PAVEMENT FAILURE ANALYSIS
EXAMPLE PROBLEMS

by

J. A. Epps and F. N. Finn

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INTRODUCTION

When pavements fail prematurely it is often in the best interest of the owner agency to identify the probable cause. Based on findings from these investigations it will be possible to initiate corrective procedures to avoid continuing problems of similar types. These corrective actions may require changing an altering existing design, construction, material testing methods and/or specification acceptance criteria.

The reliability of a failure analysis will vary depending on the information available. In some cases the cause of failure will be obvious, such as truck loads (number and weight) having increased significantly above expected levels. In many cases the analysis will not be so straightforward and a more in-depth study will be necessary to identify the factors responsible for the undesirable pavement performance. Thus, the investigation can be planned and conducted at two levels; (1) an evaluation of data which requires a minimum of additional testing and depends largely on design and construction records plus comparisons with current observations, and (2) an in-depth evaluation and analysis which would require further field and laboratory testing based on the findings from records and observations.

In some cases the major concern will be rehabilitation of an in-service distressed pavement. Depending on the circumstances, a failure investigation may or may not be appropriate. If there is nothing unusual about the occurrence of distress the main concern will be the selection of appropriate rehabilitation procedures. However, if the occurrence of distress is considered unusual it may be useful to conduct a failure investigation before selecting a rehabilitation procedure. The purpose of such an investigation would be to minimize any adverse effects of the original construction on the performance of the rehabilitated pavement.

Generally, engineers will have several options available for rehabilitation of a specific pavement. These options will depend on the functional class of roadway, traffic current condition, environment and service requirements. In choosing from among the various rehabilitated alternatives three factors should be evaluated; (1) pavement performance, (2) costs, and (3) energy requirements. Inherent in these considerations are reliability, user convenience and budgeting restraints.

Pavement failure analysis procedures have been outlined in a series of reports prepared in project 214. These reports are listed below.

Report 214-16 ...... Guidelines for Flexible Pavement Failure Investigations.

Report 214-17 ...... Pavement Failure Analysis With Guidelines for Rehabilitation of Flexible Type Pavement.

Reprot 214-18 ...... Costs Associated with Pavements, Construction, Rehabilitation and Maintenance.

Report 214-19 ..... Energy Requirements Associated with Pavement Construction, Rehabilitation and Maintenance.

Two examples of the use of these guidelines are given below. The first example involves the premature failure of pavement in North Texas. A detailed laboratory and field testing program was performed to identify the probable cause of the distress. The second example presented below involves the establishment of rehabilitation alternatives for a nineteen-year old pavement in west Texas. Life cycle cost and energy considerations are given together with field and laboratory data which support the selections of available rehabilitation alternatives.

NORTH TEXAS PAVEMENT

Pavement Distress (Report 214-16)

Severe rutting in the wheel path

Localized longitudinal cracking in wheel path

Localized alligator cracking

Possible Causes of Distress (Reports 214-16 and 214-17)

1. Structural Deficiency
2. HMAC mixture design
3. Asphalt cement properties
4. Stability of pavement layers
5. Compaction
6. Excessive air voids in HMAC
7. Stripping of asphalt from aggregates
8. Construction deficiencies

Historic Records

Pavement Structural Section. The designed pavement section for this major highway is shown below.

2 inches non-polishing AC
5 inches black base
4 inches flexible base
6 inches lime stabilized subgrade
subgrade

Construction Records. A summary of construction records is given below.

The black base was specified by Item 292 and tested according to Tex-Method 126-E. A 1 ½ inch maximum size siliceous gravel was used with a local sand fine aggregate. The asphalt cement was an AC-20 from Oklahoma Refining Company. The design for the mixture indicated a maximum strength at 3.8 to 3.9 percent. The mix appeared lean and the asphalt content was increased to 4.2 percent. At this asphalt content the mixture was borderline on strength (50 psi required for Class 1 black base). The asphalt content was reduced to 4.0 percent and utilized for the project. Five percent air voids were obtained in the laboratory compacted mixtures.

The mixture was produced at 295° for the first few weeks of the job. The temperature was reduced to 275-280°F for the remainder of the black base. Suitable coating was not obtained at 250°F. Compaction was performed at 225°F with a steel wheel roller followed by pneumatic rolling. Field densities of about 95-96% of laboratory density were obtained. Two, 2 ½ inch lifts were placed. Average production was 2000 tons per day. The haul from the plant to the job averaged 10 miles. Moisture contents of the mixture were about 0.5 percent.

The asphalt concrete hot mixture was specified by Item 340. The type D asphalt concrete was made with a non-absorptive, non-polishing sandstone coarse aggregate, sandstone screening, local field sand and 5 percent asphalt cement. The sandstone was obtained from Cyril, Oklahoma and the AC-20 asphalt cement from Oklahoma Refining company. One to three percent air voids were obtained in the laboratory; fifty-five percent of the aggregate was retained on the No. 10 sieve.

The mixture was produced at 275-280°F. Rolling was delayed to allow the mixture to cool. The high mixing temperature was required to achieve proper coating. Two 1-inch lifts were utilized on part of the job. The remainder of the job was constructed with a two-inch lift. Moisture contents of the mixture were about 0.5 percent.

Hot mix construction was performed between March, 1977 and June, 1977, with a new Barber-Greene drum mixer plant rated at 300 tons per hour. A 200-ton surge silo was also utilized on the job. The surge silo had to be maintained one-half full to reduce segregation.

Difficulties were encountered during placement of the asphalt concrete. Ripples appeared in the surface when a two-inch mat was placed. This rippling problem was solved by placing the 2-inch asphalt concrete layer in two, one-inch lifts.

The completed project was opened to traffic in September of 1977. The initial distress appeared in July of 1978. Rutting over a length of about 15 feet appeared. Several other spot locations appeared soon thereafter. Distress was first apparent near the center of the job and then began to appear on the south half of the project. There is no distress on the north half of the job. The inside wheel path of the travel base rutted initially. These locations occurred between super-elevated sections (areas of flat cross slope).

Two different subgrades exist on the project. The south end of the project has 20 P.I. clay material as a subgrade while the subgrade on the north end of the project is a 15 P.I. sandy material. Those sections of the roadway placed on sandy subgrade have less rutting than those placed on clay subgrades.

Hveem tests performed on 25 asphalt concrete samples taken during construction indicated an average stability of 44.8. The range of the values was from 29 to 57 with a standard deviation 7.1.

Field Testing

Dynaflect testing was performed on the project, a trench section excavated and core samples obtained. Results are given below.

Dynaflect Testing

Dynaflect tests were obtained to establish stiffness coefficients of the as constructed pavement and to determine the structural adequacy of the designed pavement section.

The pavement structural design was performed using the Flexible Pavement Design System (FPS) in May of 1976. The inputs to the design system were obtained from various representative samples and from D-10 Traffic Counts and Projections.

The original estimated 18,000 lb. equivalent single axle load repetitions was 2,436,000 for the period 1975-1995. For the projected traffic the life of the facility is 14 years. If the traffic was doubled to 5,000,000 the predicted life would be decreased by about one half for the designed section utilized. Increased traffic (over and above that expected) on the facility by itself is not sufficient to account for the early deterioration.

The stiffness coefficients assummed for the original design are shown on Table 1. Stiffness coefficients were determined from Dynaflect measurements made on the constructed pavement. These are shown for comparison purposes on Table 1. As constructed values were selected as shown on Table 1 and the predicted life of the pavement determined by use of FPS. The predicted life was reduced from 14 to 8 years using these new coefficients.

Some of the areas of the roadway cored, indicated an asphalt concrete thickness of only 3/4 inch. For this structural section the predicted life is only 4 years.

The analysis with the Dynaflect and FPS indicate that traffic by itself is not sufficient to cause the observed pavement failure.

Trench

A trench was excavated at station 491+50 on April 4, 1979. The entire outsection line was intersected with the trench. Pavement cross section was photographed and thickness measurements made. The thicknesses of the pavement layers where the rutting was most severe are given below.

asphalt concrete	1.69 inches
black base	5.13 inches
flexible base	4.50 inches
lime-treated subgrade	4.50 inches

Materials obtained from the trench section were utilized for additional laboratory testing. Moisture was noted in the black base while the asphalt concrete appeared dry and contained many hairline cracks.

Core Samples

Core samples were obtained at various locations along the project. Field notes taken during the coring are shown on Table 2. These notes include information on surface and base course thickness and the general condition of the core. It is evident that the black base had either failed prior to coring or during the wet coring operation. Water susceptibility problems are normally associated with this observed behavior.

Laboratory Testing

Laboratory testing programs were conducted by Division D-9 of the Texas State Department of Highways and Public Transportation and the Texas Transportation Institute. The Division D-9 test results will be summarized first.

Division D-9

The laboratory testing program conducted by D-9 has been summarized on Figures 1,2,3 and 4. Materials were obtained from the trench excavation and from the original aggregate stock piles.

Tables 3, 4, and 5 gives the results of remolded asphalt concrete and black base samples obtained from the trench excavation. Table 3 and 4 gives the gradation and asphalt content of the asphalt concrete and black base respectively. Table 5 shows the remolded mixture properties.

The asphalt concrete mixture meets all gradation specifications except the minus No. 200 sieve. Additional asphalt was added to the asphalt concrete to establish an optimum for this mixture (Table 5). The extracted asphalt content of 5.6 is near optimum for this mixture. Cohesiometer values for both the asphalt concrete and black base are very high. The resilient modulus of the black base is also exceptionally high.

Table 6 contains results obtained on black base mixtures subjected to varied compactive efforts (Figure 2). The purpose of this test series was to establish the effect of density on mixture properties. Strength increases as density increases and the moisture content increases as density decreases or air voids increase. The remolded mixture meets all the requirements of the specifications for strength when molded at the correct compaction effort. Specimens molded at reduced compactive effort produced uncoated aggregates.

Samples of aggregates were obtained from the job stockpile and soil constants were determined (Figure 3). The plastic index was 9 and the sand equivalent 53. Five percent of the material passed the number 200 sieve. The addition of 1 percent lime reduced the plastic limit to 7 and the sand equivalent was increased to 70.

The original properties of the asphalt used for the series of laboratory tests are shown on Table 7. Properties of the asphalt after laboratory molding and compaction are also shown on the same Table (Figure 3).

Properties of mixture molded from the stockpile aggregate and project asphalt are shown on Tables 8 and 9 (Figure 3). A series of black base samples were molded with the large gyratory compactor which contained 1%

lime and another series which contained 1% of a commerical antistrip additive (Table 8). The optimum asphalt content is near 4.0 percent which is the same as that used during construction. The mixture is relatively insensitive to changes in density caused by the changes in asphalt content as measured by the unconfined compression test. Both test speeds indicate a borderline strength for Grade 1 black base.

Both the lime slurry and liquid antistrip additive improved the unconfined strengths slightly and lowered the amount of moisture absorbed by a small amount. Test Method Tex-126-E is apparently not sensitive to improvements made in the mixture by adding antistripping agents.

Table 9 contains results of black base mixtures molded with the small gyratory compactor. Samples were prepared with no additive, 1 percent lime and 1 percent of antistrip additive.

Properties of the subgrade, lime treated subgrade and flexible base are shown on Table 10 (Figure 4). The subgrade and lime stablized subgrade contained moisture contents about 4 percentage points above the plastic limits. Excessive moisture appears to be present in all layers. The lime was most effective in reducing the plastic index of the subgrade. The plastic index of the flexible base appears excessive.

Texas Transportation Institute

The laboratory testing program conducted by the Texas Transportation Institute (TTI) is shown (Figure 5).

Asphalt Properties

Asphalt properties were obtained on both the original and the extracted and recovered asphalt. Results are shown in Table 11. Although the results are limited, it is evident that excessive hardening has occurred. A two to four fold increase in asphalt viscosity is normally expected during hot mixing, i.e. from 2,000 poises to 4,000 poises.

Mixture Properties

Core samples from the pavement were obtained by use of "dry" coring techniques. Coring with water was not possible as the water washed the asphalt off of the aggregate. Core samples were subjected to the test sequence shown in Figure 5. Resilient modulus, indirect tensile strength, Hveem stability and Marshall stability test results both before and after water soaking are shown on Figures 6 to 10 and Tables 12 to 15.

Two water soaking tests were performed. The test identified as the 7-day soak procedure is performed by first vacuum saturating the samples for 2 hours and then soaking the samples under water for 7 days. The Lottman procedure consists of vacuum saturating the samples followed by subjecting the samples to 18 freeze-thaw cycles (0 to 120^{o}F).

Figures 6, 8 and 10 indicate the water susceptibility of the black base as measured by the drop in resilient modulus, Hveem stability, indirect tensile strength and modulus, Marshall stability and Marshall flow. Resilient modulus drops on the order of 30 percent for the 7-day soak procedure and 50 percent for the Lottman procedure should be considered evidence of potential water stripping problems. Figures 7 and 9 and Table 12 indicate that the asphalt concrete surface course is not as sensitive to water as the black base. It should be noted that the average air void content of the asphalt concrete surface course is 9 percent and the base courses 7.7 percent (Table 12).

Hveem stability values obtained on the core samples are low for both the surface and base courses (Figures 6 and 7 and Table 13). Marshall stability values for the black base are somewhat low, while the flow values far exceed the normal 8 to 18 range.

Conclusions

The black base placed on this project is water susceptible and will strip in the presence of moisture. The laboratory test results indicating strength and stability loss in the presence of moisture confirm this statement. In addition, coring problems were noted when water was used during the coring operation. Reports from field patching crews have indicated that the black base was removed very easily and lacked cohesion.

Stability values obtained on the black base and surface course were low. These low stabilities contributed to the rutting problem. Relatively high air void contents (low density) also contribute to the low stabilities. The high air void contents in the surface course allow water to enter the black base from the surface.

The pavement will continue to rut unless it can be adequately sealed. A surface seal will reduce the rate of rutting. However water has access to the black base from the flexible base. A free draining flexible base would have provided improved performance. Accelerated rutting rates can be expected in the hot, moist summer months.

The water susceptibility test presently utilized as part of test method 126-E does not adequately define potential stripping problems in black bases. (Black bases placed in Districts 13 and 15 have similar problems.) The reason for this lack of sensitivity is not clear; however, the air void content of the laboratory prepared samples and the technique utilized to saturate the sample may contribute.

Antistrip additives should be considered for use if stripping is a potential problem. Lime slurry treatments have proven to be beneficial in laboratory tests.

WEST TEXAS PAVEMENT

Pavement Distress (Report 214-16)

Longitudinal cracking (not in wheel path) (greater than 200 ft. per station)

Transverse cracking (6-9 per station)

Minor alligator carcking

Possible Causes of Distress

Load Associated
- Structural deficiency
- Excessive air voids in HMAC
- Asphalt cement properties
- Stripping of asphalt from aggregate
- Aggregate gradation
- Construction deficiencies

Non Load Associated
- Volume change potential of foundation
- Slope stability of fill materials
- Settlement of fill or in-place materials as a result of increased loadings
- Hardness of asphalt cement
- Stiffness of asphalt concrete
- Segregation due to laydown machine
- Poor joint construction

HISTORICAL RECORDS

Pavement Structural Section

The pavement was constructed in 1961. Since 1961, chip seal coats, an asphalt concrete overlay and routine maintenance activities have been performed. The existing pavement section is shown below.

	Chip Seal Coat	1973
	Double Chip Seal Coat	1969
1.5"	Asphalt Concrete	1965
	Chip Seal Coat	1962 (inside lane only)
2"	Asphalt Concrete	1961
8"	Caliche Base	1961
	Natural Soil Fill	1961

Construction Records

All construction records are presently contained on microfilm and are of little value at this date. Field and laboratory testing data will supply almost all of the data required to select the rehabilitation alternatives.

Field Testing

Dynaflect tests were performed on the project and core samples were obtained for the pavement section.

Dynaflect Tests

Dynaflect tests were obtained to determine overlay thickness requirements from a structural standpoint. Historical records indicated that deflection measurements had been obtained on about a two-year interval. Values are summarized on Table 16.

Laboratory Testing

Eighteen cores were obtained from the pavement section. Resilient modulus stability, tensile strength, water susceptibility and asphalt properties were determined.

Resilient Modulus

The resilient modulus data obtained over a range of temperatures and at 0.1 second load duration are shown on Table 17 and Figure 11.

Stability

Hveem and Marshall stability values for the two layers of asphalt concrete in the pavement are shown on Tables 18 and 19. Both layers are characterized by relatively low Hveem stabilities and relatively high Marshall stabilities.

Tensile Strength

Tensile strength values are shown on Tables 18 and 19 for the two asphalt concrete layers in the pavement. Typical stress-strain curves for the top and bottom layers are shown on Figure 12.

Water Susceptibility

Two water susceptibility tests were performed with results shown on Tables 18 and 19 and Figures 13 and 14. The bottom layer shows evidence of water susceptibility. Prolonged exposure to water in-service would probably result in stripping of the asphalt from the aggregate in the bottom layer of asphalt concrete.

Asphalt Properties

Asphalt extraction and recovery tests were performed on selected pavement samples from the pavement. Results are shown on Table 20.

Overlay Thickness Requirement

Traffic

The existing annual truck traffic on the pavement has been calculated to be 730,000 equivalent 18,000 lbs. axle load applications. The design lane (travel lane) will carry about 70 percent of the truck traffic. Thus the design average daily equivalent 18,000 lbs. axle load application rate is about 2,000.

Overlay Thickness

Based on The Asphalt Institute's Overlay Design Method, a 2-inch overlay will be required to carry the existing traffic for the next twenty years. Traffic and deflection information as described above was utilized in this design method.

It should be noted that the FPS overlay design method could also have been used to determine the overlay thickness.

As stated above 2 inches is required for traffic loads. However, the existing cracks in the track will probably reflect through the overlay in two years or less. Thus, the use of an interlayer (stress absorbing layer) (stress relieving layer) needs to be considered. Asphalt-rubber chip seal and heater-scarification are two interlayer systems. A positive method for control of the reflection cracking is recycling of the existing asphalt bound material.

Thickness of Recycled Pavement

Deflection measurements and laboratory data were utilized to characterize the subgrade, base course, and bituminous bound materials. Layered elastic computer programs were used to calculate stresses and strains in the pavement and pavement thickness requirements were determined. Conventional pavement design approaches such as FPS could also be utilized to check the reasonableness of the computer solutions. A 6.5 to 7.5 inch asphalt bound layer will be required on top of the existing base course. A value of 7 inches is selected for design purposes at this time.

Rehabilitation Alternatives

Ten rehabilitation alternatives have been initially selected for the pavement section (Report 214-17). The alternatives are briefly defined in Table 21. The costs for evaluating the alternatives have been obtained from Report 214-18. Selected costs are shown on Table 22. Life-cycle costs are shown on Table 23. Life-cycle costing procedures as shown outlined in Report 214-19 were used. A summary for each alternative is shown on Table 24.

Life cycle energy requirements for the rehabilitation alternatives have been calculated using the data and methods described in Report 214-9. Results of these calculations are given on Table 24.

Conclusions

1. The transverse and longitudinal cracking pattern in this pavement

section is typical of other pavements in the west Texas area. This type of cracking is probably thermal cracking. The use of softer asphalt cements, asphalts with different temperature susceptibility and/or asphalts with improved aging characteristics will improve pavement performance. Absorptive aggregates, low asphalt contents and high air void content mixes contribute to the occurrence of this type of distress.

2. Ten rehabilitation alternatives have been defined, alternatives 4 to 8 involve recycling. Alternatives 2, 3, 9 and 10 provide various types of interlayers to reduce reflection cracking. Plan 1 is the typical rehabilitation method and has the lowest initial cost. Table 25 presents the advantages and disadvantages for each rehabilitation alternative. The selection of the rehabilitation alternative for the pavement section will depend on the amount of funding initially available, consideration of the life cycle costs, the life-cycle energy requirements and recognition of the advantages, disadvantages and uncertainties associated with each alternative. For example, the recycling alternatives have initial costs, and relatively low life cycle costs and reduced maintenance requirements.

CONCLUSIONS AND RECOMMENDATIONS

1. Two examples have been given which demonstrate the techniques involved in conducting pavement failure analysis. It should be recognized that each investigation may have to be tailored slightly to the individual project under investigation. However, it is desirable and extremely important that a fixed series of field measurements and laboratory tests be performed on all projects. The following is suggested as a minimum for asphalt treated materials.

A. Field Tests

1. Pavement Condition Survey

2. Dynaflect

3. Pavement Roughness

4. Core Samples - (depth measurement and laboratory testing)

B. Laboratory Testing

1. Mixtures

a. Hveem stability

b. Water-Susceptibility

c. Indirect tension

d. Resilient modulus

e. Air void content

2. Asphalts

a. Penetration - 77°F

b. Viscosity - 140°F

3. Aggregates

a. Gradation

b. Shape, surface texture, absorption

2. By accumulating pavement failure investigation data over a series of projects it will be possible to suggest changing or altering existing design, construction, materials testing methods and/or specification acceptance critiera.

3. If a decision is made to conduct a field distress investigation, it will be necessary to develop an appropriate plan for the investigation. Such a plan will assure the collection of appropriate information relevant to the specific type of distress.

In all probability both field and laboratory activities will be involved. In each case it will be important to make use of trained technologists and the laboratory facilities available. Assistance in planning and testing can be obtained by contacting, Materials and Tests Division, File D-9, State Department of Highways and Public Transportation, Austin, Texas 78703.

Table 1. Pavement Layer Stiffness Coefficients

Material	Original Design Value	As Constructed Values		
		Average	Range	Selected for Analysis
Asphalt Concrete	0.96	1.06		0.96
Asphalt Stabilized Base	0.80	0.85	0.66-0.91	0.80
Bank Run Gravel	0.50	0.65	0.48-0.93	0.65
Lime Stabilized Subgrade	0.35	0.38	0.19-0.39	0.30
Subgrade	0.25	0.22	0.21-0.27	0.22

Table 2.

Station	Location from C/L Left Lane	Asphalt Concrete Thickness, Inches	Black Base Thickness, Inches	Remarks
410+0	6' Lt. C/L Lt. Lane	2 3/8"	5"	Good stable core removed intact
412+50	11' Lt. "	2 1/8"	5"	Lt. side, Lt. lane (outside wheel path) - stable core, removed intact
413+75	3' Lt. "	2 1/8"	4 1/2"	Rt. side, Lt. lane (inside wheel path) - stable core
422+50	3' Lt. "	2"	--	Lt. side, Lt. lane (outside wheel path) - HMAC stable; Black Base failed
425+0	3' Lt. "	1 7/8"	*	Failure in Lt. lane from 425+75 to 426 * 1st course Black Base intact; 2nd course failed
426+50	3' Lt. "	1 1/2"	--	Inside Lt. lane 1st course Black Base intact; 2nd course failed
430+0	7' Lt. "	2"	--	1st course Black Base intact; 2nd course failed
432+50	4' Lt. "	2"	3"	1st course Black Base intact; 2nd course failed
440+0	9' Lt. "	1"	--	1st course Black Base intact; 2nd course failed
442+0	4' Lt.	1"	--	1st course Black Base intact; 2nd course failed
445+0		2"	5"	Good core removed intact

Table 3. Gradation and Asphalt Content for Asphalt Concrete

	% by Weight	Specification for Item 340, Type D
Passing 1/2"	100	100
Passing 3/8"	99.8	95-100
Passing 3/8", retained #4	30.6	20-50
Passing #4, retained #10	25.5	10-30
Total retained on #10	56.3	50-70
Passing #10, retained #40	12.0	0-30
Passing #40, retained #80	8.0	4-25
Passing #80, retained #200	10.6	3-25
Passing #200	7.5	0-6
Asphalt Content	5.6	

Table 4. Gradation and Asphalt Content for Black Base

Retained 1"	2.3
Retained 3/8"	31.0
Retained #4	46.1
Retained #10	56.1
Retained #40	75.8
Asphalt Content	4.3

Table 5. Properties of Remolded Asphalt Concrete and Black Base Mixtures

Material		Hveem Stability	Hveem Cohesiometer	Indirect Tensile Strength, psi	Resilient Modulus, psi x 10^6	Bulk Specific Gravity
Asphalt Concrete	As Received	48	448	133	0.900	2.361
	1% Additional Asphalt	22	363	110	0.650	2.388
	2% Additional Asphalt	0	218			2.373
	3% Additional Asphalt	0	171			2.341
Black Base	As Received	51	518	139	1.790	2.366

Table 6. Effect of Density on Black Base Mixture Properties

Specimen No.	Unit Weight, lbs/ft^3	Air Voids, Percent*	Test Speed in/min	Test Temp. °F	Unconfined Compressive Strength, psi	Moisture Content After Pressure Saturation, Percent
1	150.4	1.3	0.15	140	124.6	0.13
2	151.6	0.7	0.15	120	189.1	0.08
3	151.5	0.8	10.0	140	253.8	0.12
4	151.1	1.0	0.15	140	127.5	0.23
5	150.5	1.4	10.0	140	288.7	0.24
6	144.8	5.1	0.15	140	36.1	1.39
7	144.3	5.4	10.0	140	86.3	1.58
8	138.0	9.6	10.0	140	32.8	2.64
9	137.7	9.8	0.15	140	6.0	3.11

* Determined by pressure pycnometer.

All samples contained 4.3 percent asphalt cement.

Samples 6 - 9 molded at reduced compactive efforts.

Table 7. Properties of Asphalt Cement Used in the Laboratory Testing Program

Asphalt Condition	Viscosity, 140°F	Penetration, 100g, 5 sec, 77°F	Ductility, 77°F
Original	1970	88*	
After laboratory mixing and compaction--no lime added	5821	56	70
After laboratory mixing and compaction--1% lime added	5069	62	141

* after thin film oven test

Table 8. Black Base Mixture Properties--Aggregates Obtained from Project Stockpile and Compaction with Large Gyratory Compactor

Mixture	Specimen Number	Unit Weight, lbs/ft^3	Air Voids, Percent	Test Speed, in/min	Test Temp, °F	Unconfined Compressive Strength, psi	Moisture Content After Pressure Saturation, Percent	Asphalt Content, Percent
No Additive	1	151.3	7.6	10.0	138	86.9	0.43	3.5
	2	152.2	6.5	0.15	138	44.9	0.00	4.5
	3	147.5	10.6	10.0	138	51.8	1.49	2.5
	4	152.7	6.5	0.15	138	41.3	0.11	4.0
	5	150.1	8.7	10.0	138	77.7	0.98	3.0
	6	151.1	7.6	10.0	138	93.9	0.50	3.66
	7	152.3	7.0	0.15	138	44.3	0.37	3.5
	8	150.6	8.4	0.15	138	36.7	0.90	3.0
	9	152.0	6.6	10.0	138	95.0	0.02	4.5
	10	152.1	6.9	10.0	138	99.1	0.23	4.0
	11	152.4	6.8	0.15	138	44.9	0.31	3.66
	12	148.9	9.7	0.15	138	24.3	1.41	2.5
1% Lime		153.2	6.5	0.15	138	48.5	0.36	3.5
		151.9	6.7	0.15	142	48.0	0.00	4.5
		147.7	10.5	0.15	140	41.1	1.22	2.5
		150.5	8.5	0.15	138	42.6	0.80	3.0
		152.6	6.6	0.15	140	48.6	0.00	4.0
		151.6	7.6	10.0	140	95.3	0.58	3.25
		151.9	7.4	0.15	140	46.9	0.48	3.25
		152.9	6.7	10.0	142	91.8	0.46	3.5
		152.5	6.6	10.0	138	100.8	0.00	4.0
		151.7	6.8	10.0	138	86.0	0.00	4.5
		149.3	9.2	10.0	140	88.0	0.86	3.0
		146.2	11.3	10.0	138	87.6	1.33	2.5
1% Antistrip Agent		152.5	6.7	10.0	139	107.4	0.34	3.66
		153.4	6.2	0.15	139	50.7	0.26	3.66
		153.1	6.3	0.15	140	45.5	0.26	3.66
		152.5	6.7	10.0	140	99.8	0.38	3.66

Table 9. Black Base Mixture Properties--Aggregates Obtained from Project Stockpile and Compaction with Small Gyratory Compactor

Mixture	Hveem Stability	Hveem Cohesiometer	Indirect Tensile Strength, psi	Resilient Modulus, psi x 10^6	Water Absorption, Percent
No Additive	39	227	65	0.474	1.4
1% Lime	37	308	56	0.507	1.1
1% Antistrip	48	259	50	0.414	1.0

Table 10. Properties of Unstabilized Pavement Layers

Layer	Station	Liquid Limit	Plastic Index	Soil Binder, Percent	Moisture Content	Sieve Size							
						1 1/4	7/8	5/8	3/8	4	10	20	40
Subgrade	470+70	53	37	98	17.6					0	1	2	2
	491+50	48	33	98	19.0					0	6	1	2
Lime Treated Subgrade	470+70	49	34	96	18.3				0	1	2	3	4
	491+50	48	31	95	20.8				0	1	2	4	5
Flexible Base	470+70	27	15	40	6.0	0	2	6	16	29	39	48	60
	491+50	33	22	35	6.0	5	13	20	27	38	47	55	65

Table 11. Asphalt Cement Properties

Sample Designation	Penetration, 77°F, 100 g, 5 sec, 0.1 mm	Viscosity, 140°F poises	Ductility, 77°F cm	Ring & Ball Softening Point
Original Asphalt (August - 1978)	75	2,000	140+	
Asphalt Concrete Extracted and Recovered by SDHPT	23 38	182,000 21,377	5 15	
Asphalt Concrete Extracted and Recovered by TTI	32	15,900		144
Black Base Extracted and Recovered by SDHPT	26	57,035	4	
Black Base Extracted and Recovered by TTI	23	38,700		151

Table 12. Resilient Modulus Results on Surface and Base Materials

Material	Sample No.	Air Voids	Resilient Modulus @ 77°F, M_R X 10^6 Before Soaking	After 7-day soak	After Lottman
Surface	A	9.6	0.180		0.0530
	B	11.7			
	C	10.9	0.187	0.144	
	547	5.5	0.296		
	421	8.1	0.321		
	450	8.7	0.347		
Average		9.1	0.266	0.144	0.0530
Base	A-1	8.7	0.252	0.155	
	A-2	9.4	0.233		0.0137
	B-1	9.7	0.207		0.0180
	B-2	9.6	0.194	0.123	
	B-3	8.3	0.306	0.156	
	C-1	9.3	0.240		0.0135
	C-2	9.0	0.256		0.0200
	C-3	9.0	0.202	0.128	
	547A	5.8	0.413		
	547B	6.8	0.343		
	547C	5.2	0.427		
	421A	5.1	0.488		
	450A	5.3	0.494		
	450B	6.3	0.467		
Average		7.7	0.323	0.140	0.0163

Table 13. Hveem Stability Results on Surface and Base Materials

Material	Sample No.	Air Voids	Hveem Stability		
			Before soak	After 7-day soak	After Lottman
Surface C	A	9.6	22		20
	B	11.7			
	C	10.9	17	16	
	547	5.5			
	421	8.1			
	450	8.7			
Average		9.1	20	16	20
Base	A-1	8.7	24	17	
	A-2	9.4	15		5
	B-1	9.7	14		0
	B-2	9.6	18	3	
	B-3	8.3	24	11	
	C-1	9.3	16		0
	C-2	9.0	18		0
	C-3	9.0	16	8	
	547A	5.8			
	547B	6.8			
	547C	5.2			
	421A	5.1			
	450A	5.3			
	450B	6.3			
Average		7.7	18	10	1

Table 14. Indirect Tension Test Results on Surface and Base Materials

Material	Sample No.	Indirect Tension Before Lottman			Indirect Tension After Lottman		
		E	σ_x	ε_x	E	σ_x	ε_x
Surface	A				14,000	66	.00469
	B						
	C						
	547	39,804	137	.00345			
	421	26,289	100	.00381			
	450						
Average		33,047	119	.00363	14,000	66	.00469
Base	A-1						
	A-2				2,000	8	.00381
	B-1*				69,200	12	.00018
	B-2						
	B-3						
	C-1						
	C-2				4,670	12	.00261
	C-3				4,240	12	.00283
	547A						
	547B	23,400	46	.00327			
	547C	21,100	86	.00407			
	421A						
	450A						
	450B*	62,600	94	.00150			
Average		22,250	66	.00367	3,640	11	.00308

* Note: These values appear to be inconsistent with other data.

Table 15. Marshall Stability Test Results on Black Base Material

Material	Sample No.	Marshall Stability			
		Before 7-day soak		After 7-day soak	
		Stability lbs	Flow 0.01 in	Stability lbs	Flow 0.01 in
	547A	410	29		
	421A	1110	37		
	450A	380	35		
Base	A-1			480	29
	B-2			568	28
	B-3			670	24
	C-3			397	28
Average		630	30	529	27

Table 16. Dynaflect Deflection Data

Facility	Date of Measurements	Mean x 10^{-3} in.	Standard Deviation x 10^{-3} in.	Coefficient of Variation	Minimum Value x 10^{-3} in.	Maximum Value x 10^{-3} in.	Range x 10^{-3} in.	No. of Readings
Main Track	March, 1974	0.645	0.179	27.7	0.37	1.14	0.77	96
	June, 1976	0.790	0.201	25.4	0.41	1.32	0.99	90
	April, 1978	0.765	0.191	25.0	0.40	1.14	0.74	91
	April, 1980	0.991	0.223	22.5	0.52	1.59	1.07	92

Table 17. Resilient Modulus

Samples	Resilient Modulus x 10^6 psi				
	-13°F	32°F	68°F	77°F	104°F
1.4 A1	3.468	1.802	1.037	0.8103	0.2510
1.4 B1	3.567	2.012	0.954	0.7386	0.2671
1.4 C1	3.622	2.152	0.935	0.7600	0.2873
5 C1	4.089	2.126	1.070	0.7164	0.2767
5.8 A1	4.059	2.839	1.012	0.7513	0.2352
8.8 A1	4.725	2.536	1.114	0.8612	0.2302
5 C2	4.264	2.712	0.977	0.6950	0.2534
5.8 A2	4.579	2.299	1.075	0.7026	0.2679
7 A2	3.906	1.781	0.809	0.4885	0.2249
7 B2	4.879	2.492	1.186	0.3943	0.4458
8.8 A2	4.142	2.952	0.949	0.7545	0.4238

Table 18. Top Layer Material Properties

Sample	Bulk Sp. Gr.	Rice Sp. Gr.	% Air Voids	M_R x 10^6 psi 77°F	Hveem		Marshall		Indirect Tension			7-Day Soak M_R x 10^6 psi 77°F	7-Day Soak Hveem		7-Day Soak Marshall		Lottman Procedure M_R x 10^6 psi 77°F	Lottman Procedure Hveem		Lottman Procedure Indirect Tension		
					S	R	Stab, lbs.	Flow .01in	E psi	σ_x psi	E_x in/in		S	R	Stab, lbs.	Flow .01in		S	R	E psi	σ_x psi	E_x in/in
3A1	2.229	2.323	4.1	0.8934	39	92						.7152	28	91	2660	27						
3B1	2.245		3.4	0.8224			3658	14														
3C1	2.252		3.1	0.8331	29	96											.2748	6	76	21711	110	.0050
5A1	2.279		1.9	0.7777	13	84						1.363	16	86	2863	21						
5B1	2.277		2.0	0.6644			3333	14														
5.8B1	2.286		1.6	0.7513					70100	185	.0025											
5.8C1	2.290		1.4	0.7205	18	86											.7845	10	76	53335	177	.0033
7A1	2.256		2.9	0.7105	12	84						.6976	14	85	2531	23						
7B1	2.271		2.2	0.8858			3563	14.5														
7C1	2.270		2.3	0.7125					80152	164	.0021											
8.8B1	2.310		0.6	0.8333					59229	194	.0032											
8.8C1	2.298		1.1	0.8258	15	80											.8047	0	36	67488	168	.0025

Table 19. Bottom Layer Material Properties

Sample	Bulk Sp. Gr.	Rice Sp. Gr.	% Air Voids	M_R x 10^6 psi 77°F	Hveem S	Hveem R	Marshall Stab lbs	Marshall Flow .01in.	Indirect Tension E psi	Indirect Tension σ_x psi	Indirect Tension ε_x in/in	7-Day Soak M_R x 10^6 psi 77°F	7-Day Soak S	7-Day Soak R	7-Day Soak Stab lbs.	7-Day Soak Flow .01in	Lottman Procedure M_R x 10^6 psi 77°F	Lottman Procedure Hveem S	Lottman Procedure Hveem R	Lottman Procedure Indirect Tension E psi	Lottman Procedure Indirect Tension σ_x psi	Lottman Procedure Indirect Tension ε_x in/in
1.4A2	2.301	2.329	1.2	0.6429			3744	11														
1.4B2	2.303		1.1	0.7638	29	88						.5766	25	85	2630	17						
1.4C2	2.302		1.2	0.6355					60646	118	.0019											
3A2	2.301		1.2	0.6839			3264	12.5														
3B2	2.307		0.9	0.7108	23	86						.5485	15	76	2282	16.5						
3C2	2.304		1.1	0.8392	27	87											.0333	0	64	5673	21	.0037
5A2	2.300		1.2	0.6025			2912	10.5														
5B2	2.285		1.9	0.6289	31	88						.7310	35	89	2305	18.5						
5.8B2	2.299		1.3	0.8442					57002	143	.0025											
5.8C2	2.287		1.8	0.7150	29	89											.0417	0	63	6408	20	.0031
8.8B2	2.297		1.4	0.8418					62856	107	.0017											
8.8C2	2.301		1.2	0.8810	24	86											.0365	0	67	4390	15	.0033

Table 20. Main Track Cores - Recovered Asphalt Cement Properties

Sample Description	Asphalt Content,* Percent	Penetration at 77°F dmm	Viscosity at 140°F Poises
One location, top one inch	7.1	18	27,300
One location, top layer	6.4	45	3,460
One location, bottom layer	6.3	35	6,210
Full depth, Location 1	6.2	25	15,320
Location 2	6.3	26	16,000
Location 3	6.4	19	26,700
Location 4			
Location 5			

*Percent asphalt by weight of mixture.

Table 21. Pavement Rehabilitation Alternatives Defined

Plan 1:	Two-inch asphalt concrete overlay with maintenance on a 7-year cycle (asphalt concrete $25.00 per ton).
Plan 2:	Chip seal plus 2-inch asphalt concrete overlay with maintenance (chip seal $0.55 per square yard, asphalt concrete $25.00 per ton).
Plan 3:	Fabric reinforcement plus 2-inch asphalt concrete overlay with maintenance (fabric reinforcement $1.25 per square yard, asphalt concrete $25.00 per ton).
Plan 4:	Recycle existing 4 inches of material and blend a selected aggregate into recycled mixture. A 2-inch overlay is scheduled after 5 years (recycling at $20.00 per ton and overlay at $25.00 per ton).
Plan 5:	Recycling existing 4 inches of asphalt materials and 2 inches of asphalt concrete overlay with maintenance (recycling $16.00 per ton, asphalt concrete $25.00 per ton).
Plan 6:	Recycling existing 4 inches of asphalt materials and 2 inches of asphalt concrete overlay with maintenance which includes a 2-inch overlay (recycling $16.00 per ton, asphalt concrete $25.00 per ton).
Plan 7:	Recycling existing 4 inches of asphalt materials and 2 inches of asphalt concrete overlay with maintenance (recycling $20.00 per ton, asphalt concrete $25.00 per ton).
Plan 8:	Delay recycling 4 years and then recycle and add 2 inches of asphalt concrete overlay with maintenance (recycling $16.00 per ton, asphalt concrete $25.00 per ton).
Plan 9:	Heater-scarify to a depth of 1 to 1.5 inch and 2 inches of asphalt concrete overlay with maintenance (heater-scarification $0.90 per square yard, asphalt concrete $25.00 per ton).
Plan 10:	Asphalt-rubber interlayer and 2 inches of asphalt concrete overlay with maintenance (asphalt-rubber interlayer $1.25 per square yard, asphalt concrete $25.00 per ton).

Table 22. Cost Data Used to Analyze Rehabilitation Strategies

Material or Operation	Cost $/Ton	Cost $/Sq Yd
Asphalt Concrete	25.00	1.25*
Recycle Asphalt Concrete	20.00	1.00*
Recycle Asphalt Concrete	16.00	0.80*
Chip Seal Coat		0.55
Fabric Interlayer		1.25
Heater-Scarification		0.90
Crack Sealing		0.15
Asphalt-Rubber Interlayer		1.25

* Cost per square yard for one-inch thickness.

Table 23. Rehabilitation Alternatives Cost Schedule*

Year	Plan 1 2" A.C. Overlay	Plan 2 Seal Coat +2" A.C. Overlay	Plan 3 Fabric Reinforcement +2" A.C. Overlay	Plan 4 Recycle	Plan 5 Recycle +2" A.C. Overlay	Plan 6 Recycle +2" A.C. Overlay	Plan 7 Recycle +2" A.C. Overlay	Plan 8 Recycle +2" A.C. Overlay	Plan 9 Heater-Scarify +2" A.C. Overlay	Plan 10 Asphalt-Rubber Interlayer +2" A.C. Overlay
1980	2.50	3.05	3.75	4.00	5.70	5.70	6.50	0.15	3.40	3.75
1981								0.15		
1982								0.15		
1983	0.08							0.15		
1984	0.13	0.08	0.08					6.50	0.08	0.08
1985	0.15	0.13		2.50						
1986	0.15	0.15	0.13						0.13	0.13
1987	2.50	0.15								
1988		0.15	0.15		0.08	0.08	0.08		0.15	0.15
1989		2.50								
1990	0.08		2.50		0.13	0.13	0.13		2.50	2.50
1991	0.13			0.08				0.08		
1992	0.15	0.08			0.15	0.15	0.15			
1993	0.15	0.13	0.08	0.13				0.13	0.08	0.08
1994	2.50	0.15	0.13		0.15	2.50	0.15		0.13	0.13
1995		0.15	0.15	0.15				0.15	0.15	0.15
1996		3.05	0.15		0.15		0.15		0.15	0.15
1997	0.08		0.15	0.15				0.15	0.15	0.15
1998	0.13		0.15		0.15	0.08	0.15		0.15	0.15
1999	0.15		0.15	0.15				0.15	0.15	0.15
2000	0.15	0.08	0.15		0.15	0.13	0.15		0.15	0.15

* Numbers represent costs per square yard.

Table 24. Cost and Energy Summary

Plan No.	Method	Energy, BTU/Sq.Yd.		Cost, Dollars/Sq.Yd.		
					20 Year Life*	
		Initial	20 Year Life	Initial	0 Percent	8 Percent
1	2" AC Overlay	57,800	200,000	2.50	9.03	5.50
2	Seal Coat + 2" AC Overlay	61,700	203,000	3.05	9.85	5.80
3	Fabric + 2" AC Overlay	60,000	145,000	3.75	7.72	5.44
4	Recycle	119,600	190,000	4.00	7.16	5.91
5	Recycle + 2" AC Overlay	177,400	195,000	5.70	6.66	6.03
6	Recycle + 2" AC Overlay	177,400	244,000	5.70	8.77	6.76
7	Recycle + 2" AC Overlay	177,400	195,000	6.50	7.46	6.83
8	Recycle + 2" AC Overlay	2,200	201,000	0.15	7.76	5.52
9	Heater-Scarify + 2" AC Overlay	74,800	160,000	3.40	7.37	5.09
10	Asphalt Rubber Interlayer + 2" AC Overlay	64,000	149,000	3.75	7.72	5.44

*Equal annual costs assuming 0 and 8 percent rate of return.

Table 25. Advantages and Disadvantages of Rehabilitation Alternatives

Plan No. and Description	Advantages	Disadvantages	Time for Rehabilitation, Months*	Chance of Success**
1 - Two-inch	Minimum initial cost Minimum construction time Increased tire wear	Early reflection cracking High Maintenance requirement Probably structurally inadequate for extended use Require preliminary deep patching	0.5	60
2 - Chip seal + two-inch overlay	Somewhat delayed reflection cracking Relatively low initial cost	Reflection cracking less than Plan 1 Relatively high maintenance requirement Probably structurally inadequate for extended use Require preliminary deep patching	0.5	70
3 - Fabric reinforcement + two-inch overlay	Reduction in total amount of reflection cracking Relatively low initial cost Increased tire wear	Somewhat delayed reflection cracking Relatively high maintenance requirement Probably structurally inadequate for extended use Requires preliminary deep patching Can not recycle at a later date	0.5	75
4 - Recycling existing material without overlay	Eliminates all existing cracks Delays formation of new cracks for 3-5 year Relatively low maintenance costs	Relative high initial cost Minor improvement in tire wear Increased construction time Limited bid competition	1.0	60
5, 6 & 7 - Recycling existing material + overlay	Eliminates all existing cracks Delays formation of new cracks for 5-7 years Increased tire wear Low maintenance cost	High initial cost Increased construction time Limited bid competition	1.5	90

Table 25 (continued)

8 - Delay rehabilitation and recycle at later date and overlay	Low initial cost	High continued maintenance prior to rehabilitation	1.5	9(
9 & 10 - Heater-scarification and interlayer + overlay	Reduction total amount of reflection cracking Relatively low initial cost Increased tire wear Can be recycled at later date	Somewhat delayed reflection Relatively high maintenance requirement Probably structurally inadequate for extended use Requires preliminary deep patching	0.5	8(

*Assumes no weather delays and good contractor.

**Chance to perform 7 years without overlay

***Cost for 0 interest rate from Table 3.

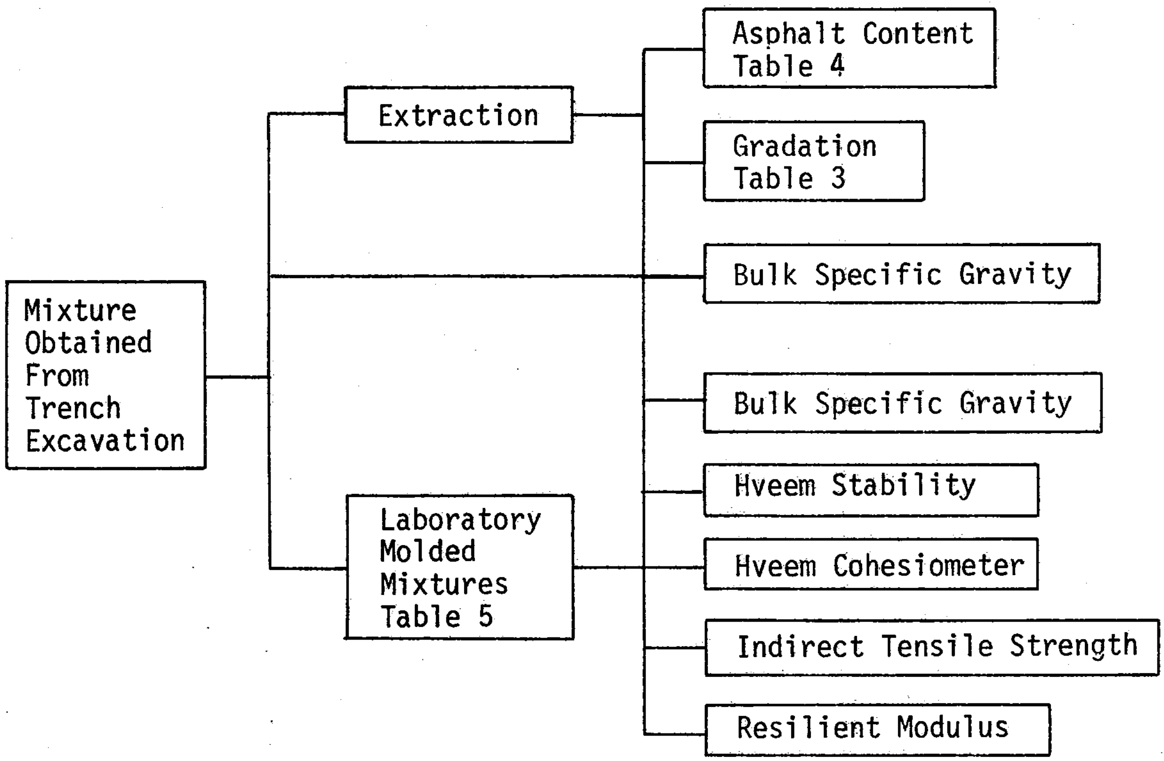


Figure 1. Laboratory Tests Performed by Division D-9 on Asphalt Concrete Surface Course Obtained from Trench Excavation

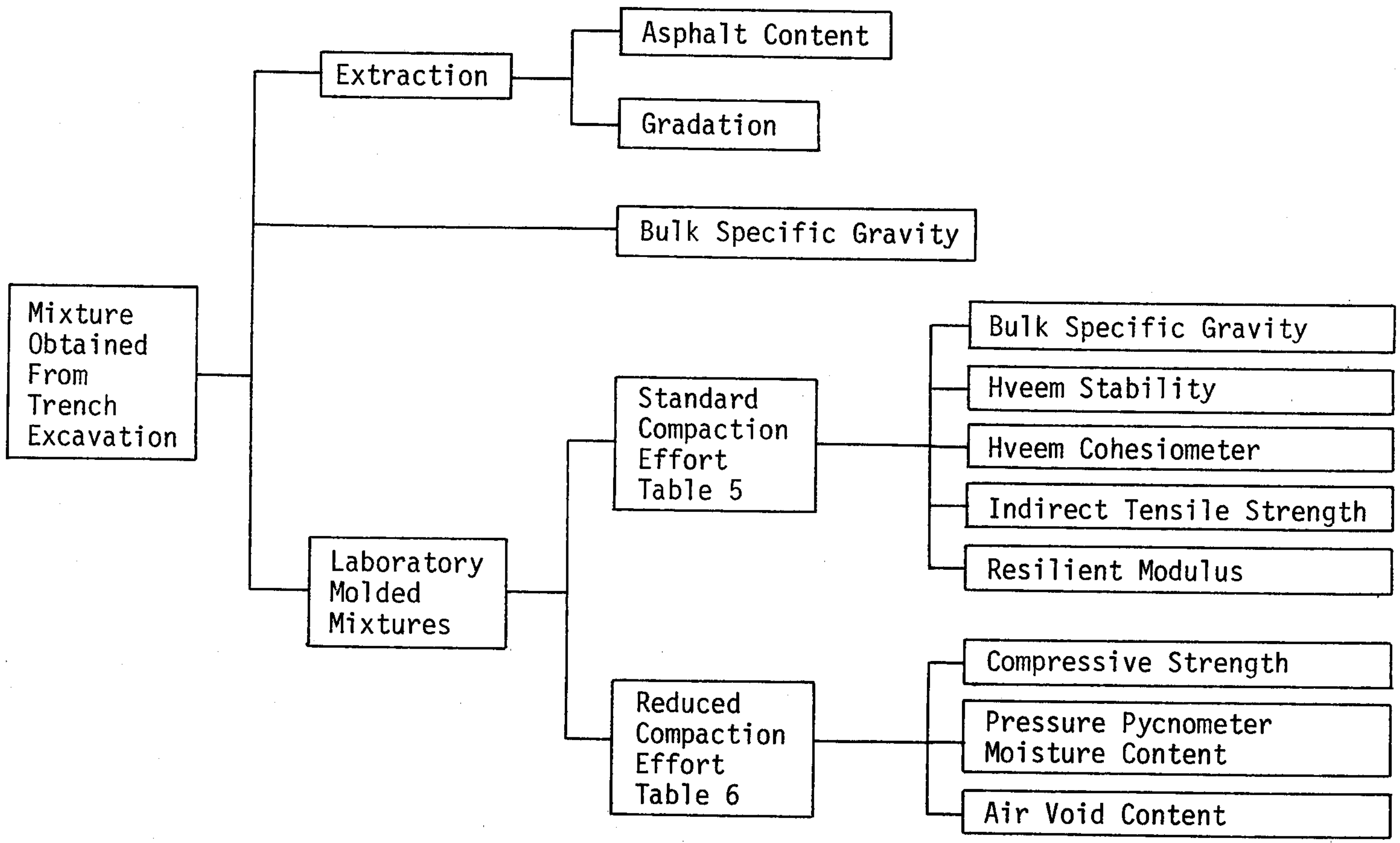


Figure 2. Laboratory Tests Performed by Division D-9 on Black Base Obtained from Trench Excavation

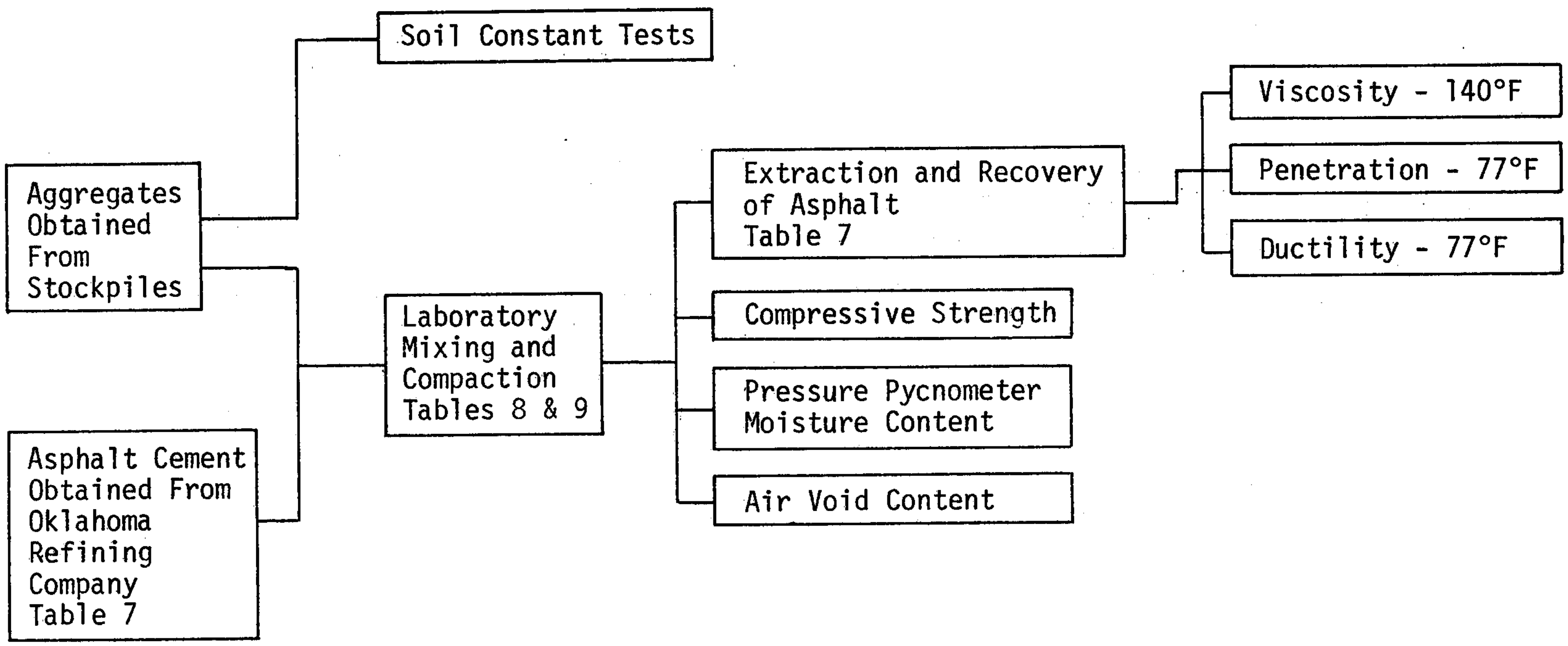


Figure 3. Laboratory Tests Performed by Division D-9 on Black Base Aggregates Obtained from Project Stockpile

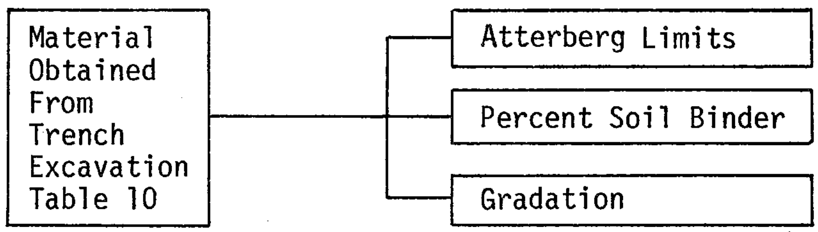


Figure 4. Laboratory Tests Performed by Division D-9 on Subgrade, Lime Treated Subgrade and Subbase Obtained from Trench Excavation

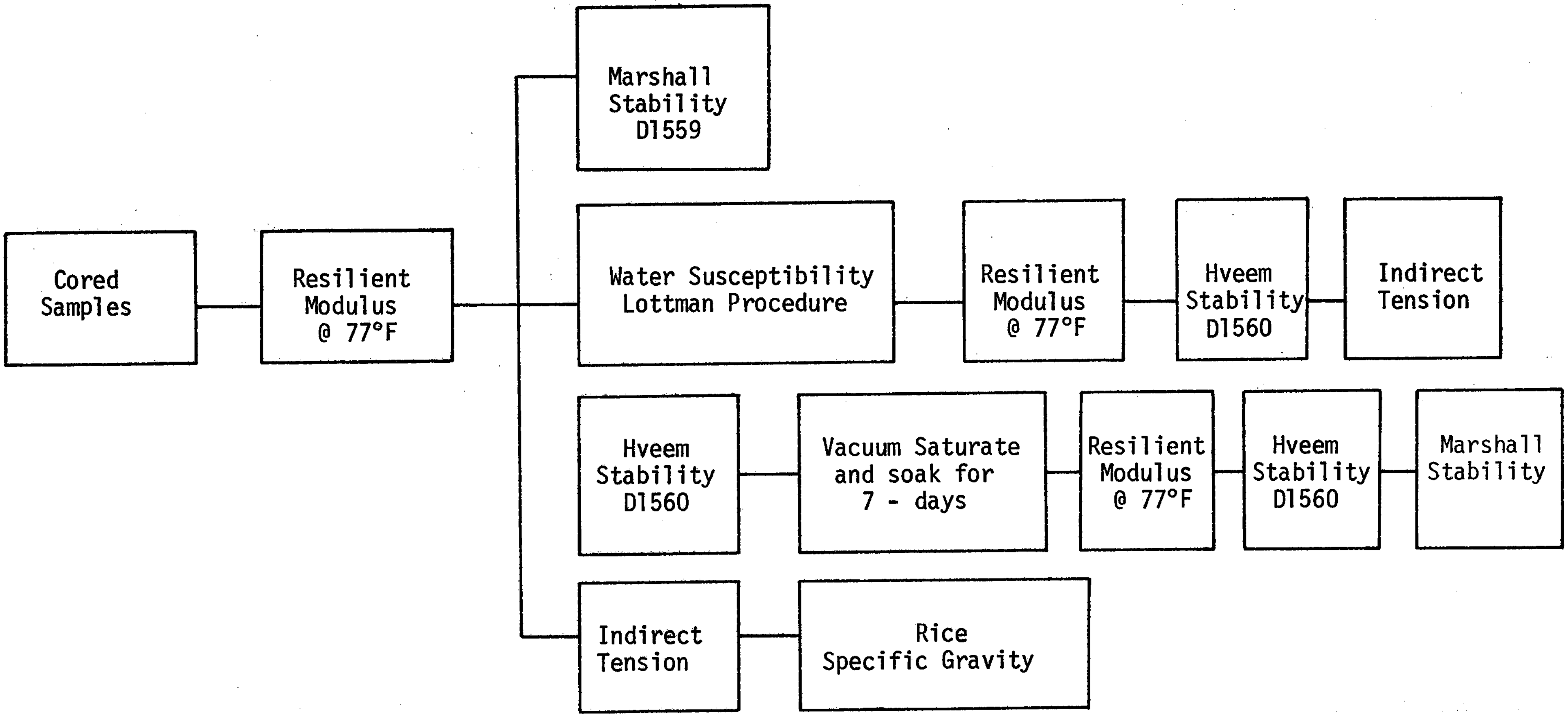


Figure 5. Test Plan for Surface and Black Base Cores

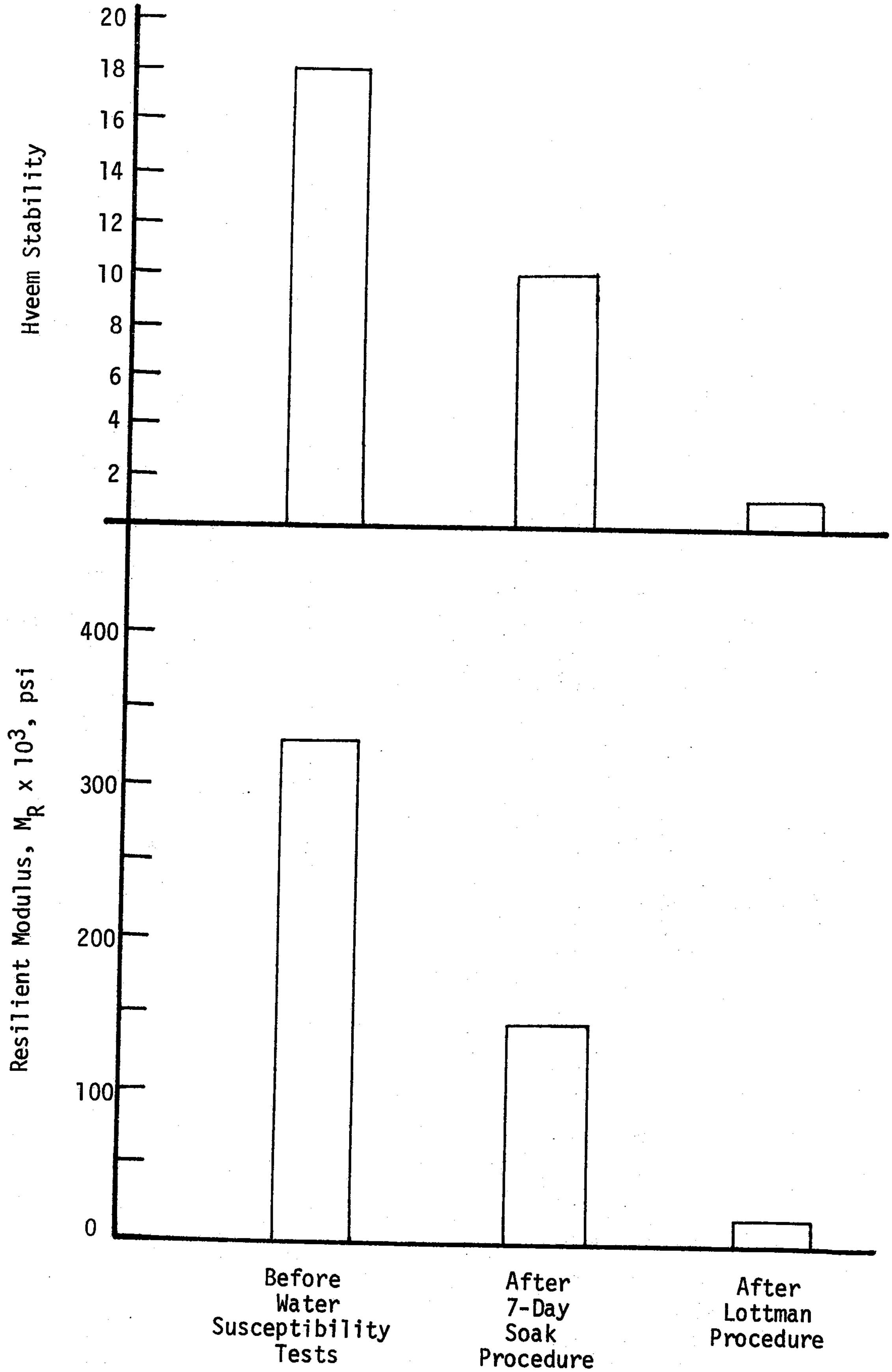


Figure 6. Water Susceptibility Tests Results on Black Base Material on US 287.

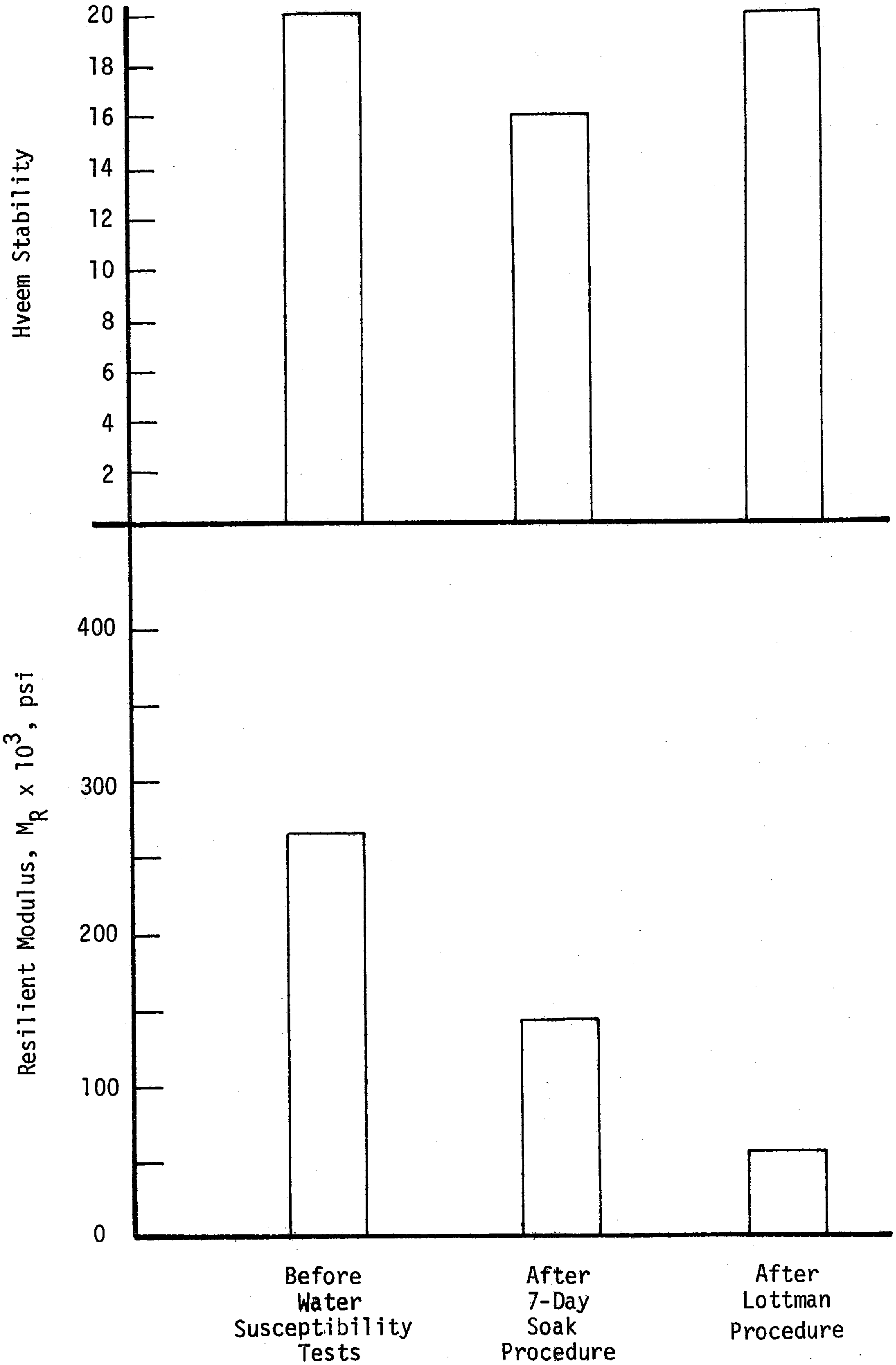
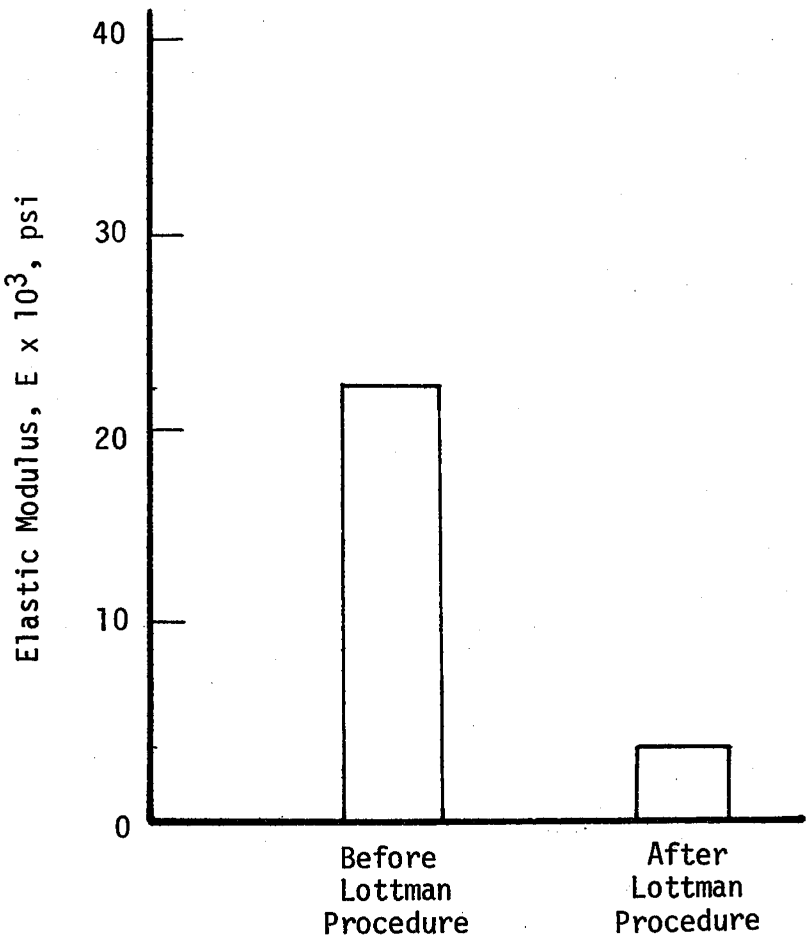


Figure 7. Water Susceptibility Test Results on Asphalt Concrete Surface Material on US 287.



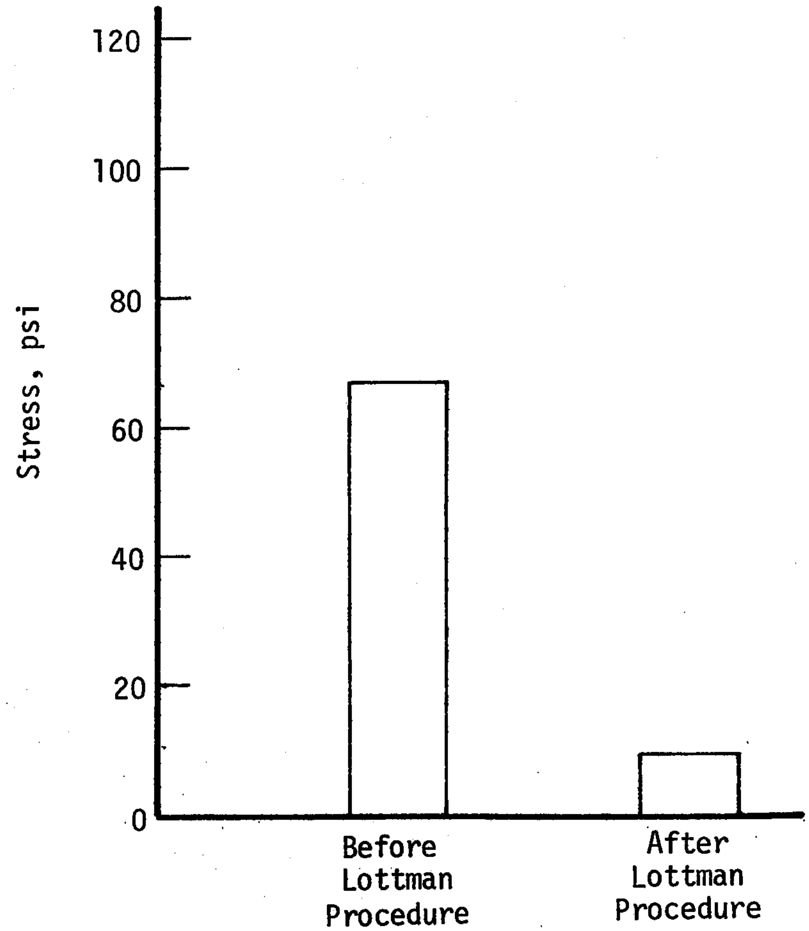


Figure 8. Indirect Tension Test Results on Black Base Material on US 287.

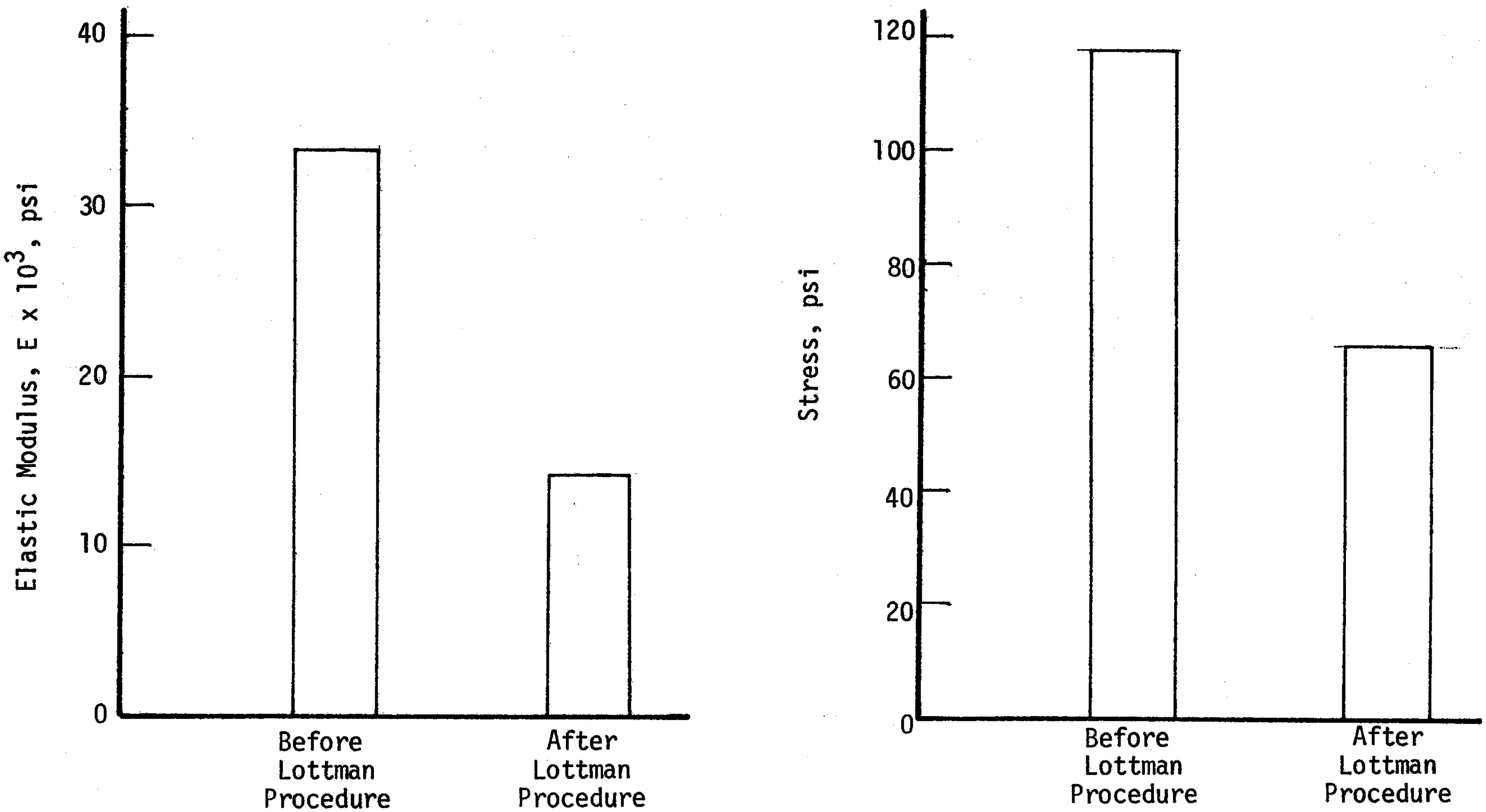


Figure 9. Indirect Tension Test Results on Asphalt Concrete Surface Material on US 287.

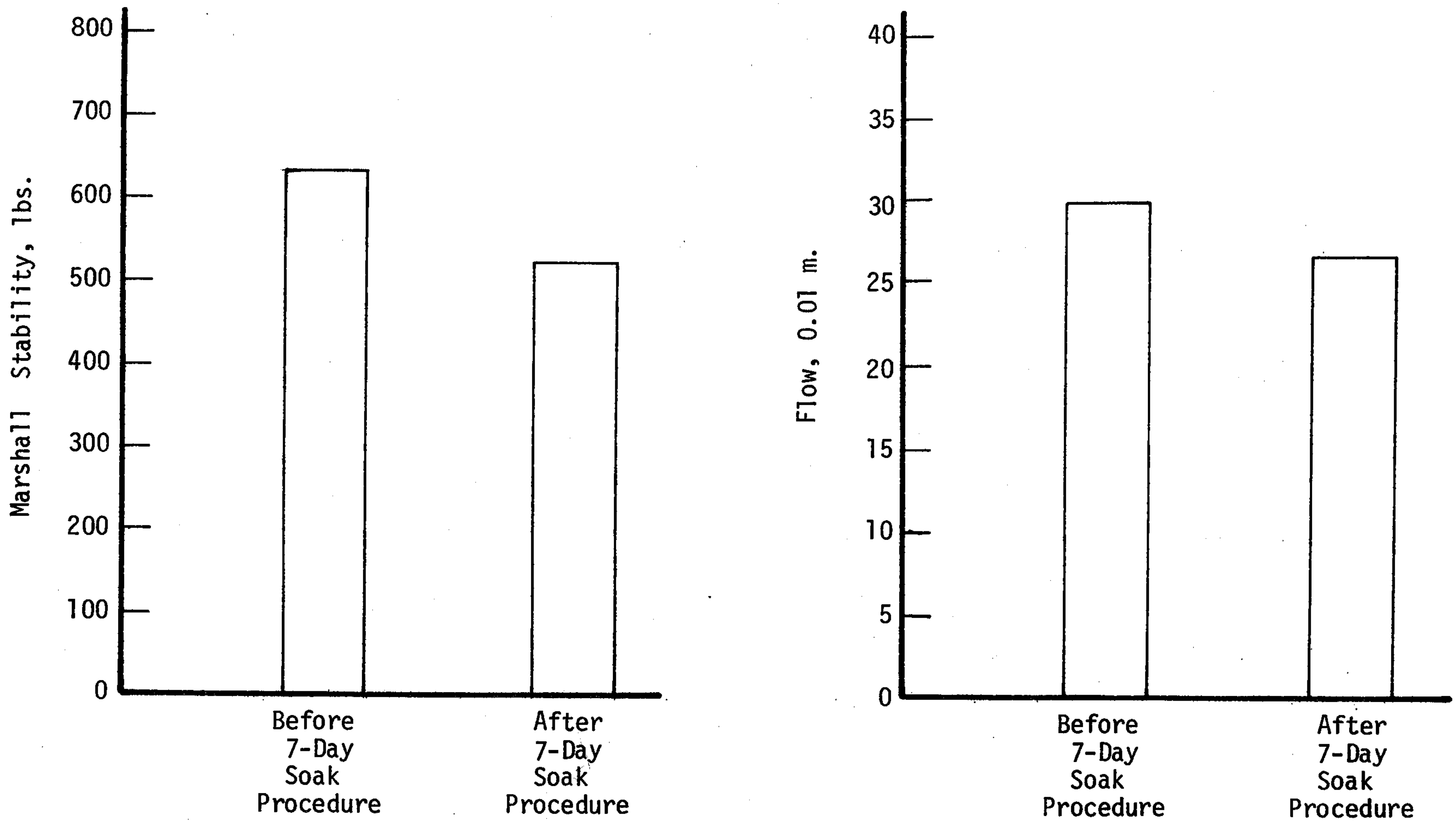


Figure 10. Marshall Test Method Results on Black Base Material on US 287.

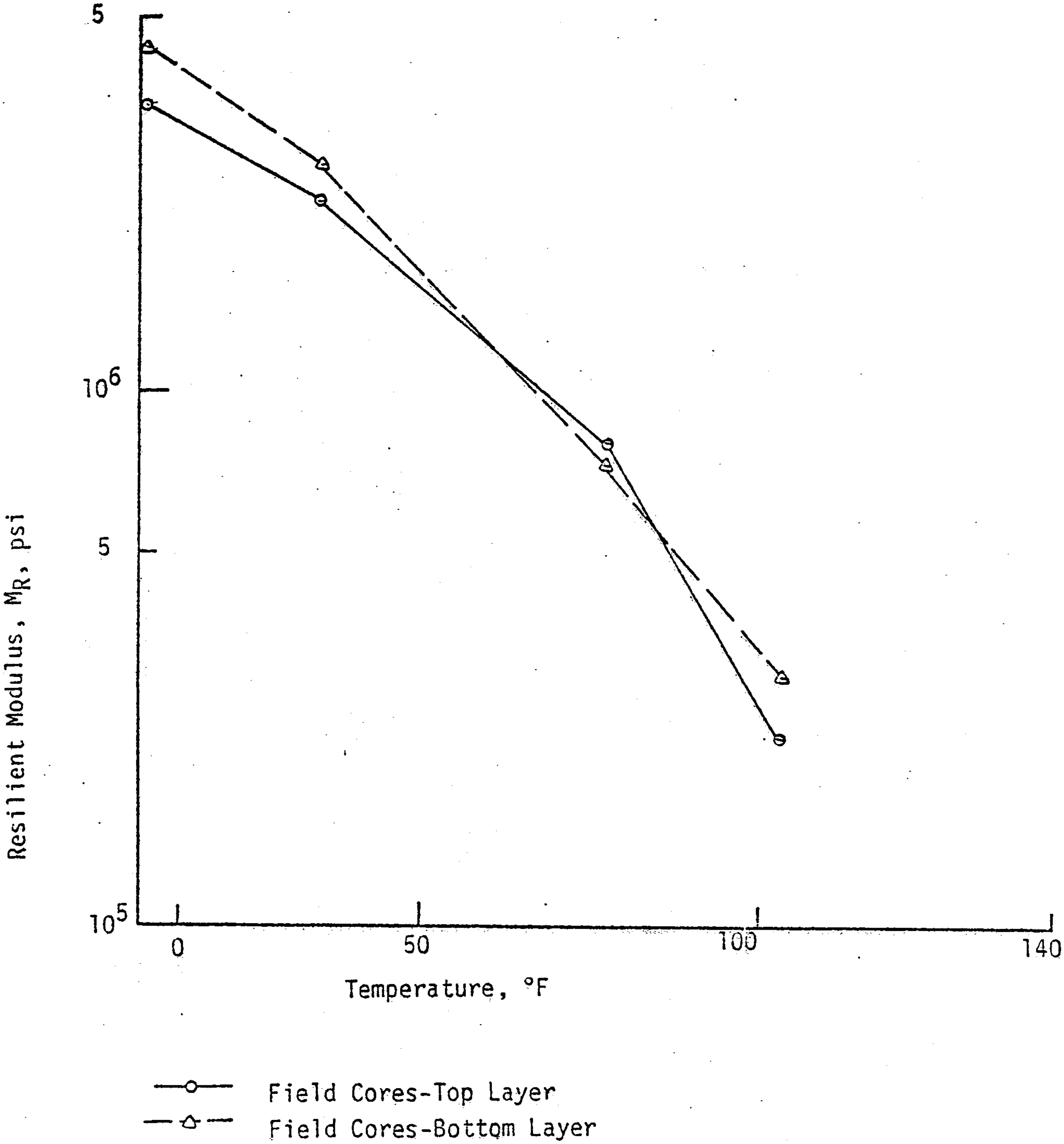


Figure 11. Resilient Modulus

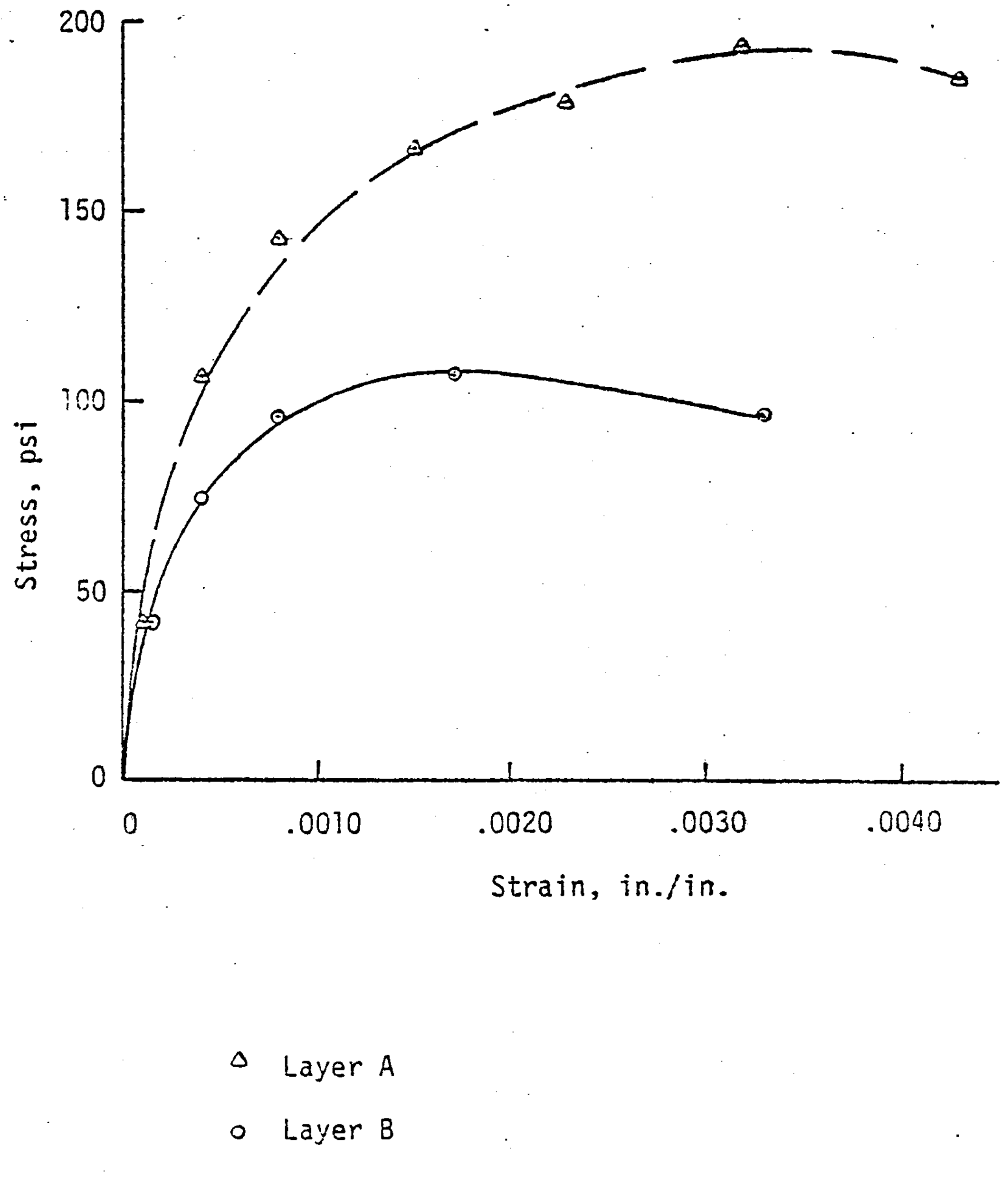
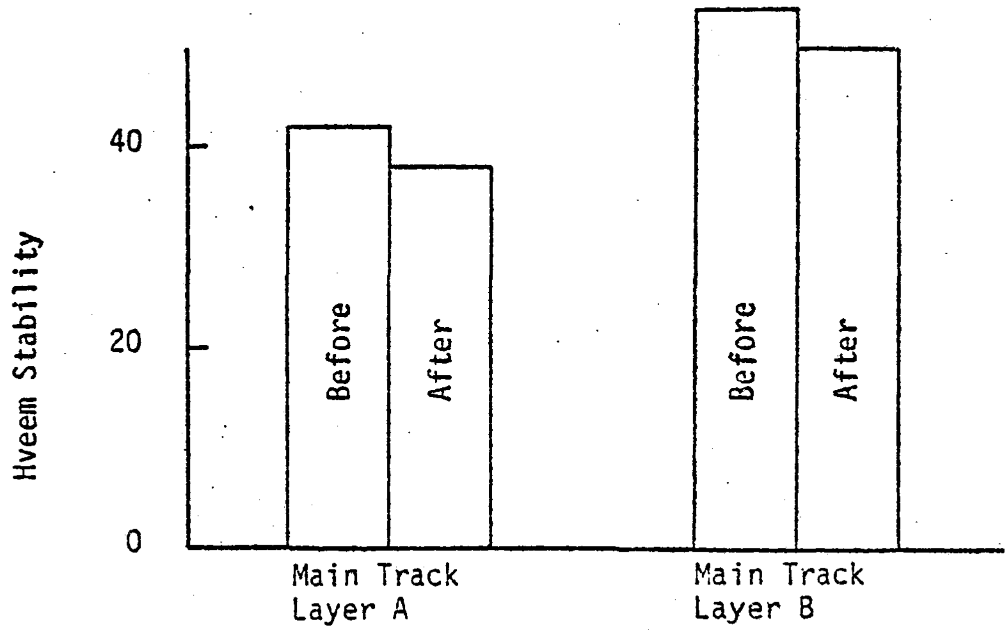


Figure 12. Stress-Strain Relationship for Layers A & B at MP 8.8



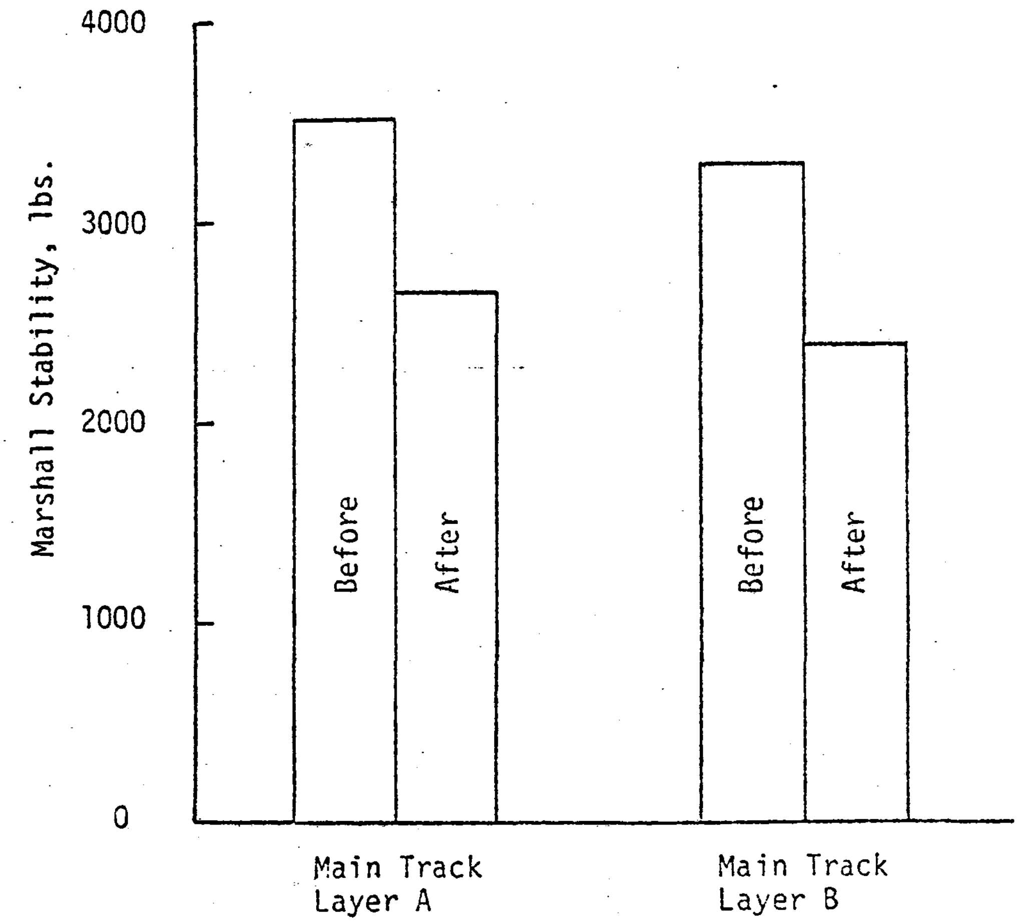


Figure 13. 7-Day Soak Water Susceptibility Test

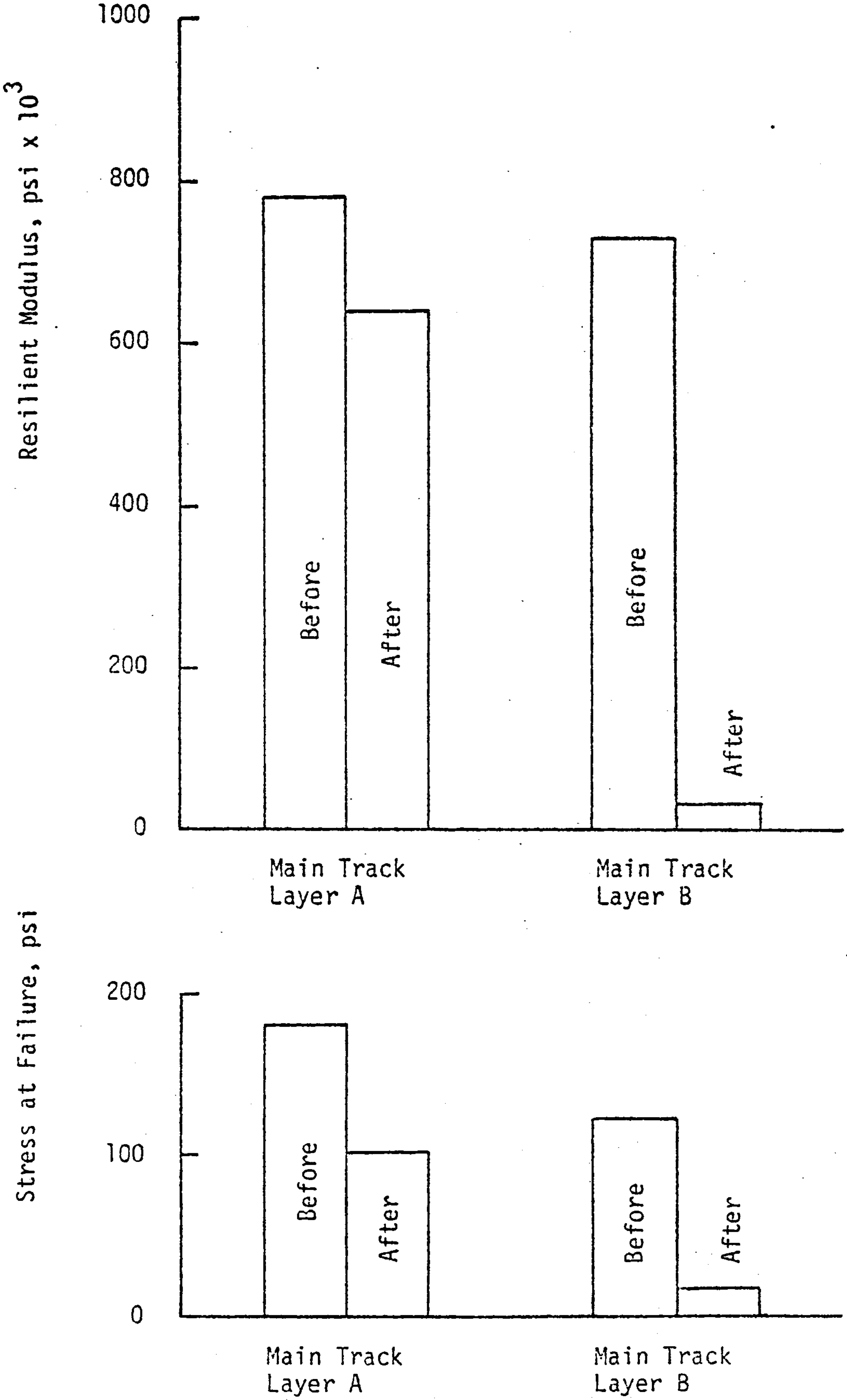


Figure 14. Lottman Water Susceptibility Test