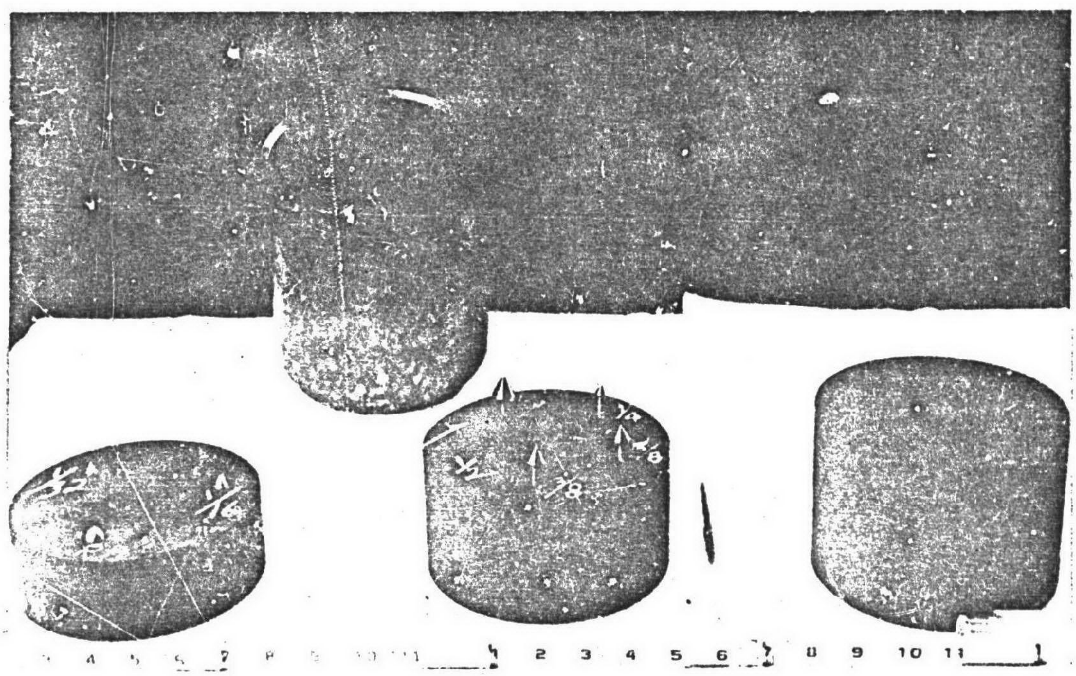

Figure 32. Steel mold, rubber subbase discs and barbs.

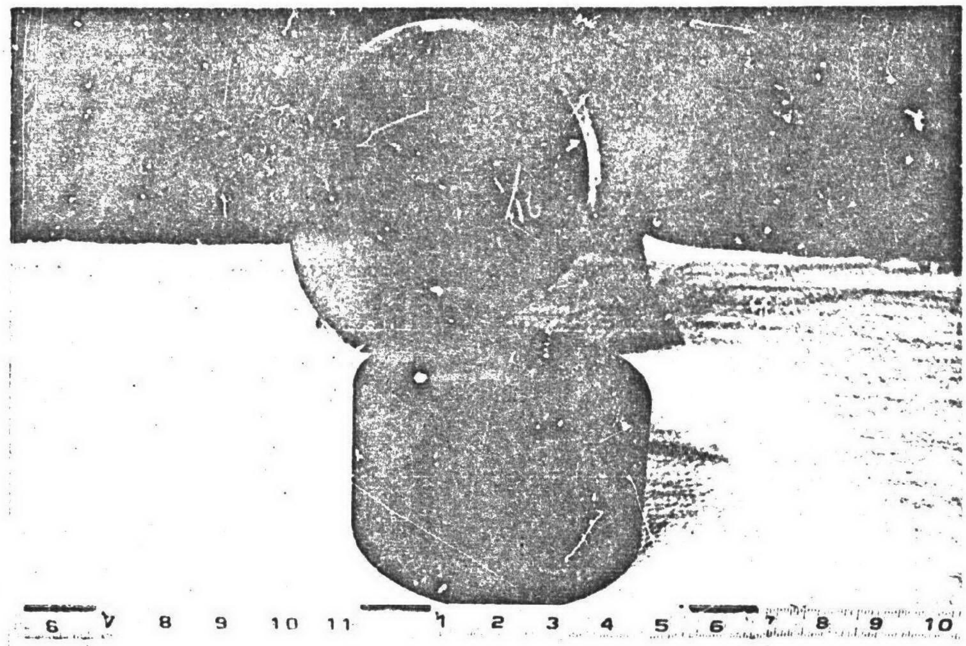

Figure 33. Two-inch-thick rubber subbase in mold with barbs, 4-in.-thick rubber subbase in foreground.

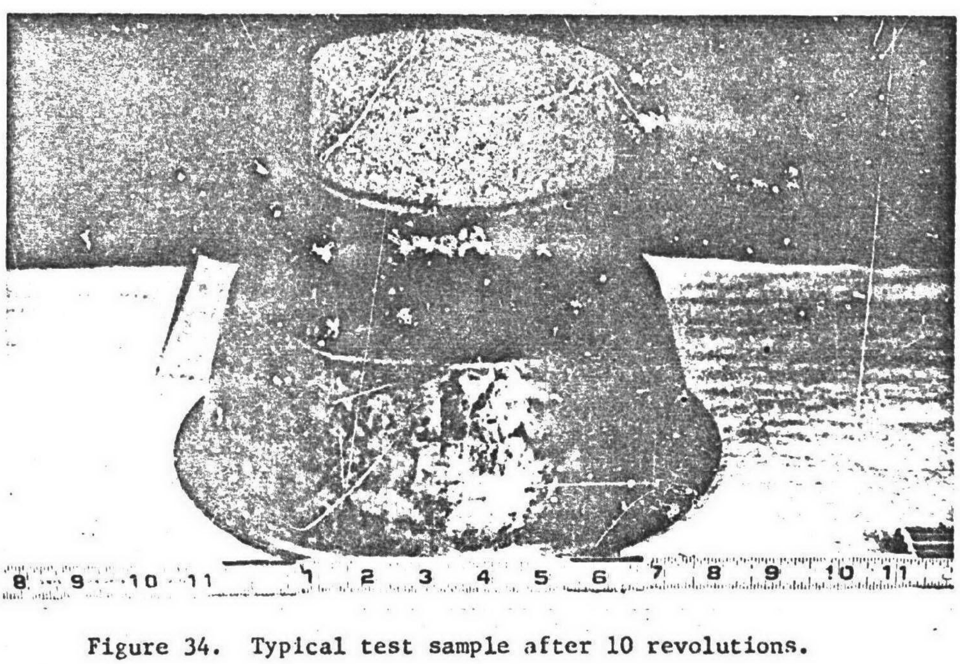

Figure 34. Typical test sample after 10 revolutions.

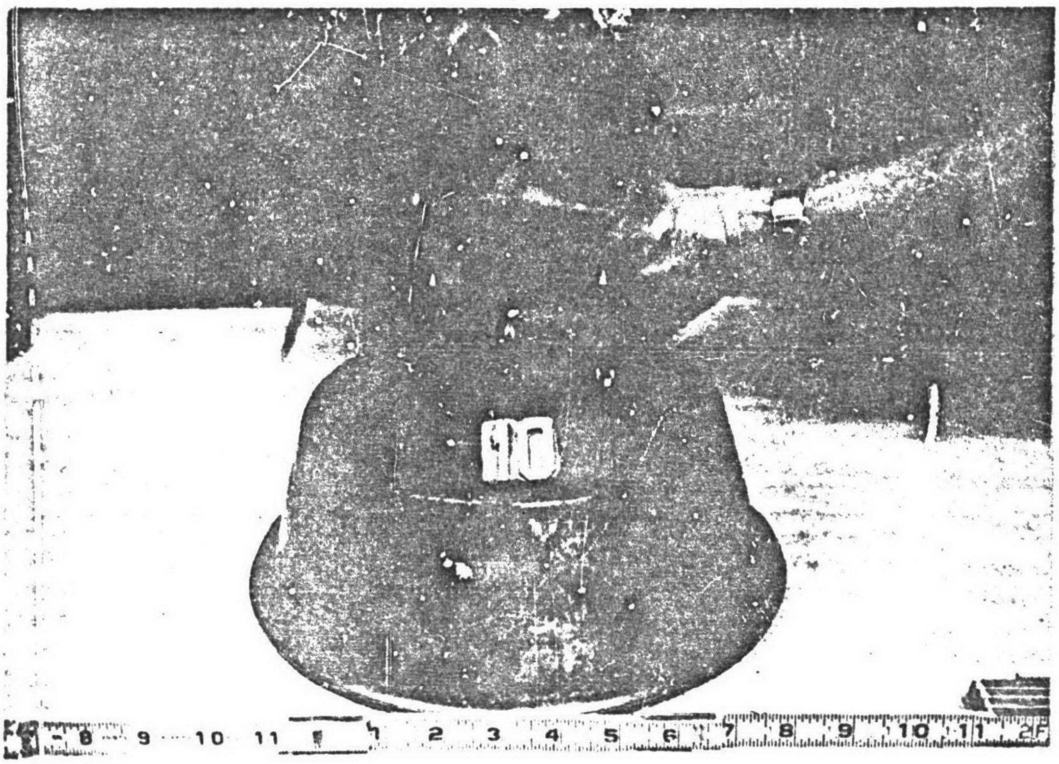

Figure 35. Indentations in membrane caused by the three barbs after 10 revolutions.

TABLE 7. RESULTS OF GYRATORY TESTS WITH VARIABLE HEIGHT BARBS MOUNTED IN RUBBER SUBBASE

Test No.	Revolution	Membrane	Number of Punctures	Punctures Produced by Barb — Barb Radius, inches 1/2	3/8	1/4	Remarks
C1	10	M2	3	x	x	x	
C2	0	M2	0	-	-	-	Sample prepared to check on membrane during construction of test specimens.
C3	0	M2	0	-	-	-	30 psi pressure for 3 min.
C4	3	M2	1		x		
C5	6	M2	2	x	x		
C6	8	M2	2	x		x	
C7	3	M2	1	x			
C8	3	M2	0	-	-	-	
C9	5	M2	2	x	x		
C10	7	M2	3	x	x	x	
C11	10	M2	2	x	x		
C12	0	M4	2	x	x		30 psi pressure for 3 min.
C13	3	M4	3	x	x	x	
C14	3	M3	1	x			
C15	5	M3	1	x			
C16	7	M3	1		x		
C17	10	M3	1		x		

NOTE: Barbs with 60-degree cones and 1/64-in. radius at the point. An x indicates a hole was produced. All barbs were located 1-1/4 in. from the center of the sample.

Four tests were then performed on the M2 at 5, 6, 7, and 8 revolutions to determine which barb produced the initial puncture. These tests are shown in Table 7 as tests C5, C6, C9, and C10. The 1/2-in. barb punctured the membrane in all 4 tests (i.e., 5, 6, 7, and 8 revolutions); the 3/8-in. barb punctured the membrane in three tests at 5, 6, and 7 revolutions; and the 1/4-in. barb punctured the membrane at 7 and 8 revolutions. These tests results indicated that the shortest barb sustained more revolutions before puncture and the longest (highest) barb punctured the membrane at the least number of revolutions.

Four tests were conducted on the M3 membrane (tests C14, C15, C16, and C17, Table 7) at 3, 5, 7, and 10 revolutions. These tests generally supported initial observations discussed above as the longest barb produced punctures at the lowest number of revolutions and the shortest barbs sustained more revolutions before puncturing the membrane.

Tests also were conducted to determine whether the locations of the barbs mounted on the rubber subbase influenced and caused punctures in the membranes. This testing was conducted on the M2 and M4 membranes with the barbs located 1-1/4 and 2-1/4 in. from the center of the specimen. The results of these tests are recorded in Table 8. During tests with the barbs at these locations on M2 membrane in each of 4 tests (C18, C19, C20, and C21), the sharpest barb (1/32-in. radius) produced a puncture. The smooth barb punctured the membrane in 3 of 4 tests (C18, C20, and C21). In only 1 of the 4 tests was there a puncture by the 1/16-in.-radius barb (test C19). In similar tests (C22, C23, C24, and C25) on M4 membrane, only one puncture was recorded (test C24) and it was caused by the sharpest barb (1/32-in. radius) located 2-1/4 in. from the center. Test C26 on M4 membrane was conducted to determine whether and if so, when the smooth barb and 1/16-in.-radius barb would puncture the membrane. After 500 revolutions, the smooth barb was the only barb that had not punctured the M4 membrane.

Plate Loading

Results of the plate-loading tests are presented in Table 9. Four tests were run on the M2 membrane, and three each on the M3 and M4 membranes. The initial test consisted of 1000 cycles of loading which resulted in three punctures of the M2 membrane on the SP subgrade. The cover material and liner were removed and a nonwoven fabric placed on the undisturbed subgrade of test P1. In test P2 the liner was placed on top of the fabric and covered with 2-1/2 in. of sand. After 1000 cycles of loading, no punctures appeared in the membrane indicating that the fabric was effective in protecting the membrane. Test P1 was duplicated in tests P3 and P4 to provide more than one test point. These tests produced punctures at 400 cycles, indicating that the punctures in test P1 may have occurred shortly after the 300 cycles at which data were obtained.

Membrane M3 sustained several punctures at 1000 cycles in tests P5 and P6, but not in P7. There also were no punctures at the intermediate number of cycles where data was taken. Membrane M4 sustained no punctures in tests P8, P9, and P10 at 1000 cycles of loading.

TABLE 8. GYRATORY TEST RESULTS WITH BARBS MOUNTED AT VARIOUS LOCATIONS IN RUBBER SUBBASE DISC

Test No.	Revolutions	Membrane	Number of Holes	Punctures Produced by Barbs With Radius of: Smooth	1/16 in.*	1/32 in.*	Distance of Barbs From Center of Disc in.
C18	10	M2	2	x		x	1-1/4
C19	30	M2	2		x	x	1-1/4
C20	10	M2	2	x		x	2-1/4
C21	30	M2	2	x		x	2-1/4
C22	10	M4	0				1-1/4
C23	30	M4	0				1-1/4
C24	10	M4	1			x	2-1/4
C25	30	M4	0				2-1/4
C26	500	M4	2		x	x	1-1/4

* Cone of 60 degrees; 1/4 in. high.

TABLE 9. PLATE-LOADING TEST DATA

Test	Membrane*	Number of Cycles	Number of Punctures	Equivalent Number of Punctures Per Square Yard	Remarks
P1	M2	300	0	0	
		1000	3	38	One puncture caused by a sharp rock, one by a flat rock, and the other in a generally smooth area (puncture appeared to occur from the top in a downward direction).
P2	M2	500	0	0	Geotextile placed over undisturbed subgrade of test 1 that produced 3 holes at 1000 cycles.
		1000	0	0	
P3	M2	400	3	38	Two holes caused by a large flat rock under the membrane.
		1000	5	63	Holes at 400 cycles did not increase in size.
P4	M2	400	7	88	
		1000	8	100	Several holes increased in size at 1000 cycles.
P5	M3	300	0	0	
		1000	7	88	
P6	M3	400	0	0	
		1000	3	38	
P7	M3	500	0	0	
		1000	0	0	
P8	M4	400	0	0	
		1000	0	0	
P9	M4	500	0	0	
		1000	0	0	
P10	M4	1000	0	0	

* One specimen of membrane per test was used.

NOTES.

The top 6 in. of the subgrade was removed, replaced, and recompacted for each test except Test P2.

Subgrade was 18 in. of gravelly sand with average water content of 6.8 percent and average dry density of 124.1.

Surface was 2-1/2 in. of loose concrete sand (passing 3/8 in. sieve) with water content of 3.9 percent.

Instron Machine applied load on 11.5-in.-diam plate at a rate of 10-12 cycles per minute.

Total Load was 3324 lb and 32 psi.

In all of these tests, the water content and dry density of the gravelly sand subgrade was controlled at an average of 6.8 percent and 124.1 pcf, respectively. The cover sand had an average water content of 3.9 percent in all plate load tests.

Standard Physical Test

Physical properties of the membranes were determined in accordance with ASTM D 751 and the data are shown on Table 2. The results of tests (ASTM D 1175) for weight loss versus abrasion cycles are plotted as shown in Figure 36.

ANALYSIS OF LABORATORY TEST DATA

Pneumatic-Tire Load

As indicated on Table 4, nine tests were run on M2 membrane over an SP subgrade. Four tests (W1-W4) were repetitive, having similar test conditions and results. Each of these tests sustained no punctures at 10 passes of the wheel load, a minimum number of punctures at 100 passes of the wheel load, and several punctures at 300 passes of the wheel load. The number of punctures seemed to be directly related to the number of rocks in contact with the membrane. Therefore, in order to prevent puncture of the membrane, it was necessary to provide a protective layer of material that would prevent the membrane from coming in contact with the rocks in the subgrade. Two different methods were tried, one being placement of a nonwoven fabric between the membrane and the SP subgrade, and the other being the placement of a layer of clay soil between the membrane and subgrade.

Test W5 shows the test results using the geotextile as a bedding material above the subgrade. As can be seen in Table 4, punctures occurred at all pass levels where observations were made. However, a comparison of punctures at the different pass levels indicates that the fabric was effective in reducing the number of punctures.

Test W6 shows the test results using 1 in. of lean clay as a bedding material above the subgrade. The lean clay was very satisfactory in that no punctures occurred in the M2 membrane at any pass level where observations were made. To further demonstrate the effectiveness of the clay bedding, three more tests were run at higher pass levels using the M2 membrane. These tests (W14-W16) also showed no punctures at 300 passes of the wheel load. However, a few punctures developed at 500- and 1000-pass levels in test W14 and at 1000 passes in test W16. Test W15 produced no punctures at 1000 passes. These tests again show the effectiveness of a clay bedding for at least 300 wheel load passes.

Since the clay material had been effective on the gravelly sand subgrade, it was decided to test it on a very severe condition using crushed limestone as a subgrade. Test W17 shows the severity of the crushed limestone when in contact with the membrane in that 36 punctures were produced

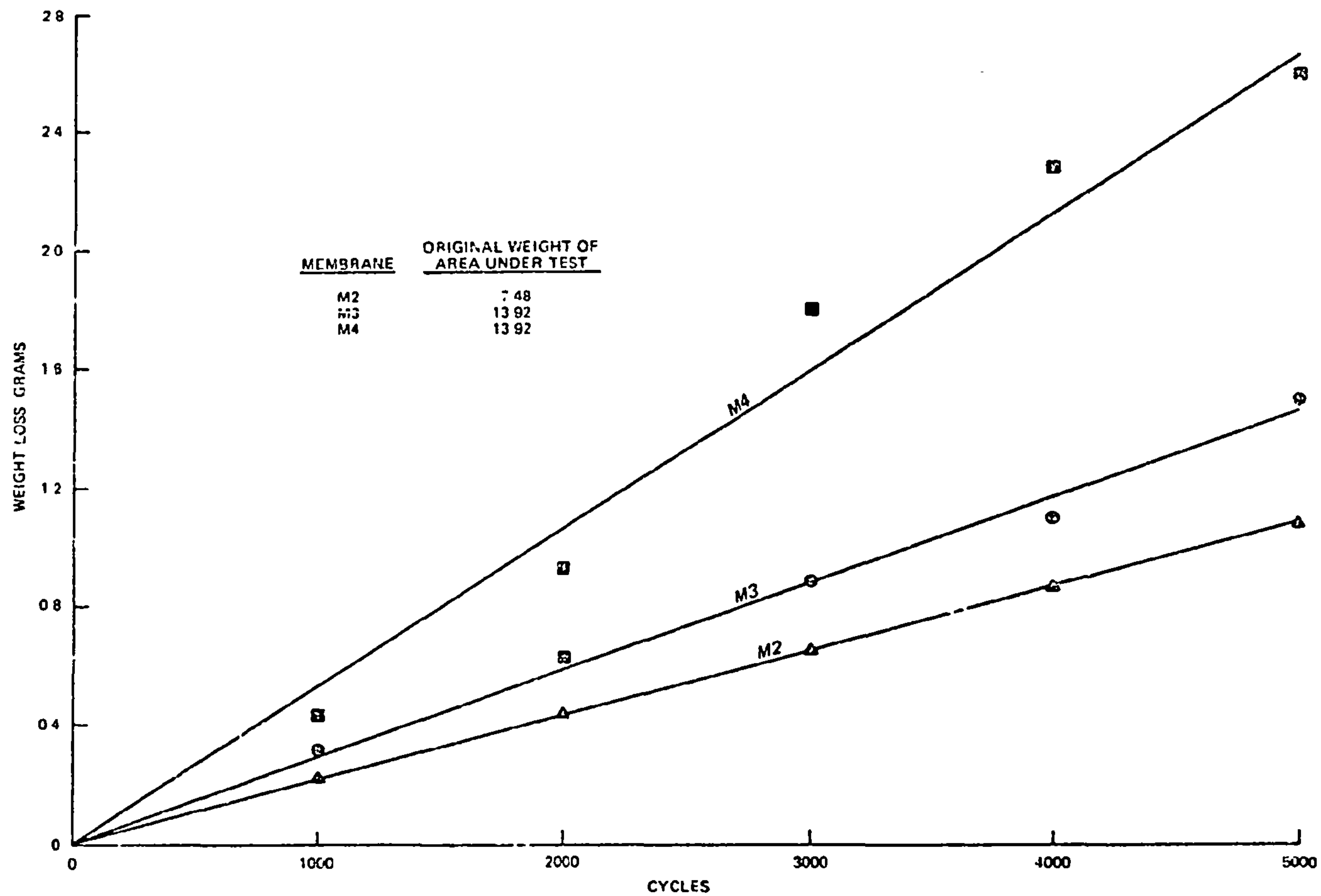

Figure 36. Weight loss versus abrasion cycles of membranes.

at 100 passes. Tests W18-W20 were then run using the lean clay as a bedding material over the limestone and below the membrane. In all three tests, the lean clay prevented punctures up to 300 passes except for test W18 which sustained 2 punctures because the clay was too soft. Test W20, which had no cover over the membrane, went up to 500 passes without any punctures. These tests also demonstrated the effectiveness of the lean clay in preventing punctures even under very severe conditions. For maximum protection of the membrane, the lean clay should be compacted adequately to prevent rutting (water content on dry side of optimum).

The initial tests run on the M2 membrane were repeated using the M3 membrane and M4 membrane. These tests consisted of the concrete sand cover over the member and the gravelly sand subgrade under the membrane. Tests on the M3 membrane produced results similar to the M2 membrane; therefore, additional tests were not considered necessary using the fabric or the clay bedding. The test results using the M4 membrane were significantly better than tests on the M2 or M3 membrane with only one puncture being produced in the 3 tests at 300 passes. Since this is the stronger of the membranes, it was considered that the bedding requirements for the M2 also would be satisfactory for the M4. The pneumatic-tire load test would be a useful test for determining cover and bedding requirements using available site soils and candidate membranes.

Gyratory Tests

Results of the gyratory tests using a crushed limestone subgrade are shown in Table 6. This was considered a severe test for the membrane materials, and as expected, numerous punctures were produced in the M2 membrane when placed on the crushed stone with the concrete sand cover as shown by tests G1 and G5. The number of punctures was reduced to zero when the membrane was protected from the crushed stone by a 1-in. layer of lean clay as indicated by tests G6 and G7. Tests on the M4 membrane showed that it had greater resistance to puncture, as only one puncture occurred during three different tests (G2, G3, and G4). Numerous abrasions were noted on the M4, and indications were that additional cycles may have produced punctures from these abrasions.

Tests also were conducted using a rubber disc containing variable-size barbs as a subgrade. These tests were conducted to see whether a standard test could be established for testing and comparing performance of different membranes. Results of these tests are shown in Table 7. Gyratory tests G3 and G12 on M2 and M4 membranes, when only pressure was applied for 3 minutes (no revolutions), indicated that sharp barbs will puncture a stiff membrane (one with low elongation, M4) faster than an elastic membrane (one with a high elongation, M2). The M4 punctured under pressure because it did not stretch, drape, and conform to the shape of the barbs. The gyratory tests also indicated that larger barbs punctured membranes rapidly and small barbs required more revolutions to produce punctures.

As indicated in Table 8, the location of the barbs in the gyratory test mold (G18-G25) did not make any significant difference as to when membranes were punctured. The tests on the M2 membrane indicated that a smooth barb and a pointed barb produced holes in the membrane at approximately the same rate.

Plate-Loading Tests

Results of the plate-loading tests are shown in Table 9. The plate-bearing tests did not develop failures in the membrane similar in extent to those observed in previous field tests nor as those produced by pneumatic-tire load and gyratory tests. The plate-loading tests indicated that the geotextile prevented punctures to the membranes, but in field tests and the model tire tests, the geotextile was not as effective in preventing punctures. The plate-loading test does not appear to be a suitable test for evaluating puncture resistance of membrane liners.

COMPARISON WITH FIELD TESTS

Some general observations were made in comparing the laboratory test results with field test results. In the field tests, punctures in the membranes occurred regardless of the thickness of cover over the membranes. The occurrence of the punctures probably was due to the fact that the membranes were directly on top of the granular subgrades and in contact with gravel particles. Where the sand and sandy silt subgrade was used, the number of punctures was reduced and was zero for some membranes. These results compare favorably with the results of the pneumatic-tire tests conducted in the laboratory, which showed that separating the membrane from the granular material by a lean clay will prevent or reduce punctures in the membrane. In the laboratory tests, the fabric bedding material prevented or reduced the number of punctures in all tests. There also was some indication in the field tests that the use of a geotextile under the liner may protect it from puncture, although not all field tests indicated this.

There were a limited number of field tests that could be used for direct comparison with the laboratory tests. The laboratory tests were conducted so as to produce a stress on the membrane liners equivalent to the stress produced by the pneumatic tire on the liners in the field test under 6 in. of cover. This restricted the comparisons to test program 1. Within test program 1, two subgrades were used that could compare with the subgrades in the laboratory tests. Test item 2 contained a crushed stone, which compares with the crushed limestone in the gyratory tests, and test item 8 contains a gravelly sand, which compares with the gravelly sand used in the pneumatic-wheel load tests and the plate-loading tests.

To compare results of field and laboratory tests, the number of punctures produced were converted to an equivalent number of punctures per square yard in order to compare results on an equal basis. These equivalent number of punctures are shown for the laboratory tests in Tables 4, 6, and 9. In the field tests, on item 2, 29 equivalent punctures were produced at 10 passes of the tire load; whereas, the gyratory test at 10 revolutions produced an equivalent number of passes equal to 926 in test G1 and 786 in test G5. These results show the gyratory test to be much more severe on the M2 membrane than the field test and therefore would not appear to be an appropriate test for determining bedding and cover requirements for liner systems.

In item 8 of the field tests, the pneumatic-tire load produced 14 equivalent punctures in the M2 membrane. In the plate-loading tests, no punctures occurred up to 300 cycles of loading, but up to 88 punctures occurred at 400 cycles of load. This indicated that the laboratory plate-loading test produces the same number of equivalent punctures on the M2 membrane as the field test between 300 and 400 cycles of load. Therefore, the plate-loading test could possibly be a candidate for use in determining cover and bedding requirements.

Zero punctures were produced at 30 passes of the pneumatic-wheel load in the laboratory and from 23 to 92 equivalent punctures at 100 passes. These compare to the 14 equivalent punctures in item 8 of the field test indicating that the number of passes required to produce similar results to the field test on the M2 is between 30 and 100. These results indicate that the pneumatic-tire load test is also a possible candidate for use in determining cover and bedding requirements.

Since the laboratory pneumatic-tire load is the same type of load as applied by construction equipment in constructing landfills, it is considered to be the most applicable test for determining bedding and cover requirements for membrane used in landfills.

REFERENCES

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