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16. Abstract

Fog seals have been used for maintenance purposes in Texas with varying degrees of success for several years. A fog seal is a light application of slow-setting or medium-setting asphalt emulsion diluted with water. The principal reasons for using fog seals are: (1) to stop shelling on chip seals and surface treatments, (2) to reduce the rate of ravelling and cracking on asphalt concrete pavements, and (3) to reduce the potential for air and water to enter into the pavement structure.

Rejuvenators have been used to a limited degree in the state. The purpose of a rejuvenator is to penetrate somewhat into the asphalt concrete and soften (rejuvenate) the asphalt binder. It is also used to seal the pavement and minimize future oxidation.

Application of fog seals and rejuvenators appears to be economically attractive. Many highway districts in Texas routinely use these products and techniques and believe they are cost effective. Information on the value of these treatments is not well documented; however, considering the widespread use of fog seals, it is obvious that a number of knowledgeable people feel that they have a significant economic value.

The objective of this study was to determine the effectiveness of fog seals and rejuvenators at performing their intended functions and thereby evaluate the economic effectiveness of these maintenance treatments.

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EFFECTIVENESS OF FOG SEALS AND REJUVENATORS FOR BITUMINOUS PAVEMENT SURFACES

by

Cindy K. Estakhri
Engineering Research Associate

and

Harish Agarwal
Graduate Assistant Research

Research Report 1156-1F
Research Study 2-18-87-1156

Sponsored by

Texas State Department of Highways and Public Transportation
United States Department of Transportation
Federal Highway Administration

Submitted by

Texas Transportation Institute
Texas A&M University
College Station, Texas 77843

April, 1991

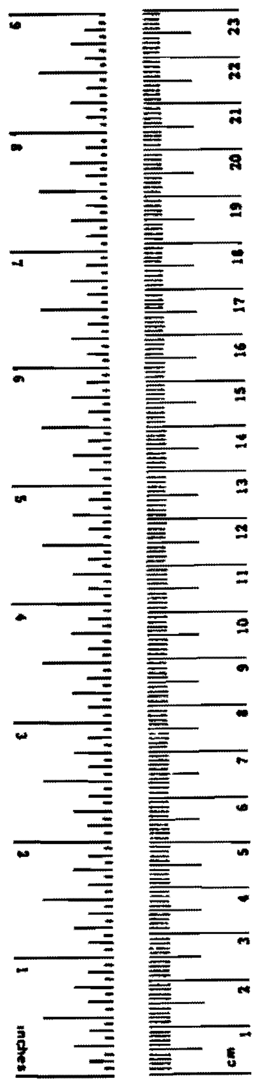
METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	2.54	centimetres	cm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in^2	square inches	645.2	centimetres squared	cm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha
	MASS (weight)			
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
	VOLUME			
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

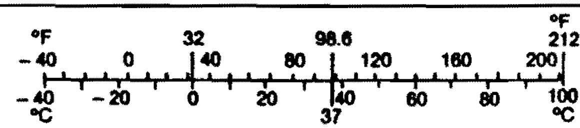
NOTE: Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
	AREA			
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac
	MASS (weight)			
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T
	VOLUME			
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

* SI is the symbol for the International System of Measurements

IMPLEMENTATION STATEMENT

The most common use of fog seals by the Department is as a corrective measure on chip seals to stop or reduce the rate of stone shelling. Results of laboratory and field tests showed that the correct fog seal application rate can be very effective in reducing aggregate loss. A fog seal applied to a chip seal generally increases the equivalent uniform annual cost of that chip seal from $0.083 to $0.10 per square yard. Based on the information obtained in this study, fog seals can be cost-effective for reducing the rate of stone shelling in chip seals if placed at the proper application rate and before the first winter season following the chip seal. Fog seals placed later than the first winter season do not appear cost effective in reducing the rate of stone shelling. Design guidelines were developed in this study for determining fog seal application rates for chip-seal surfaces.

Fog seals applied to asphalt concrete at residual rates of 0.05 gallons per square yard are not effective at sealing the surface to reduce the rate of aging within the mix. The Department generally uses 0.05 gallons per square yard or less. For asphalt concrete, fog seals can be used more effectively to correct specific surface problems such as ravelling or loss of surface fines.

Rejuvenators are used to a very limited degree by the Department. It was found that rejuvenators are effective at reducing the stiffness of a mix when air voids are as high as 10 to 12 percent. A laboratory study revealed that the combination of the asphalt source in the mix and the type rejuvenator used can influence the effectiveness of the rejuvenator.

The results of this study are primarily targeted to maintenance engineers, superintendents, and supervisors. Guidelines are presented to aid in the decision-making process of how maintenance funds can best be allocated. Information from the study can be used: (1) to determine when fog seals should be applied if at all, (2) to determine what pavement conditions warrant a fog seal or rejuvenator, and (3) to determine how a fog seal or rejuvenator affects the cost of the pavement surface as compared with other maintenance treatments such as chip seals. Design charts are also presented to aid in estimating appropriate application rates.

Some districts have maintained a practice of routinely fog sealing bituminous pavements every 3 to 4 years. Results from this study indicate that this type of practice is not cost-effective. Fog seals are most effective when used to correct specific surface problems, such as loss of stone from chip seals or loss of surface fines in asphalt concrete.

Results from this study are easily consolidated and will best be implemented through the distribution of the brief "Research Summary Report" to all districts. This research report can be used to convey further information to those interested.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

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SUMMARY AND CONCLUSIONS

Fog seals have been used for maintenance purposes in Texas with varying degrees of success for several years. A fog seal is a light application of slow-setting or medium-setting asphalt emulsion diluted with water. The principal reasons for using fog seals are: (1) to stop shelling on chip seals and surface treatments, (2) to reduce the rate of ravelling and cracking on asphalt concrete pavements, and (3) to reduce the potential for air and water to enter into the pavement structure.

Rejuvenators have been used to a limited degree in the state. The purpose of a rejuvenator is to penetrate somewhat into the asphalt concrete and soften (rejuvenate) the asphalt binder. The rejuvenator also helps to seal the pavement and minimize future oxidation.

Application of fog seals and rejuvenators appears to be economically attractive. Many highway districts in Texas routinely use these products and techniques and believe they are cost-effective remedies, while other districts believe these maintenance treatments are of no value. Information on the value of these treatments is not well documented as determined from the lack of published material; however, considering the widespread use of fog seals, it is obvious that a number of knowledgeable people feel that fog seals have a significant economic value.

The objective of this study was to determine the effectiveness of fog seals and rejuvenators at performing their intended functions and thereby evaluate the economic effectiveness of these maintenance treatments. The conclusions reached in this study are summarized below.

1. The amount of money expended on fog seals in Texas comprises about one percent of all the routine maintenance

expenditures in the state.

2. Fog seals are used primarily in the western half of the state.

FOG SEALS AS A MAINTENANCE TREATMENT FOR CHIP SEALS

3. By far, the most common use of fog seals is as a corrective measure on chip seals to stop or reduce the rate of stone shelling.
4. The Vialet test was used to evaluate the effectiveness of different application rates of fog seals on Grade 4 laboratory chip seals. No improvement in aggregate retention rate was observed with a 0.05 gallon per square yard residual application rate. However, a significant improvement was observed with 0.10 gallons per square yard.
5. A laboratory experiment was performed to characterize a number of Grade 3 and Grade 4 chip seal aggregates. The thickness of the stone layer, percent voids in the layer, and distribution of voids was measured and used to develop design charts for determining residual fog seal application quantities.
6. Four test roads were monitored to evaluate the effectiveness of fog seals for chip seals. In every test road, the fog seal improved the aggregate retention rate over that of the corresponding controls. Even as little as 0.03 gallons per square yard residual binder resulted in improved aggregate retention.
7. The critical time for fog seal applications on a chip seal is prior to its first winter. On every test road evaluated in this study, almost no stone loss occurred in the second year for either the control or the fogged sections indicating a stabilized condition is reached by the second year.
8. The average cost of a single application fog seal is approximately $.10 per square yard. Assuming an average

chip seal life of seven years, this increases the equivalent uniform annual cost of a chip seal from $.083 to $.10 per square yard.

9. Based on the information obtained in this study, fog seals can be cost-effective for reducing the rate of stone shelling in chip seals if placed at the proper application rate and before the first winter season following the chip seal. Fog seals placed later than the first winter season do not appear cost-effective in reducing the rate of stone shelling.

FOG SEALS USED AS A MAINTENANCE TREATMENT FOR ASPHALT CONCRETE

10. Asphalt concrete specimens were molded in the laboratory using asphalt from three different sources. Half of the samples were treated with a fog seal and aged at 140°F for six weeks to determine the effectiveness of fog seals at sealing the surface to reduce the rate of age-hardening within the mixture. Resilient modulus and indirect tensile tests were used to evaluate mixture stiffness. All mixtures showed an increase in stiffness after aging. No significant improvement was noted in the samples which were treated with a fog seal.
11. A fog seal placed on an asphalt concrete pavement was monitored for two years. No visual differences were observed between the fogged and control sections.
12. For a fog seal to be as cost-effective as a chip seal, it would need to be effective at delaying further rehabilitation for approximately 18 months based on an annualized cost analysis.
13. Based on the limited information obtained in this study, fog seals, applied at residual asphalt rates of 0.05 gallons per square yard, are not effective at sealing the surface to reduce the rate of aging in the mix. They can be used more effectively to correct specific surface

problems such as ravelling or loss of surface fines. However, fog seals are generally not applied to asphalt concrete by the SDHPT. There is insufficient information in this study to conclude when and how much fog seal to apply on asphalt concrete to reduce aging.

REJUVENATING SEALS AS A MAINTENANCE TREATMENT FOR ASPHALT CONCRETE

14. A study done for the U. S. Army Corps of Engineers found that rejuvenating seals were effective at reducing the loss of surface fines; however, they were not effective at reducing the rate of cracking. It was also concluded in the study that rejuvenators penetrated the top 3/8 inch of the surface and reduced a pavement's skid resistance for at least one year.
15. A laboratory investigation performed in this study on mixtures with high void contents (10 to 12 percent) showed that rejuvenators can significantly reduce the mixture stiffness.
16. Another laboratory experiment evaluated the effects of three different rejuvenators applied to asphalt concrete samples molded with asphalts from three different sources. The results of this study indicated that the combination of the asphalt source in the mix and the type rejuvenator used can influence the effectiveness of the rejuvenator.
17. Even though rejuvenators may only penetrate the top 3/8 inch of the surface, they can increase the flexibility of the mixture.
18. An effective method of controlling the skid resistance when using a rejuvenator was determined through a field experiment. The rejuvenator should be applied to the pavement and allowed to penetrate the surface 45 minutes to one hour prior to sanding. Sand should then be applied and lightly rolled. Approximately two hours after sanding the

surface should be swept. Using this method, the pavement's skid resistance was back to its original condition within 24 hours.

19. A rejuvenating seal costs approximately $.15 per square yard. For a rejuvenator to be as cost-effective as a chip seal, it would need to be effective at delaying further rehabilitation for approximately two years based on an annualized cost analysis.

20. Based on the information obtained in this study, it is not cost-effective, and not recommended, for rejuvenators to be applied to asphalt-concrete pavements (ACP) with an air void content less than seven to eight percent. Application of rejuvenators to ACP with an air void content greater than seven to eight percent can reduce the stiffness of the mixture (thereby improving its resistance to cracking); however, this may unfortunately increase its potential for permanent deformation (rutting and shoving).

USE OF FOG SEALS AND REJUVENATORS IN TEXAS

A survey of maintenance personnel in all of the highway districts was conducted in order to determine how and to what extent fog seals and rejuvenators were used across the state.

EXTENT OF USE

Information obtained from the Maintenance Section of the Maintenance and Operations Division (D-18M) of the Texas State Department of Highways and Public Transportation (SDHPT) revealed that the amount of money expended on fog seals in Texas comprises about one percent of all the routine maintenance expenditures in the state as shown in Figure 1 for three fiscal years. While some districts in the state spend no money on fog seals, others spend significantly more than one percent as shown in Figure 2. Those districts which generally devote more than one percent of their routine maintenance expenditures to fog seals are shaded in Figure 3. From this, it appears that fog seals are used to a greater extent in the western half of the state.

TYPES OF USES

A survey of all the highway districts in Texas revealed that, by far, the most common use of fog seals is as a corrective measure on chip seals to stop or reduce stone shelling. Shelling of the stone from the chip seal is usually the result of an insufficient binder application quantity during the construction of the chip seal. The application of a fog seal effectively increases the stone embedment depth into binder thereby reducing the potential for that stone to be dislodged from the pavement surface. District 23, Brownwood, sometimes uses a fog seal as part of the construction process of a chip seal. The design binder application quantity is altered to account for placement of a fog seal soon after the chip-seal construction. This is believed to aid in aggregate retention.

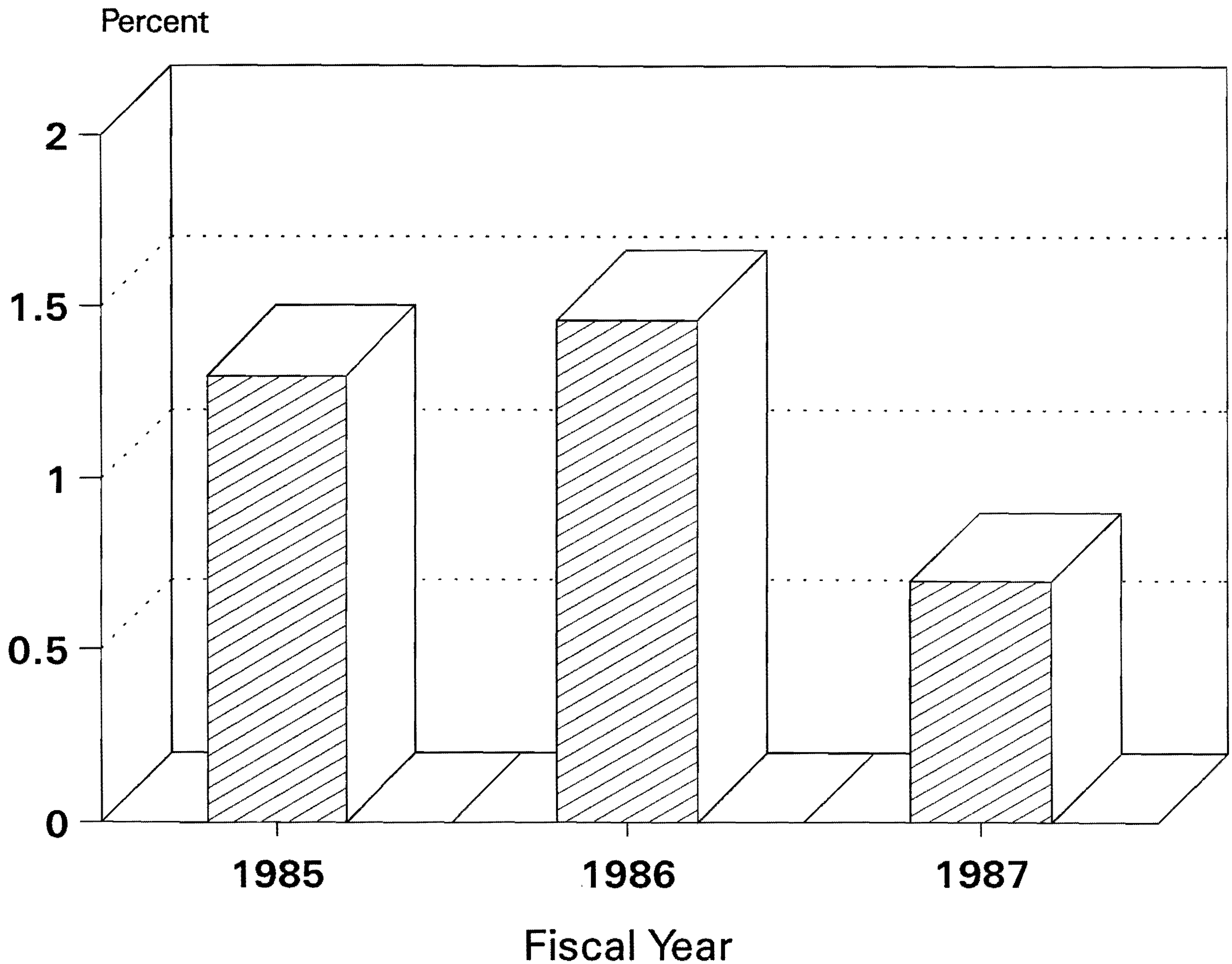


Figure 1. Percentage of Routine Maintenance Expeditures in Texas Devoted to Fog Seals for a Three-Year Period.

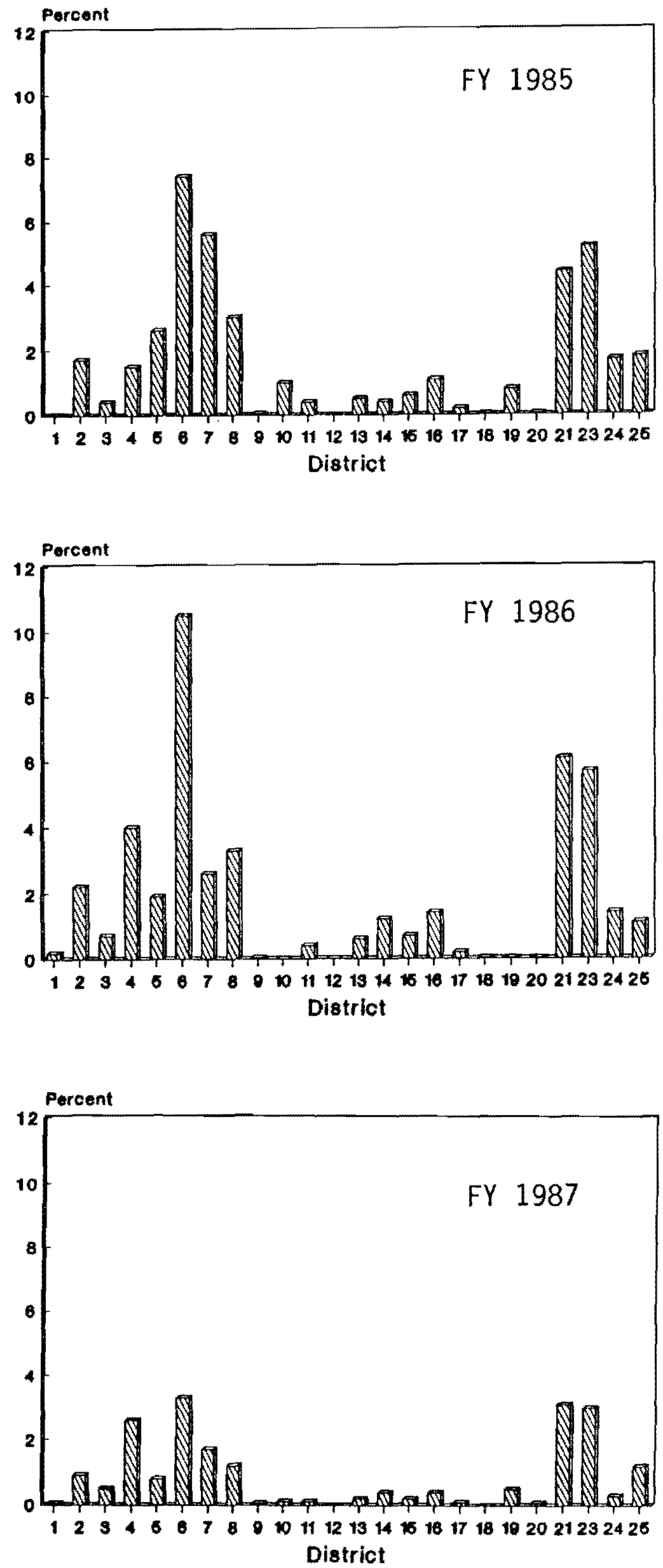


Figure 2. Percentage of Routine Maintenance Expenditures Devoted to Fog Seals by District for a Three-Year Period.

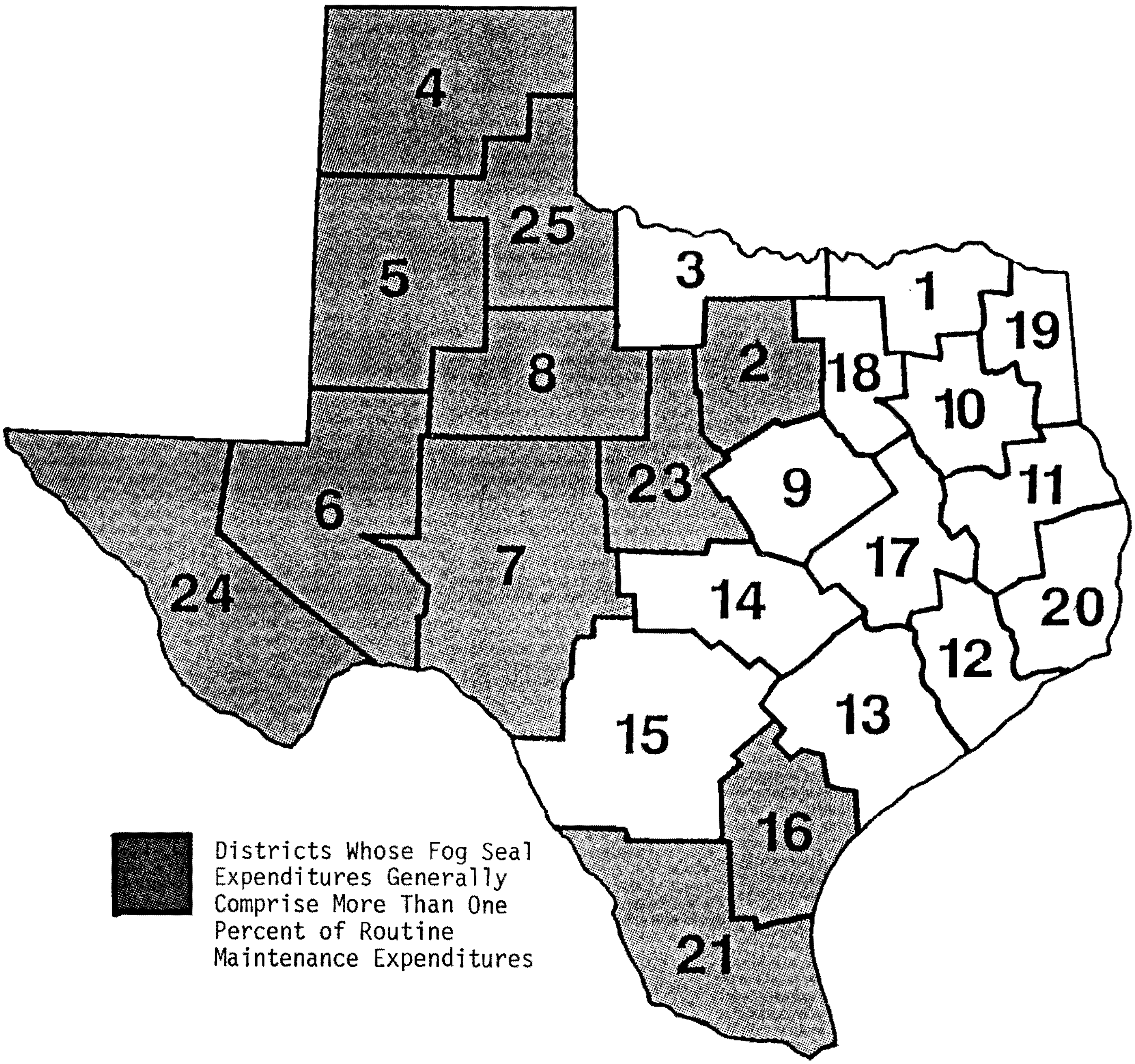


Figure 3. Districts Whose Fog Seal Expenditures Generally Comprise More Than One Percent of Their Routine Maintenance Expenditures.

Fog seals are used to a much less degree as a maintenance treatment on asphalt-concrete pavement surfaces. Those districts which do use fog seals for asphalt concrete do so when the surface appears to be dry and ravelling.

Most of the districts use either a slow-setting or medium-setting emulsion for fog seals. The emulsion is further diluted with water at a ratio of from 1:1 to 2:1 and application quantities vary from district to district. Total residual asphalt application rates can be as little as 0.03 gallons per square yard and as high as 0.2 gallons per square yard. However, a total residual application rate of as much as 0.2 gallons per square yard is achieved through several applications over time.

Rejuvenating agents are used to a limited degree in District 15, San Antonio, and in District 21, Pharr. These agents are used mostly to rejuvenate asphalt-concrete pavement surfaces, although District 21 has also used rejuvenating agents on aged chip-seal pavement surfaces.

FOG SEALS AS A MAINTENANCE TREATMENT FOR CHIP SEAL PAVEMENTS

Chip seals are used extensively in Texas on low volume roads and are usually placed on existing bituminous pavements. If a chip seal is constructed with an insufficient binder quantity, the action of traffic will dislodge the stones from the pavement surface. This is most likely to happen in the winter months when low temperatures cause the asphalt binder to behave in a more brittle fashion. It appears to be most critical in the first winter after construction. Depending on the traffic level, temperature, and hardness of the underlying pavement, the aggregates in chip seals are gradually pushed into the underlying pavement to some degree. This effectively increases the level of the binder around the stone potentially improving the aggregate retention rate especially in the wheel paths. Experience has shown that if a chip seal has adequate aggregate retention through the first year of service particularly throughout the first winter, it is not likely that further stone loss will occur. Therefore, the critical time for placement of a fog seal on a chip seal is prior to the first winter after the chip seal has been constructed.

LABORATORY EVALUATION

The objective of the laboratory study was to determine appropriate fog seal application quantities to effectively improve the aggregate retention properties of chip seals.

Vialet Test

Some districts use a residual binder application rate for fog seals as low as 0.05 gallons per square yard, and there is some doubt as to whether this amount of binder actually has any measurable effect on pavement performance. A laboratory investigation was performed using the Vialet test to determine the effects of various fog seal application rates on aggregate retention of laboratory chip seal samples. While there are very few laboratory tests in existence to evaluate field performance of chip seals, the Vialet test has been shown to be an indicator of chip seal aggregate retention rate (1). The Vialet test uses a 0.25-inch steel plate, seven by seven inches square as a sample preparation medium. A 0.25-inch rim prevents binder runoff. A force is imparted to an inverted chip seal sample by means of dropping a steel ball, two inches in diameter from a height of 18 inches.

In this testing program, asphalt was applied to the plate, and the plate was rotated until the binder was evenly distributed over the surface. Aggregate was then applied at the design quantity and the sample was rolled using a hand-held rubber roller.

Each sample was then left undisturbed for 24 hours at 77°F (plus or minus 5°F) and 50 percent relative humidity (plus or minus 10 percent) prior to application of a laboratory fog seal. After the fog seal was applied, the samples were allowed to cure for 24 hours at 140°F (plus or minus 5°F) and 35 percent relative humidity (plus or minus 10 percent). The samples were brought to the test temperature of 77°F two hours prior to testing.

An initial weight of the sample and the plate was obtained, then the specimen was inverted in the test apparatus and a steel ball was dropped in the center of the plate three times within a ten-second period. A final weight was then taken and percent material retained after impact was calculated.

Vialet Test Laboratory Experiment Design. The asphalt used to construct the chip seal samples was an AC-10 grade asphalt cement. Crushed limestone and river gravel aggregates were used which conformed to the Texas SDHPT Specifications Item 302, Grade 4 (2) as shown in Figure 4. These two aggregates were chosen due to their dissimilar surface characteristics. MS-1 asphalt emulsion was diluted with water at a 1:1 ratio and applied to each chip seal sample using a hand-held sprayer. The chip seal samples were constructed with a binder application rate less than optimum such that the aggregate was embedded in the asphalt to approximately 20 percent. Fog seals were applied to the samples at residual binder rates of 0, 0.05, 0.10, and 0.20 gallons per square yard. Thus,

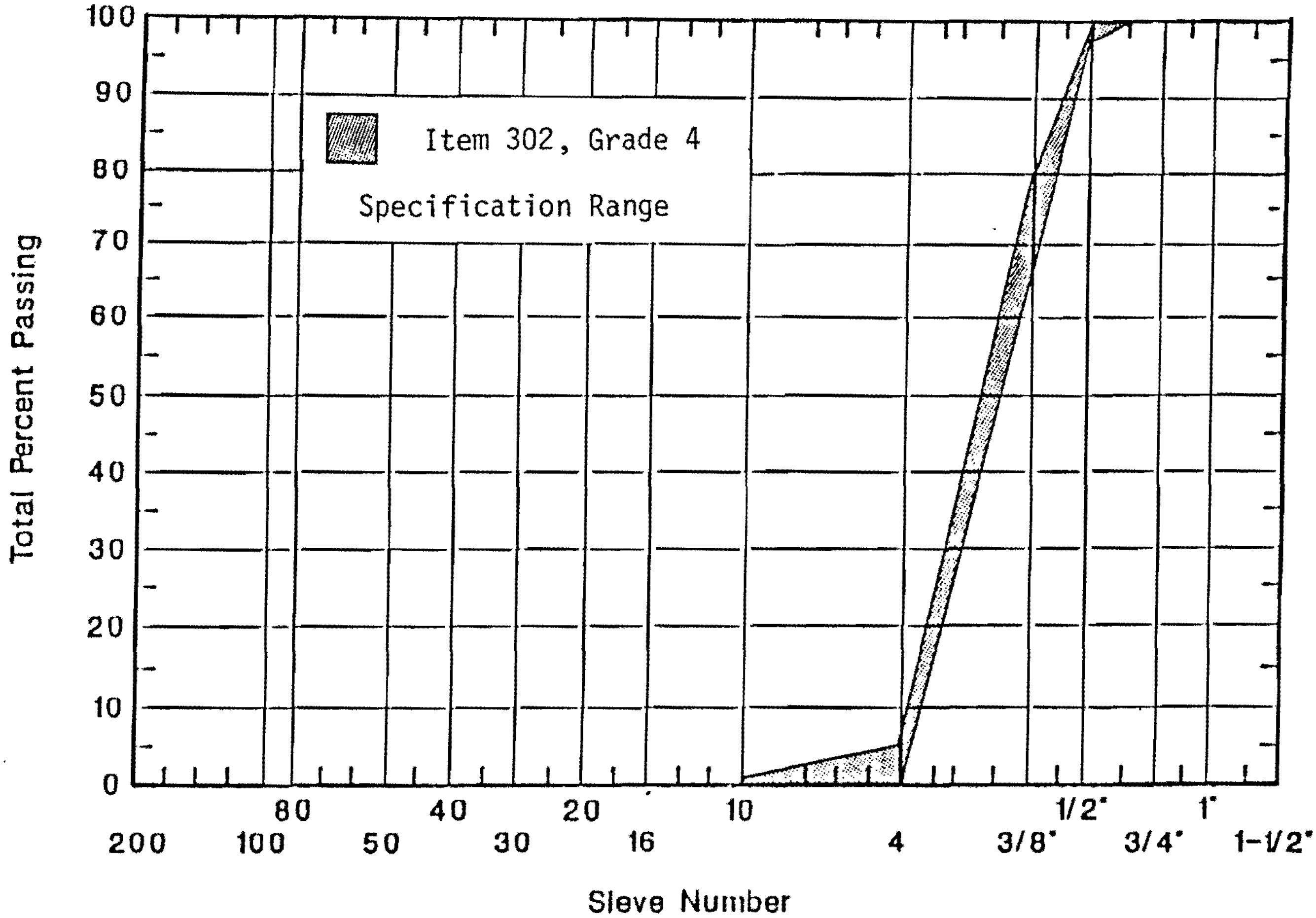


Figure 4. Texas SDHPT Specification Range for Item 302, Grade 4 Chip Seal Aggregate Gradation (2).

with increasing fog seal application rates, the aggregate embedment depth increased. Three replicate tests of each combination of materials and application rates were performed. The experiment design is shown in Table 1.

Vialet Test Laboratory Results. The laboratory test results for this experiment are shown in Table 2. Table 2 shows the standard deviations for each application rate. At the low application rates, and thus low embedment depths, the standard deviations are greater indicating the bond between the asphalt and aggregate was more variable at low embedment depths. As more material was retained, the standard deviation decreases indicating a more consistent bond.

The Vialet test results are shown graphically in Figures 5 and 6. Each bar represents the average of three replicate tests. The data indicate that, overall, a higher rate of asphalt will increase the percent of aggregate retained except in the case of the limestone aggregate at the 0.05 g/sy application rate. Considering the variability associated with the low application rates or low embedment depths, there is essentially no improvement in aggregate retention with an application rate of 0.05 gallons per square yard for either the river gravel or limestone aggregates. There is a significant improvement in retention rates for an application rate of 0.10 gallons per square yard: over 80 percent for the river gravel and over 90 percent for the limestone. No further improvement was observed with 0.20 gallons per square yard. For the laboratory situation consisting of a Grade 4 chip seal constructed with an inadequate embedment depth of approximately 20 percent, a fog seal applied at a residual asphalt application rate of 0.10 gallons per square yard showed significant improvement in aggregate retention rates according to the Vialet test.

Laboratory Investigation to Determine Fog Seal Design Quantities

The asphalt application rate used for most fog seals is currently determined by experience and/or a trial-and-error basis. Sometimes the quantity of asphalt selected is based on routine

Table 1. Vialet Test Laboratory Experiment Design.

	Residual Asphalt Application Rate, g/sy			
Aggregate	**0**	**0.05**	**0.10**	**0.20**
River Gravel	3*	3	3	3
Limestone	3	3	3	3

* Three replicate tests were performed for each combination.

Table 2. Vialet Test Laboratory Results.

Percent Aggregate Retained After Impact				
	Fog Seal Residual Asphalt Application Rate, g/sy			
Aggregate	**0**	**0.05**	**0.10**	**0.20**
River Gravel	52	66	87	95
	64	65	92	87
	46	53	79	84
Sample Mean	54	65	86	89
Standard Deviation	9.2	8.5	6.6	5.5
	85	58	93	100
Limestone	62	79	95	100
	68	46	100	98
Sample Mean	72	61	96	99
Standard Deviation	11.9	16.7	3.6	0.7

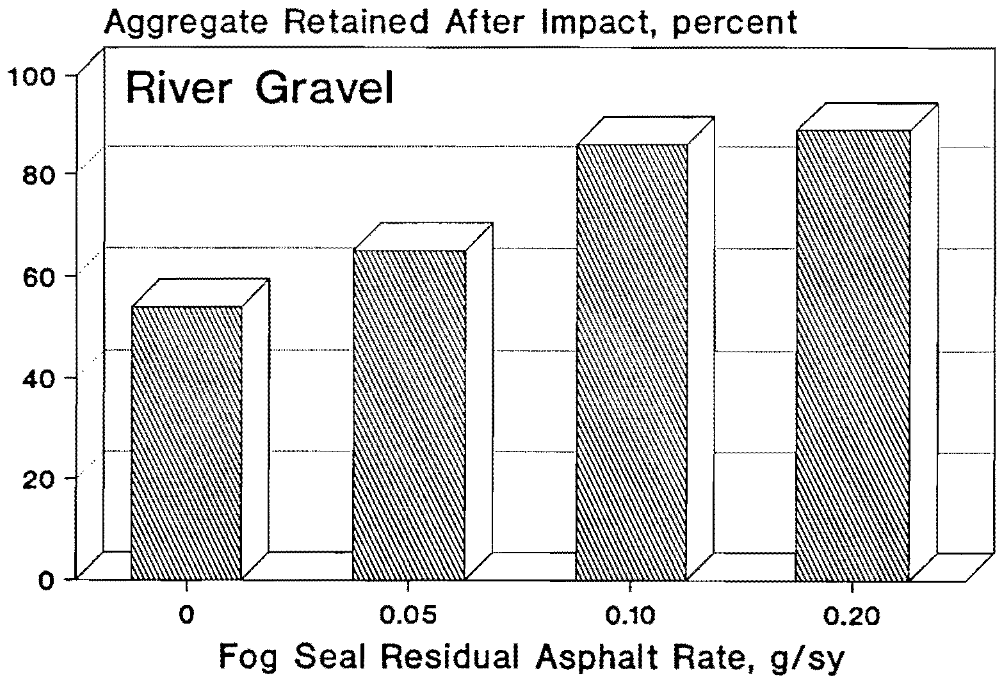


Figure 5. Vialet Test Results for River Gravel Chip Seal Samples With Increasing Fog Seal Application Rates.

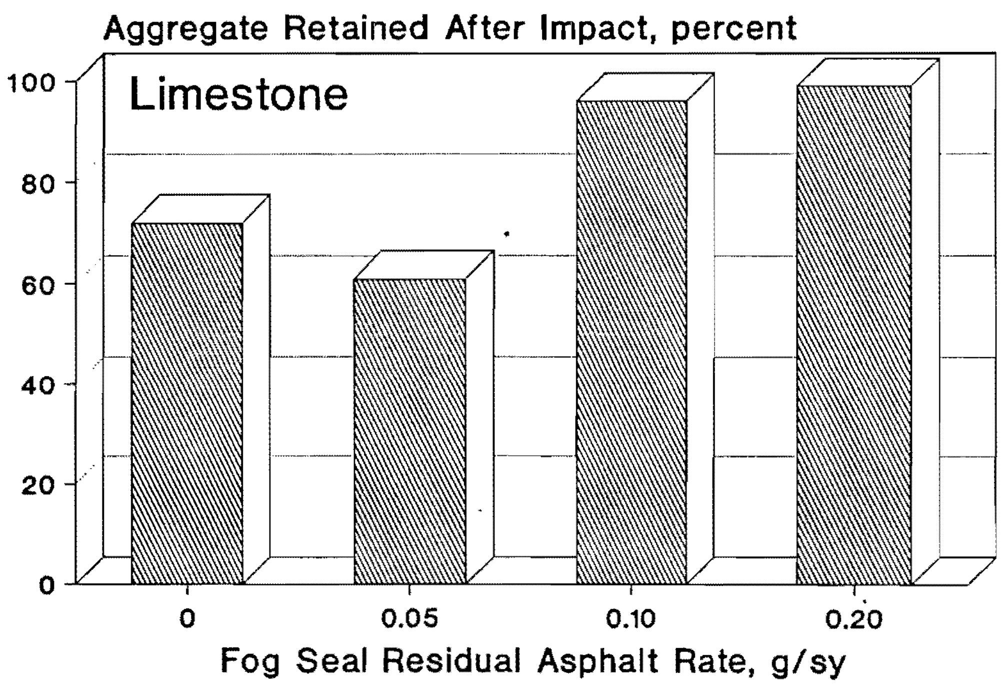


Figure 6. Vialet Test Results for Limestone Chip Seal Samples With Increasing Fog Seal Application Rates.

practice: regardless of the situation, the same standard quantity is applied at regular intervals. For example, some districts have a fog seal maintenance program whereby every three to four years certain pavements receive fog seals. These methods can be successful. However, an objective in this study was to provide the engineer with additional information to make decisions regarding the appropriate asphalt quantity.

To determine the correct quantity of asphalt to be applied as a fog seal to rectify an inadequately designed chip seal, one must know the volume of available void space in that chip seal which can be filled with binder. This can be determined with the following information:

1) the average stone-layer thickness of the chip seal,
2) the portion of the chip seal which is void space,
3) the distribution of voids in that stone layer, and
4) the portion of those voids already filled with asphalt.

While it would be ideal for this information to be determined for every chip seal individually, it is probably not practical for most maintenance engineers. Therefore this information was determined for some typical chip seal aggregates in this laboratory investigation and then used to develop design guidelines for fog seal application rates.

Materials Used. There are primarily two aggregate gradations used for the construction of chip seals in the state: Grade 3 and Grade 4. The gradation range for Item 302, Grade 3 (2) is shown in Figure 7 and Grade 4 was shown previously in Figure 4. The four types of aggregates used in this experiment included crushed limestone, river gravel, sandstone, and lightweight. A Grade 3 and Grade 4 of each type was evaluated.

Determination of Aggregate-Layer Thickness and Void Content. In an attempt to accurately measure the actual void content of a single layer of stone in shoulder-to-shoulder contact, South African researchers (Marais and Semmelink) developed a very simple test known as the Modified Tray Test (3, 4, 5, 6). This test was

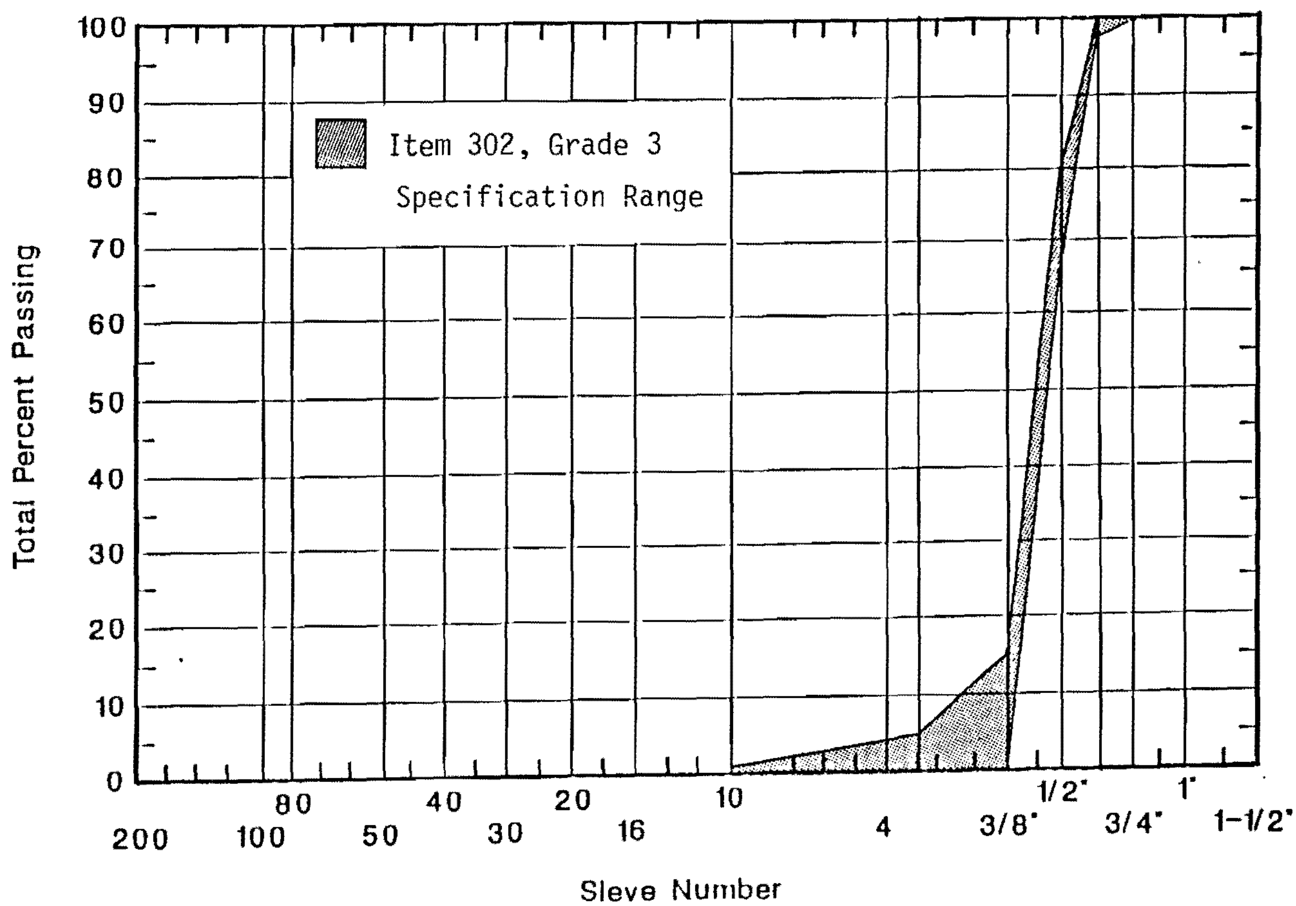


Figure 7. Texas SDHPT Specification Range for Item 302, Grade 3 Chip Seal Aggregate Gradation (2).

developed to determine the true layer void content and the effective layer thickness (ELT) of the aggregate layer. The Modified Tray Test was previously evaluated by Texas Transportation Institute as a means for designing multiple chip seals for the Texas SDHPT (7).

The test equipment essentially consists of a circular tray and a shoulder piece which fits snugly on top of the tray. The shoulder piece has the same internal diameter as the tray and is fitted to a loose-fitting cloth membrane. The purpose of the membrane is to prevent "density sand" from flowing into the voids between the stone.

The test is performed by packing the stones in the tray in a single layer with the least dimension of the stone vertical. The shoulder with the membrane is then placed on top of the tray, and the membrane is smoothed out without disturbing the stone. This mass is then determined.

The space above the stone is then filled with "density sand" in one smooth pour. The tray should be overfilled and the excess sand scraped off with a straight-edge. The mass of the tray, stones, membrane, and sand is determined.

A schematic illustration of the Modified Tray Test is shown in Figure 8. The total void space that is occupied by the aggregate sample plus the voids in the layer is determined as follows (5):

$$V_3 = V_1 - V_2$$

$$= \frac{M_1 - M_2}{BDS}$$

where

V_3 = volume of the aggregate plus the voids between the aggregate (ml),
V_1 = volume of the density sand required to fill the tray without the aggregate (ml),
V_2 = volume of the density sand required to fill the tray with the aggregate (ml),
M_1 = mass of the density sand required to fill the tray without the aggregate sample (g),

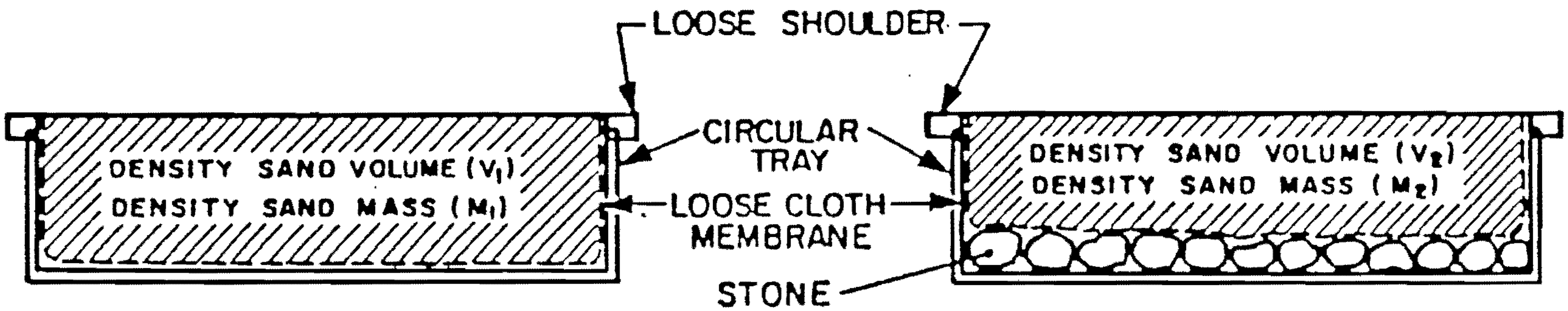


Figure 8. Schematic Illustration of the Modified Tray Test (3).

M_2 = mass of the density sand required to fill the tray with aggregate sample (g), and
BDS = bulk density of the sand (g/ml).

The thickness of the stone layer, called the effective layer thickness (ELT), in millimeters, is determined as follows:

$$ELT = 10 \times V_3/A$$

where

A = area of the tray (sq. cm.)

The true layer void content *Vl* is determined as follows:

$$Vl = (V_3 - V_a)/V_3 \times 100\%$$

$$= (V_3 - (M_a/RD_a))/V_3 \times 100\%$$

where

V_a = volume of the aggregate sample required to cover the tray area (ml),
M_a = mass of the aggregate sample required to cover the tray area (g), and
RD_a = relative density of the aggregate sample.

Using the Modified Tray Test, the effective layer thickness (ELT) and void content were determined for each aggregate sample. These data are presented in Table 3. The Grade 3 aggregates had a mean layer thickness of 7.96 millimeters and 46 percent voids. The Grade 4 aggregates had a mean layer thickness of 6.85 millimeters with 45 percent voids.

Distribution of Voids in a Stone Layer. The distribution of the voids within a layer of stone varies with depth. If one assumed stones were of a spherical form in a closely packed configuration, the void distribution would be as shown in Figure 9. However, most chip seal aggregates do not approach the shape of a sphere; therefore, attempts were made to measure the void distribution in the laboratory for the above mentioned aggregates. Each aggregate sample was packed in the tray used to perform the Modified Tray Test. The increase in water level was measured as increments of water were added to fill the voids in the layer. The ELT and void contents previously determined were used to determine

Table 3. Effective Layer Thicknesses and Voids as Measured With the Modified Tray Test for Grade 3 and Grade 4 Aggregate Samples.

Aggregate Type	Effective Layer Thickness, mm		Voids, percent	
	Grade 3	Grade 4	Grade 3	Grade 4
Limestone	7.35	6.44	51.7	48.1
River Gravel	8.38	7.00	46.4	42.3
Sandstone	8.26	7.08	42.8	45.8
Lightweight	7.86	6.89	43.4	45.1
Sample Mean	**7.96**	**6.85**	**46.0**	**45.3**

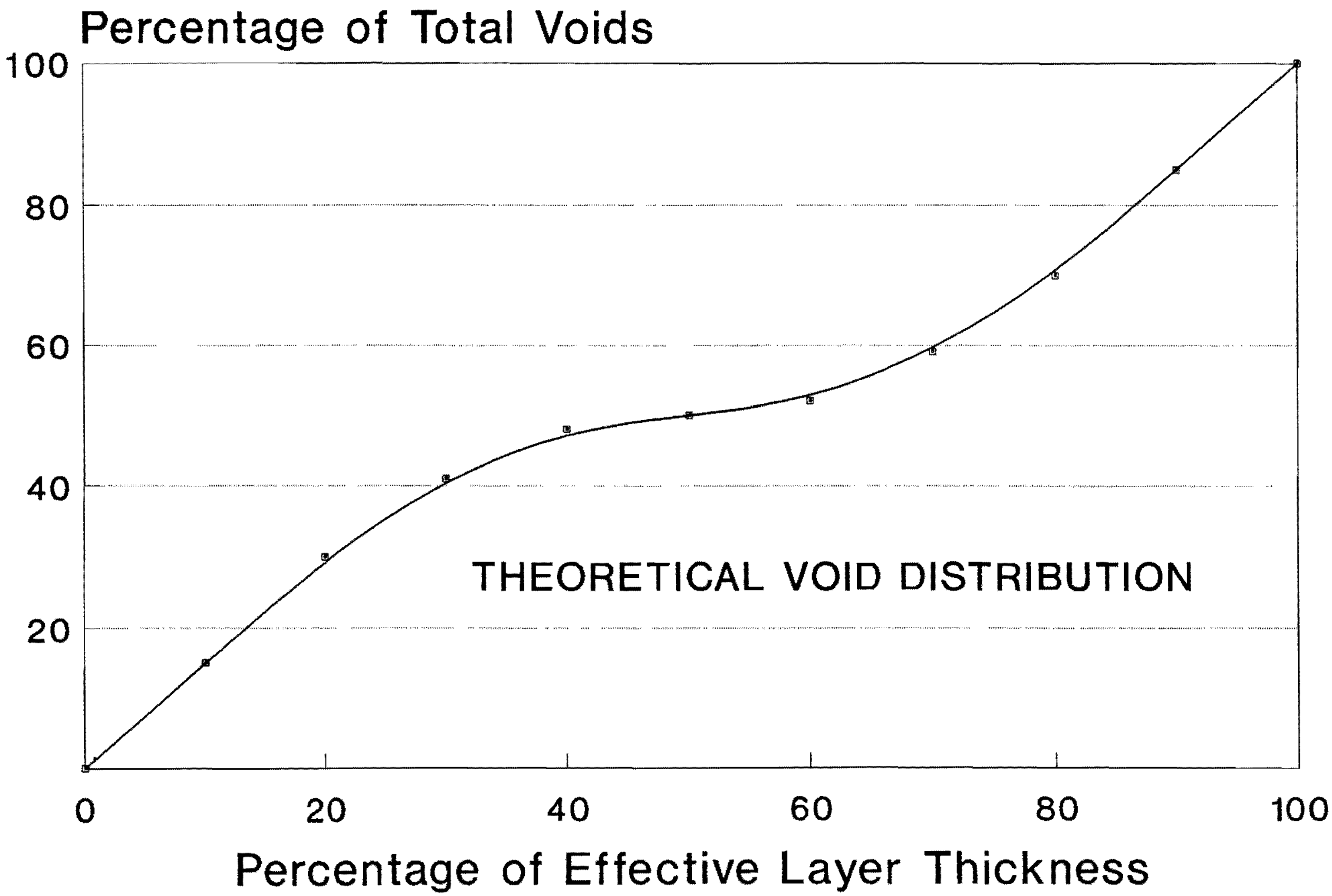


Figure 9. Theoretical Void Distribution for Single Layer of Spheres Closely Packed.

the void distribution.

The void distributions for each type of the Grade 3 aggregates are shown in Figure 10, and the Grade 4 aggregates are shown in Figure 11. Using this data, an average void distribution was calculated for the Grade 3 and Grade 4 aggregates and is shown in Figures 12 and 13. The distributions presented in Figures 12 and 13 were used to calculate approximate design application quantities which are presented in the following section.

Suggested Design Guidelines for Fog Seals on Chip Seal Surfaces

Using the information obtained in the laboratory investigation, fog seal application rates were calculated for Grade 3 and Grade 4 chip seals. These residual asphalt application quantities are shown in Tables 4 and 5. To use these tables, one must have a measure of the existing stone embedment depth for the chip seal in question and the desired embedment depth after fog seal application.

Determination of the stone embedment depth should be done through a visual inspection of the chip seal surface. Stones should be pried from the chip seal surface and carefully inspected to estimate the percent embedment of the stone in the asphalt. This percentage is termed the embedment depth. A representative number of stones should be sampled to adequately characterize the pavement. Stone samples should be taken in the wheel paths, between the wheel paths, and the centerline. At the discretion of the engineer, all of the embedment depths can be averaged to obtain a single value or if the stone embedments are significantly different at various locations, a strategy may be developed to vary the fog seal application rate accordingly. Under certain conditions it may be desirable to vary the transverse distribution of asphalt. For example, aggregate in the wheel paths may have a significantly greater embedment depth than between the wheel paths. Since this surface demand for asphalt can vary transversely on the pavement, it is desirable to vary the applied rate transversely. District 23 has successfully installed different-size nozzles in the spray bar to achieve the desired transverse variation.

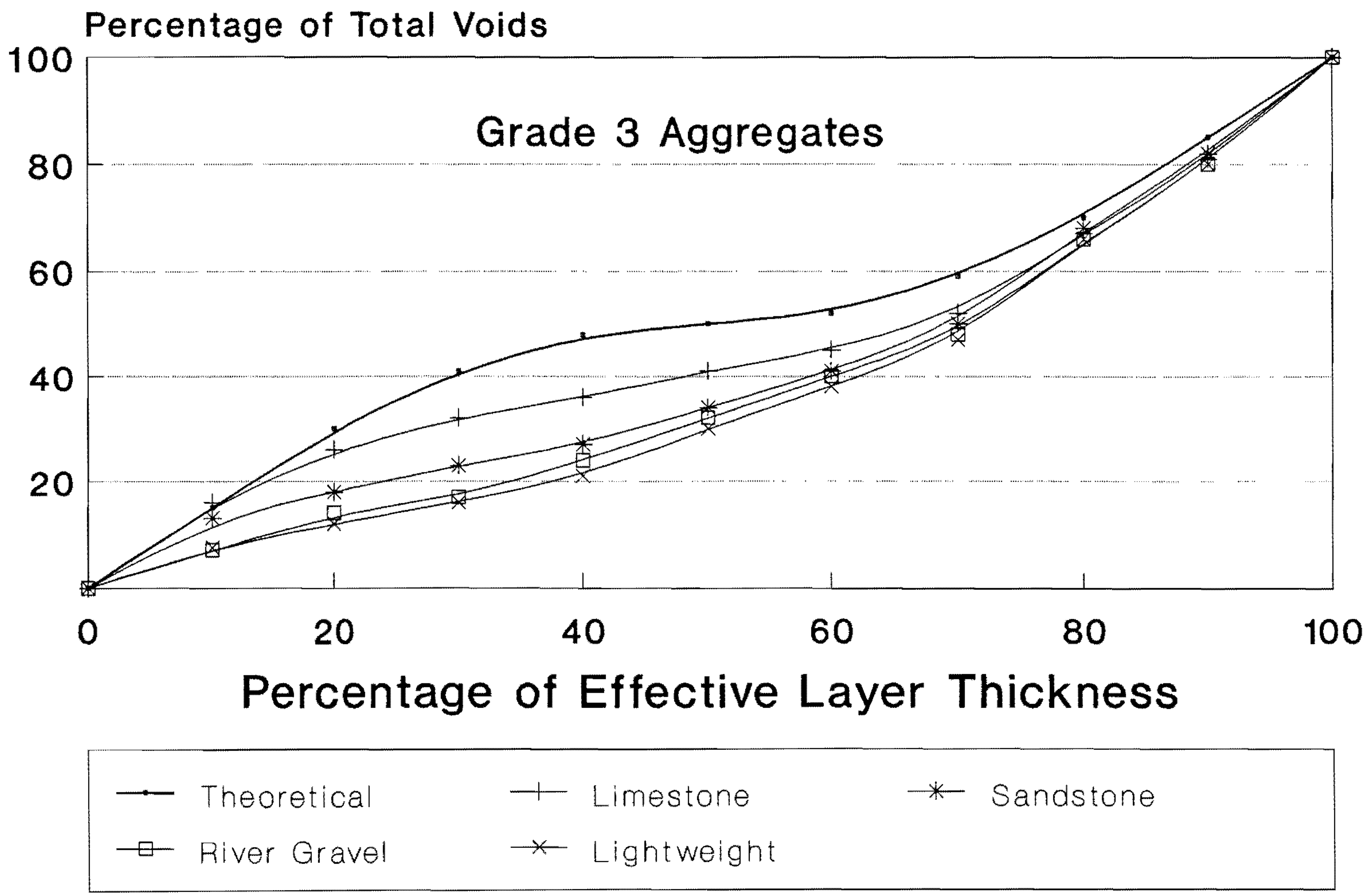


Figure 10. Measured Void Distributions for Grade 3 Aggregate Samples.

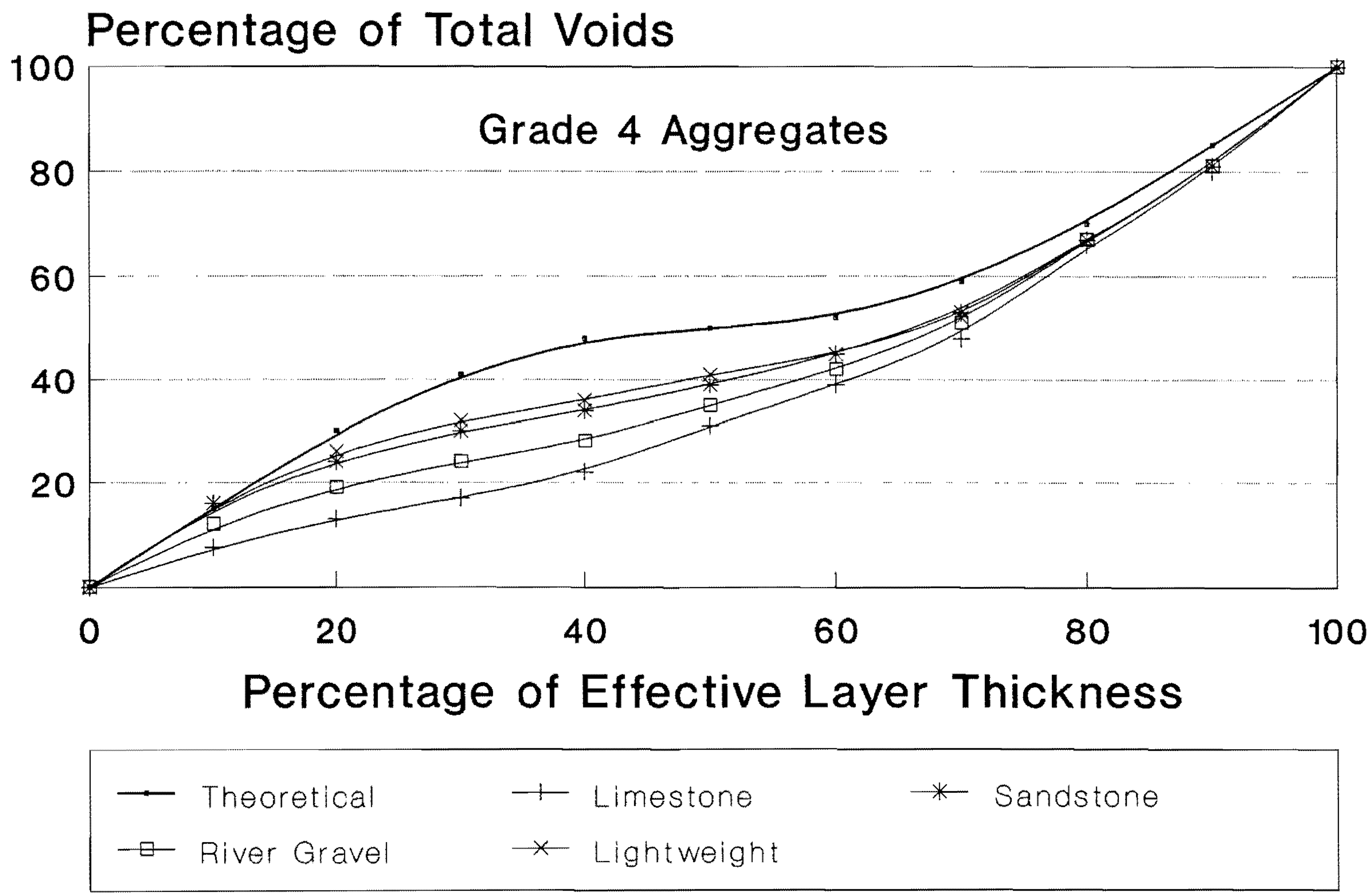


Figure 11. Measured Void Distributions for Grade 4 Aggregate Samples.

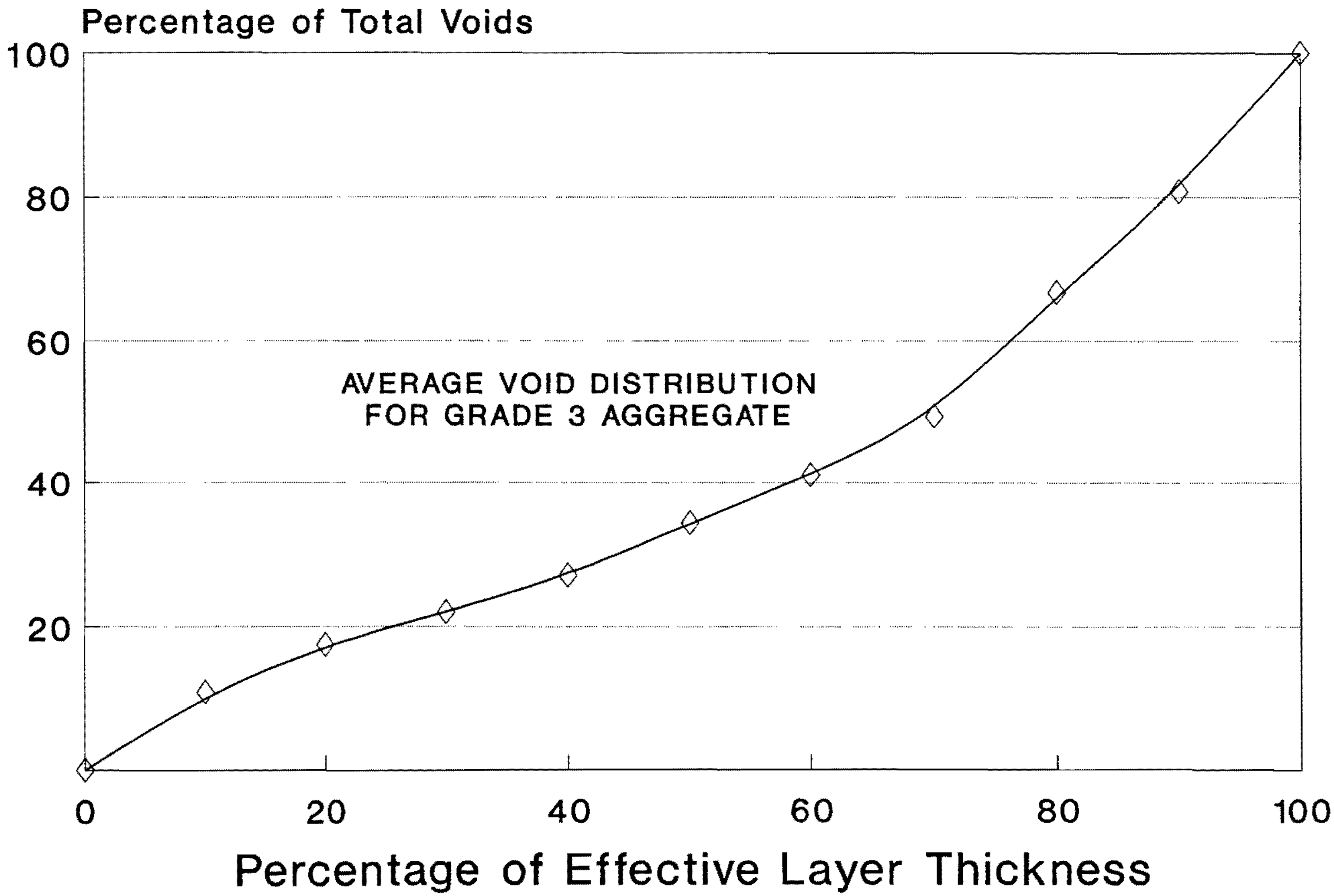


Figure 12. Average Void Distribution for Grade 3 Aggregate Samples.

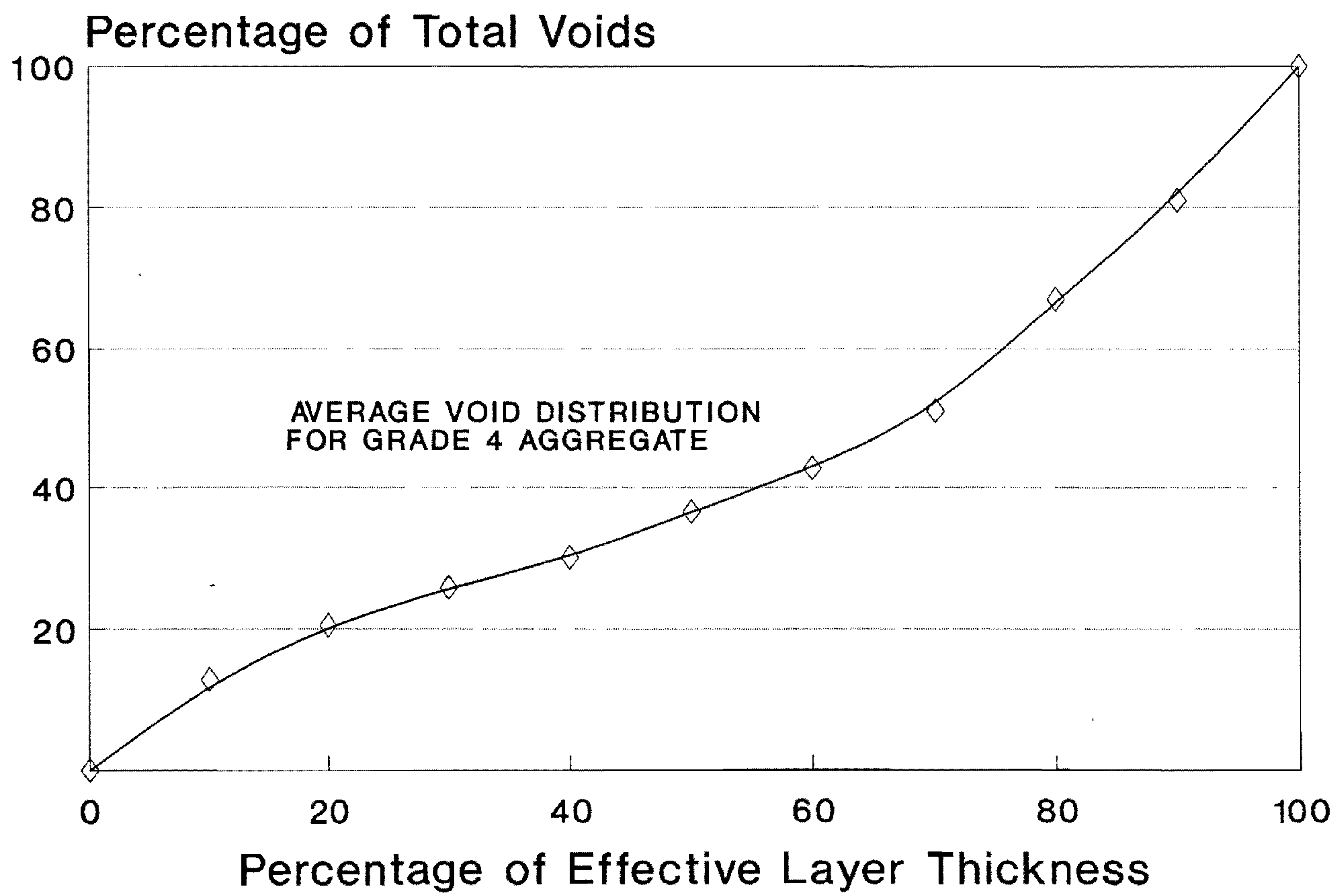


Figure 13. Average Void Distribution for Grade 4 Aggregate Samples.

Table 4. Estimated Fog Seal Application Rates to Achieve Desired Embedment Depth for a Grade 3 Chip Seal (Residual Binder, gallons per square yard).

Measured Embedment Depth, %	Desired Embedment Depth, percent									
	15	20	25	30	35	40	45	50	50	55
10	0.03	0.06	0.08	0.10	0.12	0.14	0.16	0.18	0.21	0.25
15	0	0.02	0.05	0.06	0.09	0.10	0.13	0.15	0.18	0.21
20	0	0	0.02	0.04	0.06	0.08	0.10	0.13	0.16	0.19
25	0	0	0	0.02	0.04	0.06	0.08	0.10	0.14	0.17
30	0	0	0	0	0.02	0.04	0.06	0.09	0.12	0.15
35	0	0	0	0	0	0.02	0.04	0.06	0.10	0.13
40	0	0	0	0	0	0	0.02	0.05	0.08	0.11
45	0	0	0	0	0	0	0	0.02	0.06	0.09
50	0	0	0	0	0	0	0	0	0.03	0.06

Table 5. Estimated Fog Seal Application Rates to Achieve Desired Embedment Depth for a Grade 4 Chip Seal (Residual Binder, gallons per square yard).

Measured Embedment Depth, %	Desired Embedment Depth, percent									
	15	20	25	30	35	40	45	50	50	55
10	0.03	0.05	0.08	0.09	0.10	0.12	0.14	0.16	0.19	0.21
15	0	0.03	0.05	0.06	0.08	0.10	0.11	0.14	0.16	0.18
20	0	0	0.02	0.03	0.05	0.07	0.08	0.11	0.14	0.16
25	0	0	0	0.01	0.03	0.05	0.06	0.09	0.12	0.14
30	0	0	0	0	0.01	0.03	0.05	0.08	0.10	0.12
35	0	0	0	0	0	0.02	0.03	0.06	0.09	0.11
40	0	0	0	0	0	0	0.01	0.04	0.07	0.09
45	0	0	0	0	0	0	0	0.03	0.05	0.08
50	0	0	0	0	0	0	0	0	0.03	0.05

The application quantities suggested in Tables 4 and 5 are intended to be used as a guide only and not as a substitute for experience. The four types of aggregates used to develop these calculations cannot possibly cover the spectrum of aggregate sizes and shapes available in Texas. These quantities were calculated to the nearest 0.01 gallons per square yard. It is realized that, with most distributors, asphalt rates cannot be controlled that closely; however, sensitivity of embedment depth to asphalt rate can be evaluated and weighed by the engineer. The table should be used by determining a measured embedment depth through a field inspection of the chip seal and estimating a desired embedment depth to determine residual asphalt application quantity. For example, using Table 4, if the existing embedment depth for the chip seal is approximately 20 percent and it is desirable to increase the embedment depth to 45 percent, the residual binder application rate should be 0.10 gallons per square yard. The engineer should decide how many separate fog seals should be applied to achieve that residual rate of 0.10 gallons per square yard. The desired embedment depth may be based on experience considering expected traffic levels, temperatures, and hardness of underlying surface. Epps et. al. (8) suggests the following embedment depths during the life of chip seals:

immediately after construction	20% to 40%,
start of cool weather (first year)	25% to 45%,
start of cold weather (first year)	35% to 55%, and
after two years of service	60% to 80%.

For low traffic facilities, aggregate embedment after construction should be in the range of 30 to 40 percent while 20 to 30 percent embedment is the preferred range for high traffic volume facilities.

FIELD EVALUATION

Four test roads were evaluated in this study to determine the effectiveness of fog seals at improving the aggregate retention rate of chip seals. The locations of these test roads are as follows:

FM 2134, Concho County, San Angelo District,
FM 134, Harrison County, Atlanta District,
FM 1997, Harrison County, Atlanta District, and
US 80, feeder road, Parker County, Fort Worth District.

All of these test sections experienced low traffic volumes. Each of the above chip seals was constructed with a Grade 4 aggregate except for FM 134 which was a Grade 3. All test roads displayed evidence of aggregate loss at the time the fog seal was applied. Each fog seal was applied prior to the first winter after the chip seal was constructed. A portion of each chip seal (500 to 1000 feet) was not fogged and was used as a control for monitoring purposes.

Criteria used to evaluate the performance concentrated on identifying aggregate loss. One method used to achieve this was through a visual examination of the pavement estimating the percentage of aggregate loss. This type of evaluation can be subjective; therefore, another method was also devised for this particular study. Ten 12-inch by 9-inch rectangles were painted on the pavement surface in the control section and in the fogged section. Five were painted in the outside wheel path and five were painted between wheel paths (See Figure 14). Close-up photographs, called photorecords, were taken of each rectangle at the time of the fog seal construction and then periodically thereafter. Examination of the photorecords allowed identification of individual stones lost with time for a more accurate representation of actual aggregate loss.

Other field measurements obtained with each evaluation included aggregate embedment depth and surface texture.

FM 2134 Test Road in San Angelo District

A fog seal was placed on FM 2134 in order to improve aggregate retention. At the time the fog seal was placed, a significant amount of aggregate loss had occurred: as much as approximately 30 percent appeared to be gone from between wheel paths. An MS-1 emulsion was diluted and applied to the pavement with an asphalt

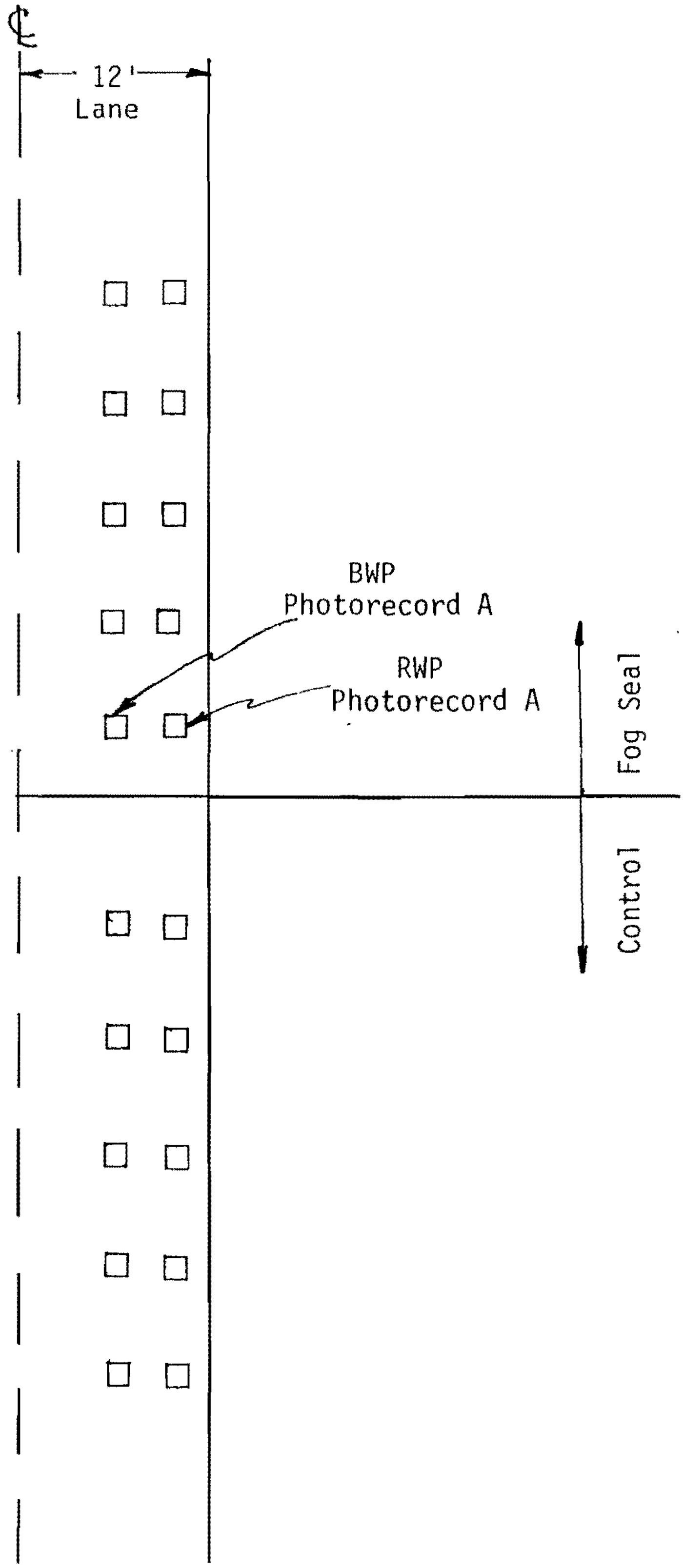


Figure 14. Typical Test Section Layout for Photorecords.

distributor at a residual asphalt rate of approximately 0.08 gallons per square yard. Performance evaluations were made after the first winter the fog seal was placed and again after the second winter.

The actual number of stones lost as measured from the photorecords are shown in Tables 6 and 7. These results are presented graphically in Figure 15. Each bar shown in Figure 15 represents the average of five photorecords. A significant amount of stone loss occurred in the control section over the first winter particularly between the wheel paths. There was a marked improvement in stone retention in the pavement which received the fog seal.

Very little additional stone loss occurred during the second winter indicating the rate of stone loss had stabilized in both the control and the fogged sections. The fogged section which had no stone loss, however, still performed better than the control section.

Additional data supporting the information obtained from the photorecords are shown in Tables 8 and 9. The aggregate loss presented in this table was estimated through a visual assessment of the pavement condition. Aggregate embedment was determined by removing individual stones from the chip seal surface and estimating the percentage covered with binder. Each number representing aggregate embedment in Tables 8 and 9 is the average of five stone samples. Embedment tended to increase with time, as expected, thereby contributing to the improvement in aggregate retention. Surface texture was determined using the sand-patch method (9).

FM 134 Test Road in Atlanta District

Approximately 20 percent aggregate loss was observed between the wheel paths of FM 134 at the time the fog seal was placed. A CSS-1 emulsion was diluted 1:1 with water and applied in two separate application rates of 0.15 gallons per square yard for a total residual asphalt rate of 0.10 gallons per square yard. Performance evaluations were made after the first winter the fog

Table 6. Stone Loss as Measured from Photorecords After First Winter for FM 2134 Test Road.

Photorecord	Number of Stones Lost			
	Right Wheel Path		Between Wheel Paths	
	Control	Fogged	Control	Fogged
A	1	0	15	0
B	5	0	54	3
C	14	0	23	0
D	0	0	67	2
E	5	0	8	1
Mean	5	0	33	1

Table 7. Additional Stone Loss as Measured from Photorecords After Second Winter for FM 2134 Test Road.

Photorecord	Number of Stones Lost			
	Right Wheel Path		Between Wheel Paths	
	Control	Fogged	Control	Fogged
A	0	0	0	0
B	3	0	8	0
C	0	0	0	0
D	*	0	17	0
E	2	0	0	0
Mean	1	0	3	0

* Photorecord not legible.

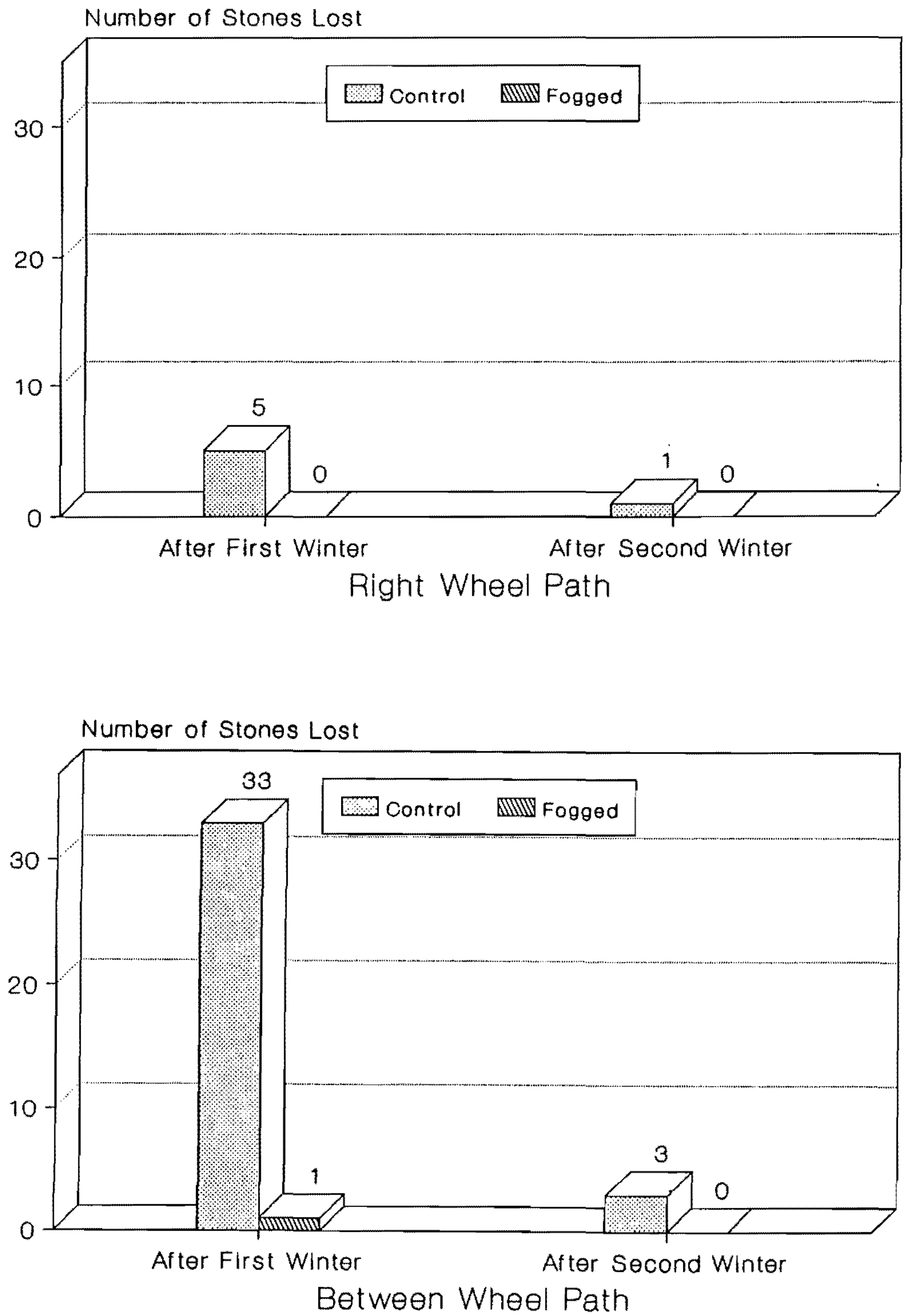


Figure 15. Stone Loss as Measured from Photorecords for FM 2134.

Table 8. Field Evaluation Data for FM 2134, Control Section.

Time of Evaluation	Aggregate Loss, %			Aggregate Embedment, %			Surface Texture, in.		
	RWP*	BWP*	CL*	RWP	BWP	CL	RWP	BWP	CL
At the Time of Fog Seal Application	10	30	20	50	30	30	0.114	0.137	0.119
After First Winter	10	60	30	60	40	40	0.093	0.103	0.113
After Second Winter	10	60	30	60	40	40	0.080	0.094	0.113

Table 9. Field Evaluation Data for FM 2134, Fogged Section.

Time of Evaluation	Aggregate Loss, %			Aggregate Embedment, %			Surface Texture, in.		
	RWP	BWP	CL	RWP	BWP	CL	RWP	BWP	CL
At the Time of Fog Seal Application	8	30	15	50	30	30	0.125	0.141	0.137
After First Winter	10	30	20	60	40	40	0.113	0.125	0.113
After Second Winter	10	30	20	60	40	40	0.094	0.108	0.098

* RWP - Right Wheel Path
BWP - Between Wheel Paths
CL - Centerline

seal was placed and again after the second winter.

Results from the photorecords are shown in Tables 10 and 11 and in Figure 16. A similar trend was observed here as for the FM 2134 test road. A significant amount of stone loss occurred in the control section over the first winter primarily between the wheel paths. No stone loss was observed in the photorecords for the fogged section.

No stone loss occurred over the second winter in either control or fogged sections, again indicating a stabilization in stone-loss rate during the first year. Additional field data are shown in Tables 12 and 13.

FM 1997 Test Road in Atlanta District

A fog seal was constructed on FM 1997 similar to the previous test road. A CSS-1 emulsion was diluted 1:1 with water and applied in two separate application rates of 0.15 gallons per square yard for a total residual asphalt rate of 0.10 gallons per square yard. Aggregate loss at the time the fog seal was placed was about 20 percent in the centerline of the pavement, 25 percent between the wheel paths, and 10 percent in the wheel paths. Performance evaluations were made after the first winter the fog seal was placed and again after the second winter.

Results from the photorecords are shown in Tables 14 and 15 and in Figure 17. For this test road, the fog seal provided less improvement in aggregate retention than detected in the previous two test roads. No stone loss was observed in the fogged section during the first and second winters. Only a marginal amount of stones were lost in the control sections during the first winter. This indicates that the fog seal was probably not necessary for this particular road; however, the stone loss occurring at the time the fog seal was placed appeared to be significant enough to warrant it. Additional field data are shown in Tables 16 and 17.

U.S. 80 Feeder Test Road in Fort Worth District

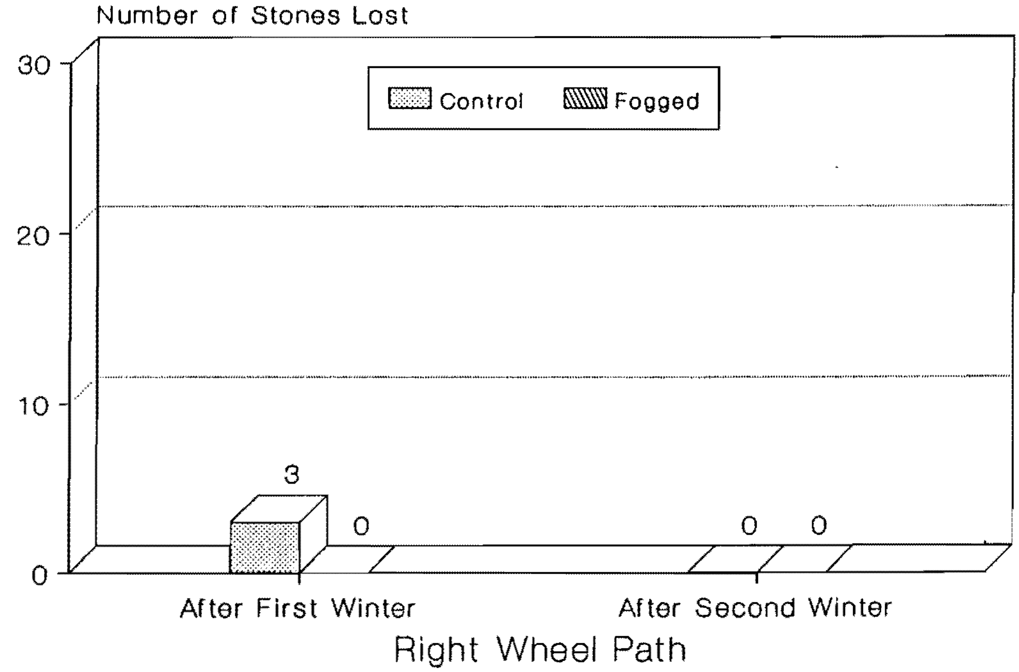
About 15 percent aggregate loss was observed between the wheel

Table 10 . Stone Loss as Measured from Photorecords After First Winter for FM 134 Test Road.

Photorecord	Number of Stones Lost			
	Right Wheel Path		Between Wheel Paths	
	Control	Fogged	Control	Fogged
A	5	0	26	0
B	2	0	37	0
C	5	0	17	0
D	0	0	6	0
E	1	0	8	0
Mean	3	0	19	0

Table 11. Additional Stone Loss as Measured from Photorecords After Second Winter for FM 134 Test Road.

Photorecord	Number of Stones Lost			
	Right Wheel Path		Between Wheel Paths	
	Control	Fogged	Control	Fogged
A	0	0	0	0
B	0	0	0	0
C	0	0	1	0
D	0	0	1	0
E	0	0	0	0
Mean	0	0	0	0



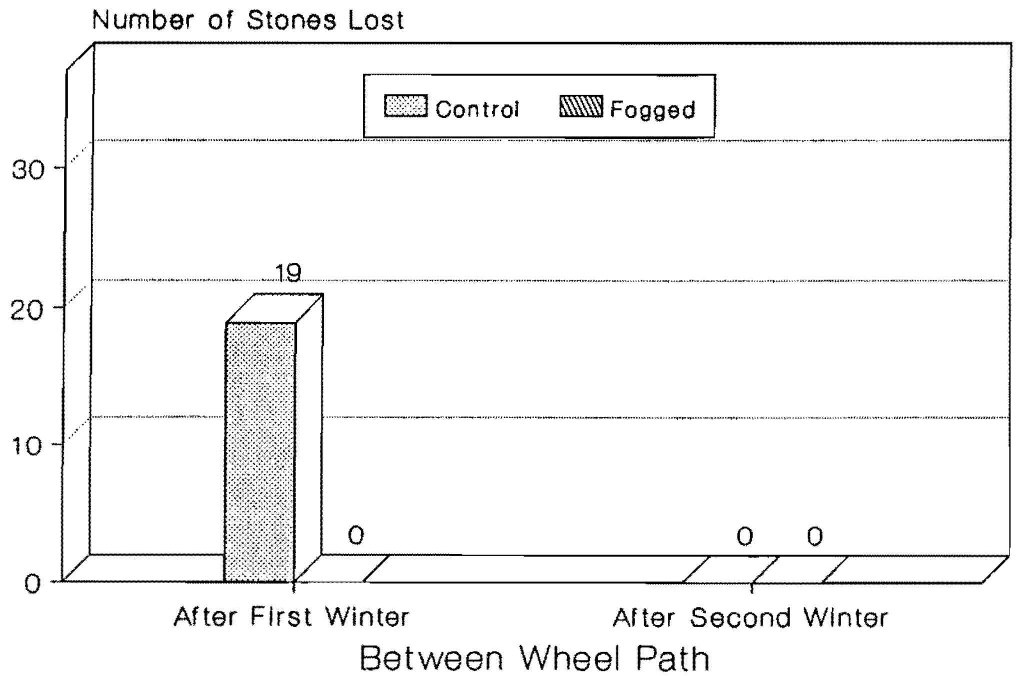


Figure 16. Stone Loss as Measured from Photorecords for FM 134.

Table 12. Field Evaluation Data for FM 134, Control Section.

Time of Evaluation	Aggregate Loss, %			Aggregate Embedment, %			Surface Texture, in.		
	RWP*	BWP*	CL*	RWP	BWP	CL	RWP	BWP	CL
At the Time of Fog Seal Application	5	20	5	45	35	40	0.125	0.128	0.128
After First Winter	10	30	10	55	40	45	0.098	0.119	0.113
After Second Winter	10	30	10	60	45	50	0.086	0.119	0.119

Table 13. Field Evaluation Data for FM 134, Fogged Section.

Time of Evaluation	Aggregate Loss, %			Aggregate Embedment, %			Surface Texture, in.		
	RWP	BWP	CL	RWP	BWP	CL	RWP	BWP	CL
At the Time of Fog Seal Application	5	20	5	45	35	40	0.125	0.125	0.113
After First Winter	5	20	5	60	50	50	0.083	0.119	0.098
After Second Winter	5	20	50	70	60	60	0.077	0.119	0.094

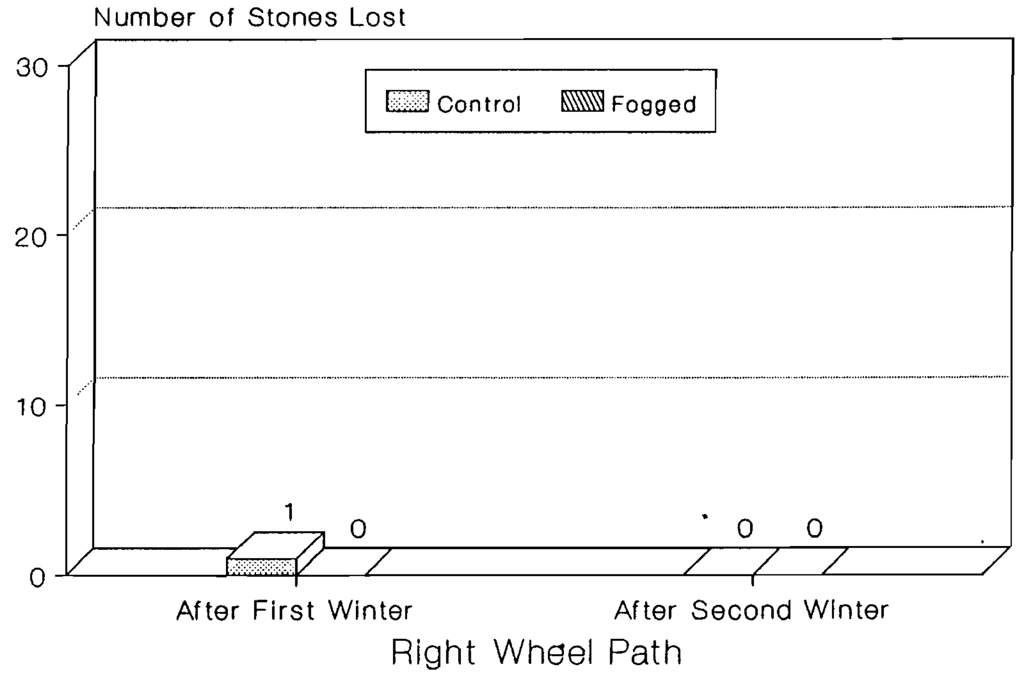
* RWP - Right Wheel Path
BWP - Between Wheel Paths
CL - Centerline

Table 14. Stone Loss as Measured from Photorecords After First Winter for FM 1997 Test Road.

Photorecord	Number of Stones Lost			
	Right Wheel Path		Between Wheel Paths	
	Control	Fogged	Control	Fogged
A	0	0	4	0
B	1	0	4	0
C	1	0	0	0
D	1	0	10	0
E	1	0	4	0
Mean	1	0	4	0

Table 15. Additional Stone Loss as Measured from Photorecords After Second Winter for FM 1997 Test Road.

Photorecord	Number of Stones Lost			
	Right Wheel Path		Between Wheel Paths	
	Control	Fogged	Control	Fogged
A	0	0	1	0
B	0	0	2	0
C	0	0	0	0
D	1	0	1	0
E	0	0	0	0
Mean	0	0	1	0



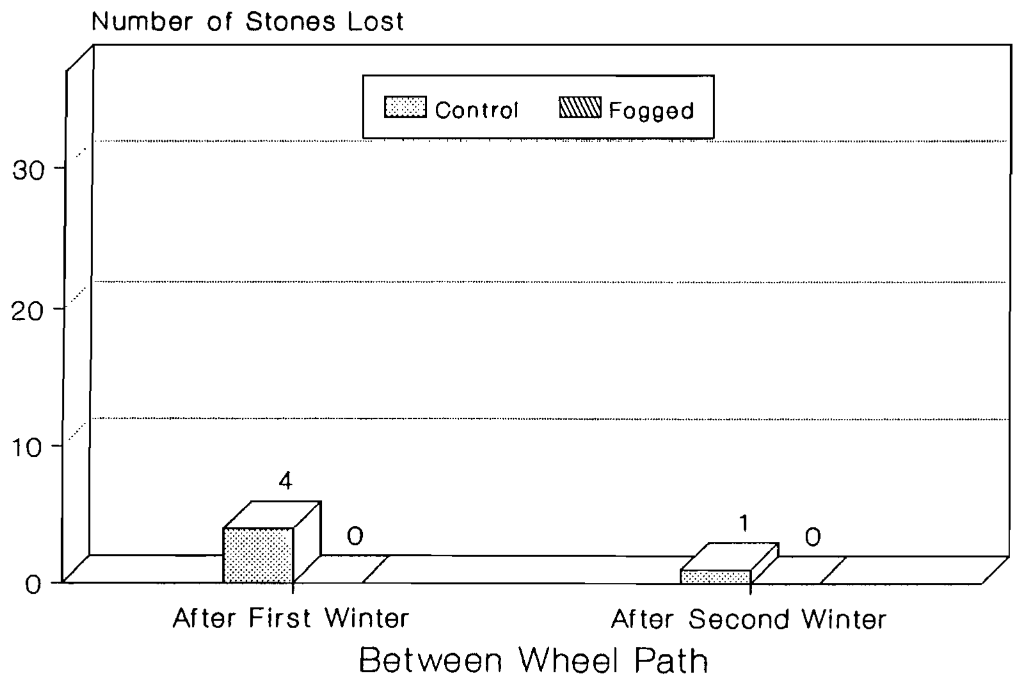


Figure 17. Stone Loss as Measured from Photorecords for FM 1997.

Table 16. Field Evaluation Data for FM 1997, Control Section.

Time of Evaluation	Aggregate Loss, %			Aggregate Embedment, %			Surface Texture, in.		
	RWP*	BWP*	CL*	RWP	BWP	CL	RWP	BWP	CL
At the Time of Fog Seal Application	10	25	20	40	35	35	0.132	0.151	0.151
After First Winter	10	25	20	50	40	40	0.090	0.137	0.094
After Second Winter	10	25	20	60	50	50	0.083	0.125	0.086

Table 17. Field Evaluation Data for FM 1997, Fogged Section.

Time of Evaluation	Aggregate Loss, %			Aggregate Embedment, %			Surface Texture, in.		
	RWP	BWP	CL	RWP	BWP	CL	RWP	BWP	CL
At the Time of Fog Seal Application	10	25	20	50	45	45	0.137	0.159	0.141
After First Winter	10	25	20	55	50	50	0.063	0.101	0.068
After Second Winter	10	25	20	60	50	50	0.053	0.074	0.061

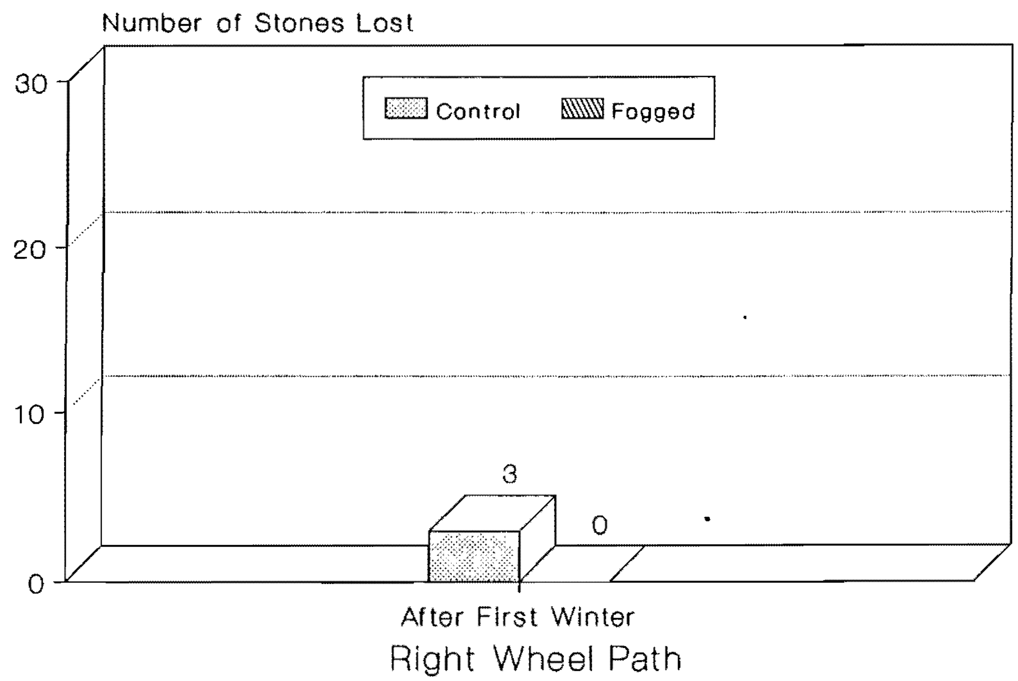
* RWP - Right Wheel Path
BWP - Between Wheel Path
CL - Centerline

paths of the feeder road to U.S. 80 at the time a fog seal was placed. An MS-2 emulsion was diluted 1.3:1 with water and applied in one application at a rate of 0.15 gallons per square yard for a total residual asphalt rate of 0.03 gallons per square yard. This test road was constructed during the final year of the study; therefore, only one performance evaluation was performed.

Results from the photorecords are shown in Table 18 and in Figure 18. This test road had the lowest fog seal residual binder application rate of any of the test roads; yet some improvement in aggregate retention was observed in the photorecords for the fogged section. Supplementary field data are exhibited in Tables 19 and 20.

Table 18. Stone Loss as Measured from Photorecords After First Winter for US 80 Feeder Road.

Photorecord	Number of Stones Lost			
	Right Wheel Path		Between Wheel Paths	
	Control	Fogged	Control	Fogged
A	0	0	4	0
B	1	0	4	0
C	1	0	0	0
D	1	0	10	0
E	1	0	4	0
Mean	1	0	4	0



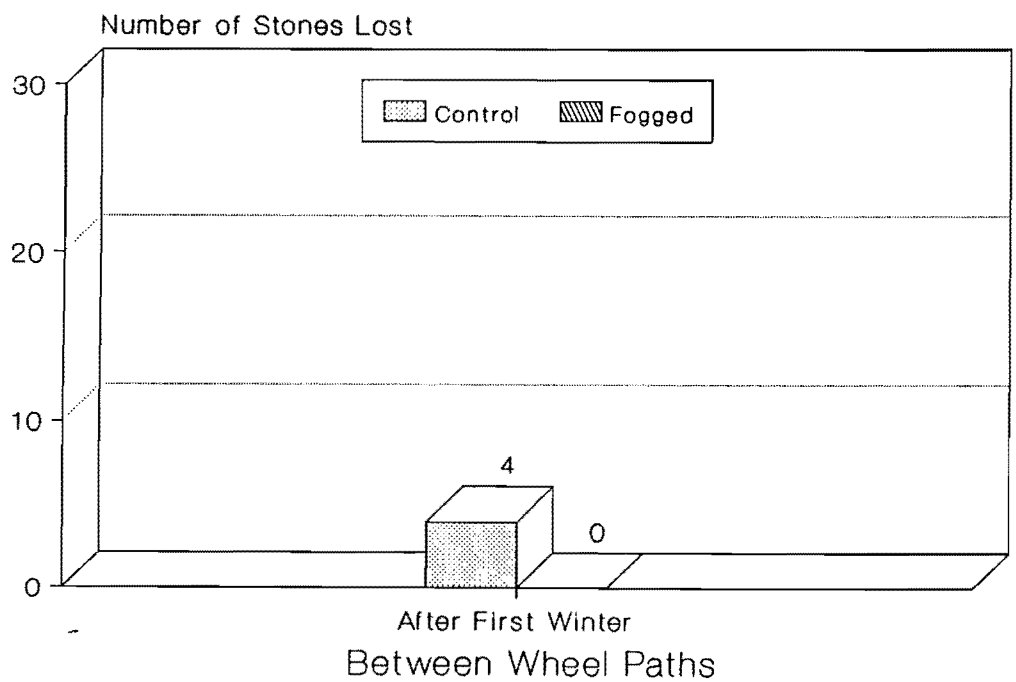


Figure 18. Stone Loss as Measured from Photorecords for US 80 Feeder Road.

Table 19. Field Evaluation Data for US 80 Feeder, Control Section.

Time of Evaluation	Aggregate Loss, %			Aggregate Embedment, %			Surface Texture, in.		
	RWP*	BWP*	CL*	RWP	BWP	CL	RWP	BWP	CL
At the Time of Fog Seal Application	5	10	5	45	35	35	0.113	0.125	0.119
After First Winter	5	15	5	50	40	40	0.080	0.119	0.119

Table 20. Field Evaluation Data for US 80 Feeder, Fogged Section.

Time of Evaluation	Aggregate Loss, %			Aggregate Embedment, %			Surface Texture, in.		
	RWP	BWP	CL	RWP	BWP	CL	RWP	BWP	CL
At the Time of Fog Seal Application	5	10	5	45	35	35	0.108	0.133	0.137
After First Winter	5	10	5	60	50	50	0.098	0.108	0.103

* RWP - Right Wheel Path
BWP - Between Wheel Path
CL - Centerline

EVALUATION OF FOG SEALS FOR ASPHALT CONCRETE

Fog seals are used on asphalt concrete to reduce the rate of ravelling from the pavement surface. They are also used to seal the surface to reduce the potential for air and water to enter into the pavement structure thereby causing the mixture to age-harden.

LABORATORY EVALUATION

The objective of the laboratory investigation was to determine the effectiveness of fog seals when applied to laboratory-molded samples at reducing the rate of age-hardening in an asphalt concrete mixture.

Mixture Design

The aggregate used in the mixture tests consisted of a subrounded, siliceous river gravel and similar sand, with limestone crusher fines added to improve stability. This material was selected because it produces a relatively binder-sensitive mixture which accentuates the properties of the binder more than a high-stability mix. Details of the aggregate blend and gradation are given in Appendix A.

The asphalts used in this study included Texaco, Exxon and Fina products. All asphalts were AC-20.

A binder content of 4.5 percent by weight was selected based upon mixture design results. Twelve samples of each asphalt mixture were molded for a total of 36 samples. Compaction effort was reduced below optimum in an effort to produce specimens with void contents more typical of field compacted mixtures. The average void content for all the mixtures was approximately six percent.

Sample Preparation

Half of the samples were treated with an MS-2 fog seal applied with a hand-held sprayer at a residual asphalt rate of 0.05 gallons per square yard while the other half of the samples were left untreated to serve as controls. The fog seal was applied to the top surface of the sample only. Half of the treated and half of the untreated samples were exposed to 140°F for six weeks in a forced-draft oven. The sides and bottom of the samples were insulated and sealed so that any aging that occurred would be through the surface. Indirect tension and resilient modulus tests on both aged and unaged samples were used to evaluate the effectiveness of the fog seal at reducing the rate of aging.

Resilient Modulus

Mixture stiffness was measured in accordance with ASTM D 4123-82 using the Mark III Resilient Modulus device. Typically, a diametral load of approximately 72 pounds was applied for a duration of 0.1 seconds while monitoring the diametral deformation perpendicular to the loaded plane. All of these tests were performed at 77°F.

The resilient moduli data for the unaged specimens are shown in Table 21. Table 22 presents the properties after exposure to 140°F for six weeks. Aging ratios were calculated by dividing resilient moduli after aging by corresponding values before aging. These data are shown in Figure 19. If the fog seal reduced the rate at which aging occurred, one would expect the aging ratio to be less than the corresponding control. In the Texaco and Fina mixtures, the control and fogged samples were not significantly different. The fogged samples in the Exxon mixture exhibited a slightly lesser propensity for age-hardening.

Indirect Tension

The indirect tension test employs the indirect method of measuring mixture tensile properties. Two-inch high and four-inch diameter cylindrical specimens were loaded diametrally at a constant rate of deformation until complete failure occurred. Diametral deformation perpendicular to the loaded plane was monitored in order to quantify mixture stiffness. The tests were

Table 21. Properties of Control and Fogged Specimens Before Exposure to 140°F.*

Type Sample	Air Voids, percent	Resilient Modulus, psi x 10^3	Tensile Strength, psi	Strain @ Failure, in/in
Texaco (Control)	6.5	430	210	0.0021
Texaco (Fogged)	6.4	446	223	0.0023
Exxon (Control)	6.2	392	205	0.0028
Exxon (Fogged)	6.2	384	201	0.0025
Fina (Control)	6.4	376	197	0.0023
Fina (Fogged)	6.3	358	210	0.0027

Table 22. Properties of Control and Fogged Samples After Exposure to 140°F for Six Weeks.*

Type Sample	Air Voids, percent	Resilient Modulus, psi x 10^3	Tensile Strength, psi	Strain @ Failure, in/in	Aged Resilient Modulus Ratio**	Aged Tensile Strength Ratio**	Aged Flexibility or Strain Ratio**
Texaco (Control)	6.3	642	251	0.0021	1.49	1.20	1.00
Texaco (Fogged)	6.5	678	270	0.0020	1.52	1.21	0.87
Exxon (Control)	6.2	627	228	0.0024	1.60	1.11	0.86
Exxon (Fogged)	6.0	560	241	0.0023	1.46	1.20	0.92
Fina (Control)	6.0	540	227	0.0021	1.44	1.15	0.91
Fina (Fogged)	6.3	501	231	0.0024	1.40	1.10	0.89

* Each value represents an average of three separate tests.
** Parameters computed by dividing the value after aging by its corresponding value before aging.

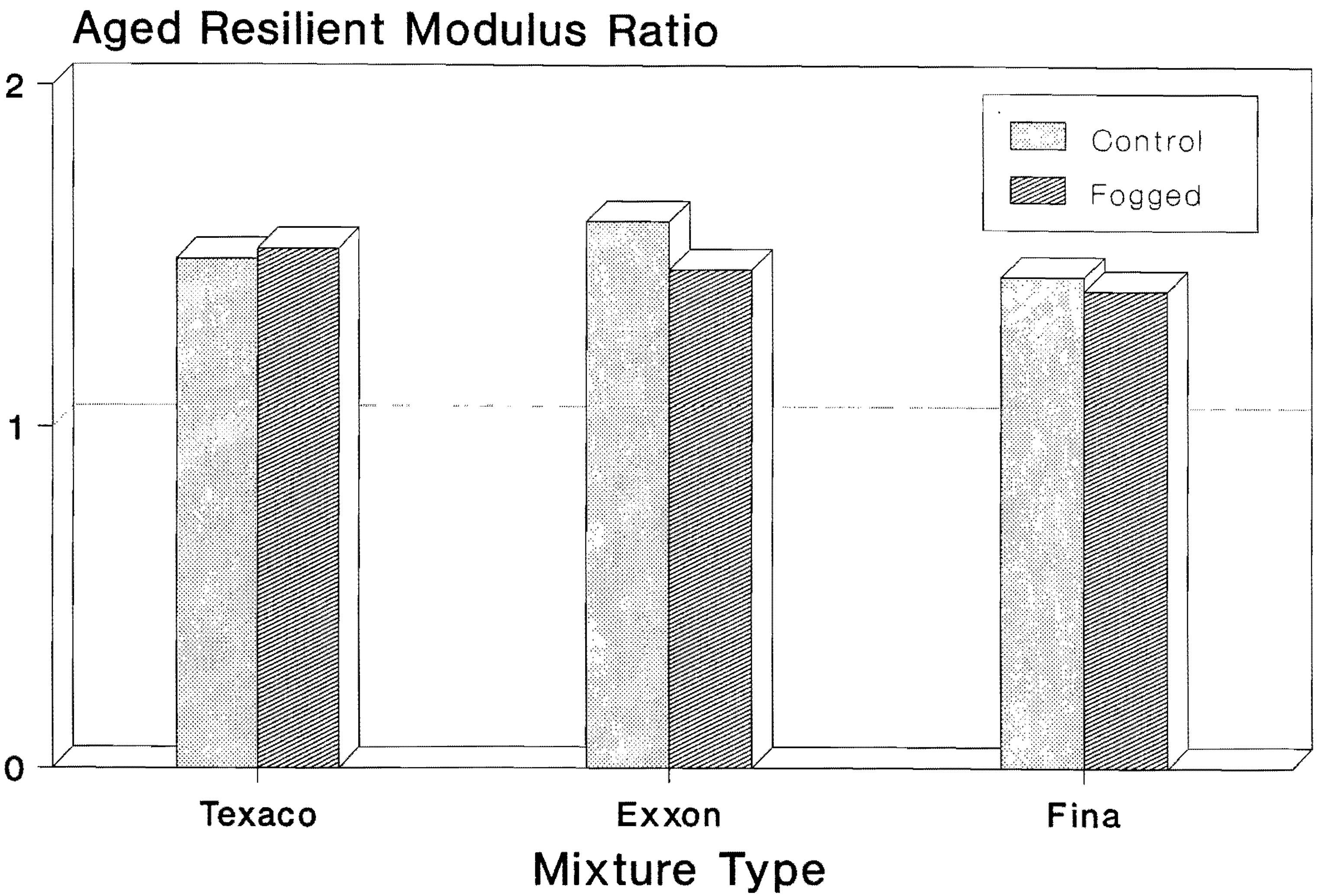


Figure 19. Aged Resilient Modulus Ratios for Fog-Seal Treated and Untreated Asphalt Concrete Samples.

performed at 77°F and at a deformation rate of two inches per minute. Data are tabulated in Tables 21 and 22. Strain at failure is the total diametral strain in the specimen at the maximum load in the plane perpendicular to the applied load. The aged tensile strength ratios are shown in Figure 20. Again there is no difference between the control and fogged samples for both the Texaco and Fina mixtures. However, the fogged samples of the Exxon mixture showed a slightly greater propensity for age-hardening than the controls which is the reverse of the results obtained in the previous resilient modulus tests.

Retained flexibility was estimated by dividing tensile strain at failure after aging by its corresponding value before aging. These data are shown in Figure 21. The fogged Exxon mixtures showed a slight improvement in retained flexibility while no improvement was observed in the Texaco and Fina mixtures.

FIELD EVALUATION

A fog seal was constructed in Kimble County on IH 10 near Junction, Texas, on an asphalt concrete pavement. The pavement surface looked "dry" and appeared to be losing some of the surface fines at the time of the seal; therefore, it seemed to be a good candidate for a fog seal.

The fog sealing material was MS-1, and it was diluted to an emulsion-water ratio of 1:1.8 and applied at 0.12 gallons per square yard for a residual application rate of 0.03 gallons per square yard.

As in the field evaluation of the chip seal pavements, ten 12-inch by nine-inch rectangles were painted on the pavement surface in the control section and in the fogged section. Five were painted in the outside wheel path and five were painted between wheel paths. Close-up photographs were taken of each rectangle at the time of the fog seal construction and then after the first and second winters following construction.

There was no obvious difference in the photorecords with time in either the control or fogged sections. No discernable loss of fines or larger aggregate was observed in the photorecords.

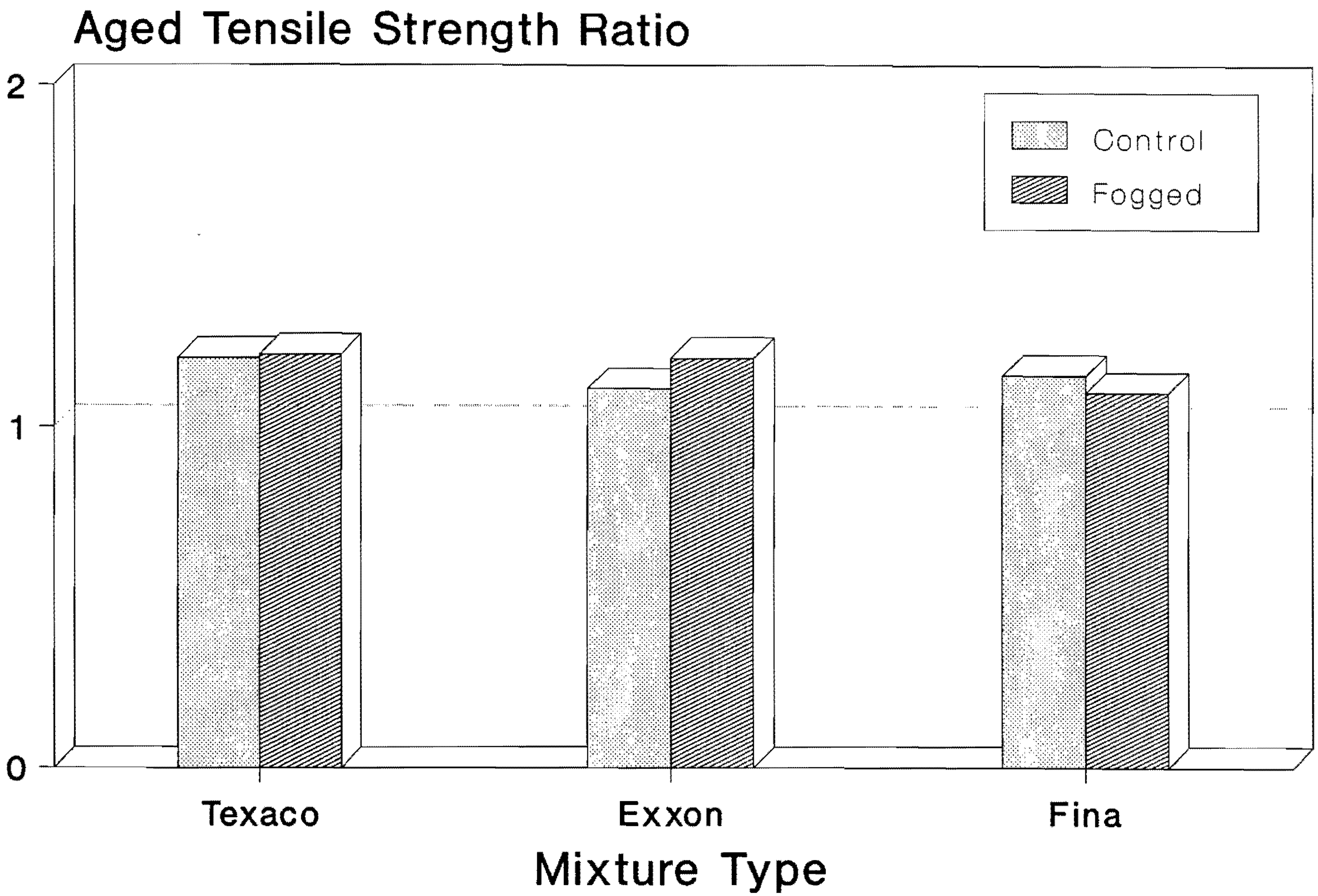


Figure 20. Aged Tensile Strength Ratios for Fog Seal Treated and Untreated Asphalt Concrete Samples.

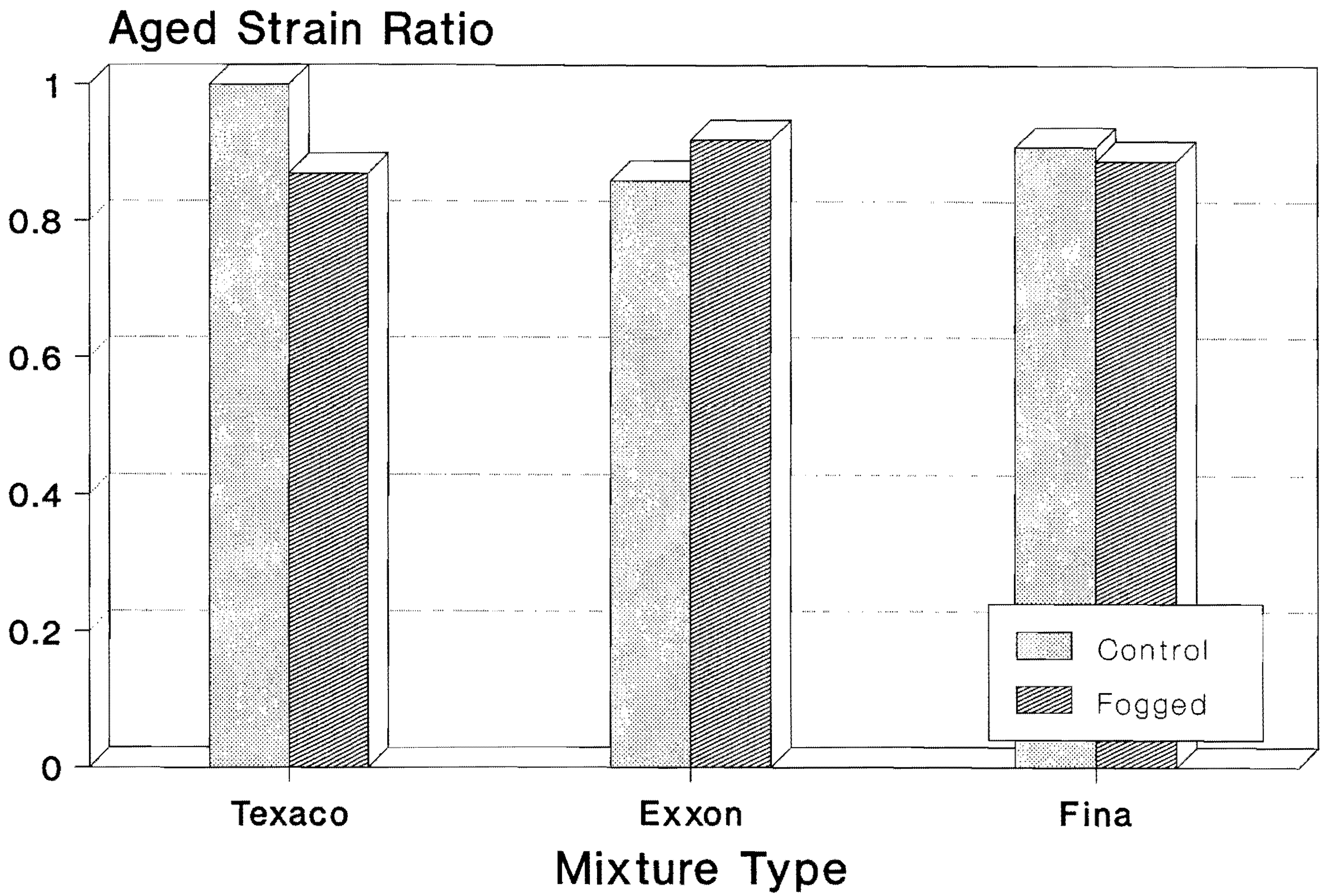


Figure 21. Aged Strain Ratios at Failure for Fog-Seal Treated and Untreated Samples Asphalt Concrete Samples.

No cracking was evident at any time during the pavement evaluations; therefore, cracking could not be used as a performance indicator. Surface texture measurements made in the control and fogged sections also indicated there was no change in the surface properties of the pavement. The overall pavement condition appeared to be about the same for the control and the fogged section.

EVALUATION OF REJUVENATING SEALS FOR ASPHALT CONCRETE MIXTURES

There are a number of rejuvenators on the market today that are being used to seal and rejuvenate asphalt concrete. Most of these rejuvenators are proprietary materials and, thus, often difficult to specify with a generic specification. Very little information is available that describes the expected performance when using rejuvenators to maintain pavements.

The rate of oxidation of asphalt concrete is highly dependent on the voids in the total mixture (VTM) (10). If the VTM is below seven to eight percent, then the effects of oxidation will be greatly minimized (10). Oxidation causes the asphalt mixture to stiffen and crack at low temperatures. The purpose of the rejuvenator is to penetrate somewhat into the asphalt concrete and soften (rejuvenate) the asphalt binder. The rejuvenator also helps to seal the pavement and minimize future oxidation.

In order for a rejuvenator to be effective, it must penetrate into the asphalt concrete. If it does not penetrate, it cannot soften the asphalt, and it will cause the surface to become slick, especially in wet weather (10). The VTM must be approximately seven to eight percent or more to provide sufficient permeability to allow for penetration of the rejuvenator into the mixture (10).

A study was conducted by Brown and Johnson for the U. S. Army Corps of Engineers to evaluate the performance of pavement sections treated with rejuvenators (11). The following five paragraphs are a discussion of the results from the Corps of Engineers study. Five different rejuvenators were applied to asphalt concrete pavements in three locations across the U.S. One of the rejuvenators was selected was an SS-1 asphalt emulsion. The rejuvenators were evaluated to determine their ability to penetrate oxidized pavements, to soften the asphalt binder, to reduce the amount of surface cracking, to reduce the loss of surface fines, and to minimize reduction in skid resistance.

After the pavements were rejuvenated, cores were taken and observed to determine approximate penetration of rejuvenator.

Three materials appeared to penetrate into the surface approximately 3/8 inch on the average. The SS-1 and another rejuvenator showed no significant penetration. For this reason, the top 3/8 inch of all the cores was removed and evaluated to determine the effect of rejuvenators.

Asphalt was extracted from the top 3/8 inch of each core and penetration and viscosities were measured on the recovered binder. Three of the rejuvenators appeared to provide some rejuvenation while the other two actually stiffened the mix. The data showed that the application of the materials being evaluated modified the asphalt properties for at least three years.

Data obtained with a British Portable Skid Tester showed that most of the materials reduced skid resistance for at least one year. The two and three-year tests showed that the skid resistance of the treated sections was approximately equal to the skid resistance of the untreated sections.

After the rejuvenators had been in place for three years, the amount of cracking was evaluated. The data showed that the total amount of cracking for each of the test sections was approximately equal to the total amount of cracking in the control sections.

After three years, it was observed that the untreated sections, in some cases, had lost surface fines while the treated sections appeared to perform better. The loss in surface fines was measured by quantifying the surface texture. All five materials tested resulted in a reduction in surface texture indicating a reduction in fines being lost. At some locations, a difference in surface texture was visually observed. The material which appeared to hold the surface fines the best was the same material which appeared not to penetrate into the surface but did apparently seal the surface.

LABORATORY EVALUATION

Effects of Rejuvenator When Full-Depth Penetration is Achieved

Sample Preparation. Twelve asphalt concrete samples were molded in the laboratory using a Texaco AC-20 asphalt and the same aggregate and mixture design as presented earlier. Because rejuvenators tend to penetrate only the top 3/8 inch of an asphalt concrete surface, it is difficult to assess the effects of the rejuvenator on the mixture itself. Therefore, in this study, compaction effort was reduced, and samples were molded at a high air void content in order to achieve full depth penetration of a rejuvenator when applied to the surface of the sample. The laboratory samples had air voids ranging from 10 to 12 percent. A rejuvenator, which will be called Rejuvenator A, was applied onto the surface of half of the samples at a rate of 0.05 gallons per square yard. Full-depth penetration of the rejuvenator through the sample was achieved since some of the rejuvenator was observed to pass through the bottom side of the sample. The samples were then allowed to cure at 104°F.

Skid Resistance. The samples were periodically tested to evaluate skid resistance using the British Portable Skid Tester. The samples were measured three days after application of the rejuvenator and then again at three weeks and six weeks. These results are compared with untreated specimens in Figure 22. The tabular results are shown in Appendix B. A significant reduction in skid resistance was observed at the three-day test; however, at three weeks and six weeks, skid resistance was at least equivalent to the untreated samples. Field results obtained by Brown showed that the skid resistance was reduced for at least a year after rejuvenator application (10). This indicates that the void content in the mixture has an important effect on the ability of the rejuvenator to penetrate the pavement surface thereby affecting the skid resistance of the surface.

Resilient Modulus. Mixture stiffness was measured using the Mark III Resilient Modulus Device as described previously. A diametral load of approximately 72 pounds was applied for a duration of 0.1 seconds while monitoring the diametral deformation perpendicular to the loaded plane. The load is normally reduced to about 20 pounds for tests performed at 100°F or higher to prevent

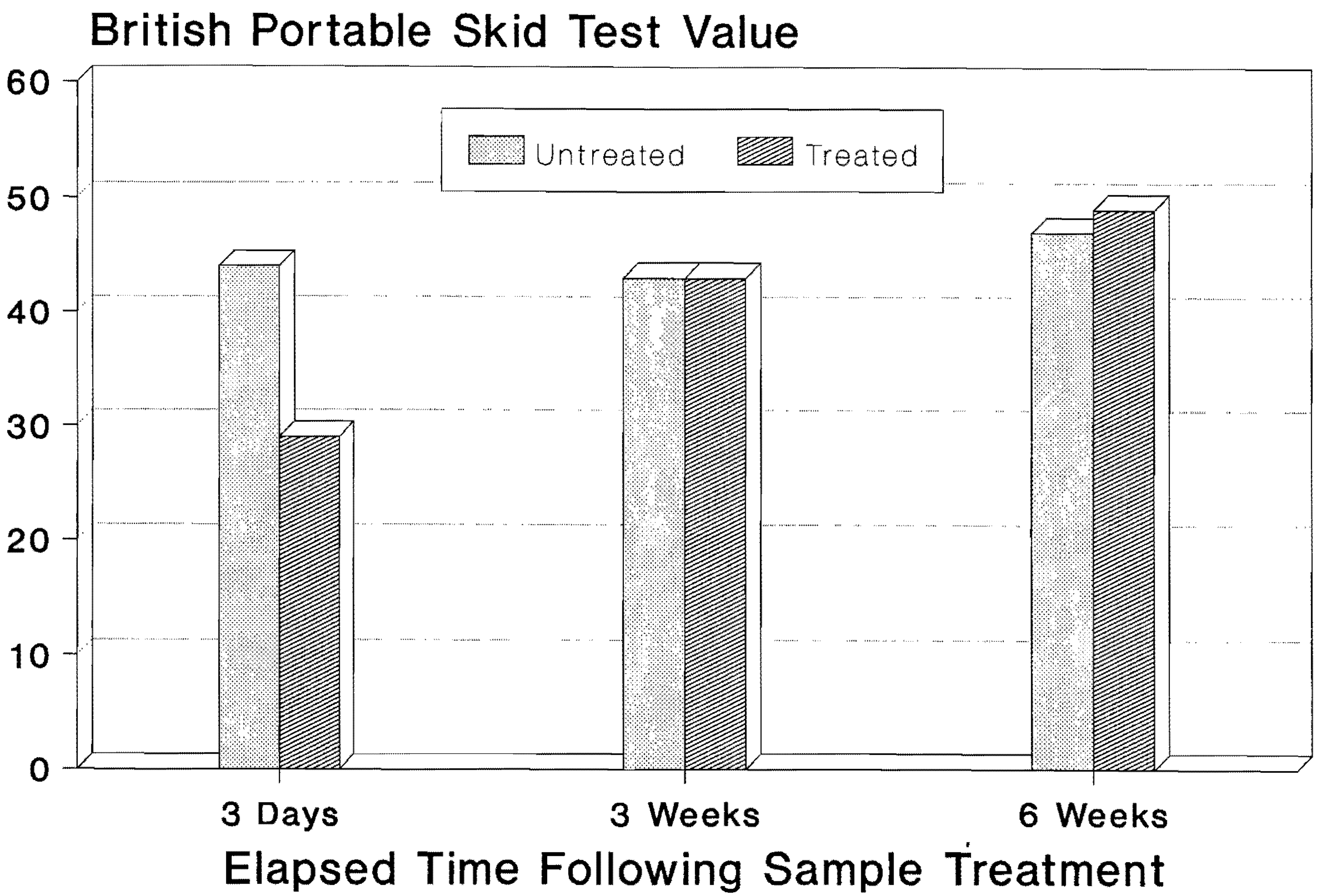


Figure 22. British Portable Skid Test Values for Rejuvenated Asphalt Concrete Samples.

damage to specimens. Resilient modulus was measure on the treated and untreated specimens over a range of temperatures to quantify mixture temperature susceptibility. These results are shown in Figure 23 and are tabulated in Appendix B. Results at the lower temperatures show both the treated and untreated specimens approaching a limiting value of about 1.5 million psi. Above 25°F the resilient modulus of the treated mixtures is significantly less than the untreated mixtures. While a reduction in mixture stiffness at 25°F has obvious benefits, it can certainly be a detriment at 104°F. A decrease in mixture stiffness at high temperatures can cause the mixture to be susceptible to permanent deformation.

Indirect Tension. Indirect tension tests were performed on all of the samples as described previously. The tests were performed at 77°F and at a deformation rate of two inches per minute. Data are tabulated in Appendix B and summarized in Figures 24 and 25. A 20 percent decrease in tensile strength was observed in the rejuvenated samples and a 50 percent increase in strain at failure. These data indicate that the rejuvenator can significantly reduce the stiffness of the mixture thereby improving the resistance of the mixture to cracking; however, the rejuvenator may also be increasing the potential of the mixture to permanently deform.

Evaluation of Different Rejuvenators

Using the same mixture design as used to evaluate fog seals in the previous chapter, laboratory molded samples prepared with three different sources of AC-20 were treated on the top surface with three different rejuvenators at an application rate of 0.05 gallons per square yard. Air void contents ranged from 6.0 to 6.8 percent. The sides and bottom of the samples were insulated and sealed so that any aging that occurred would be through the surface. The results were compared with the control samples in the previous chapter. These data are shown in Table 23. Each number represents the average of three tests.

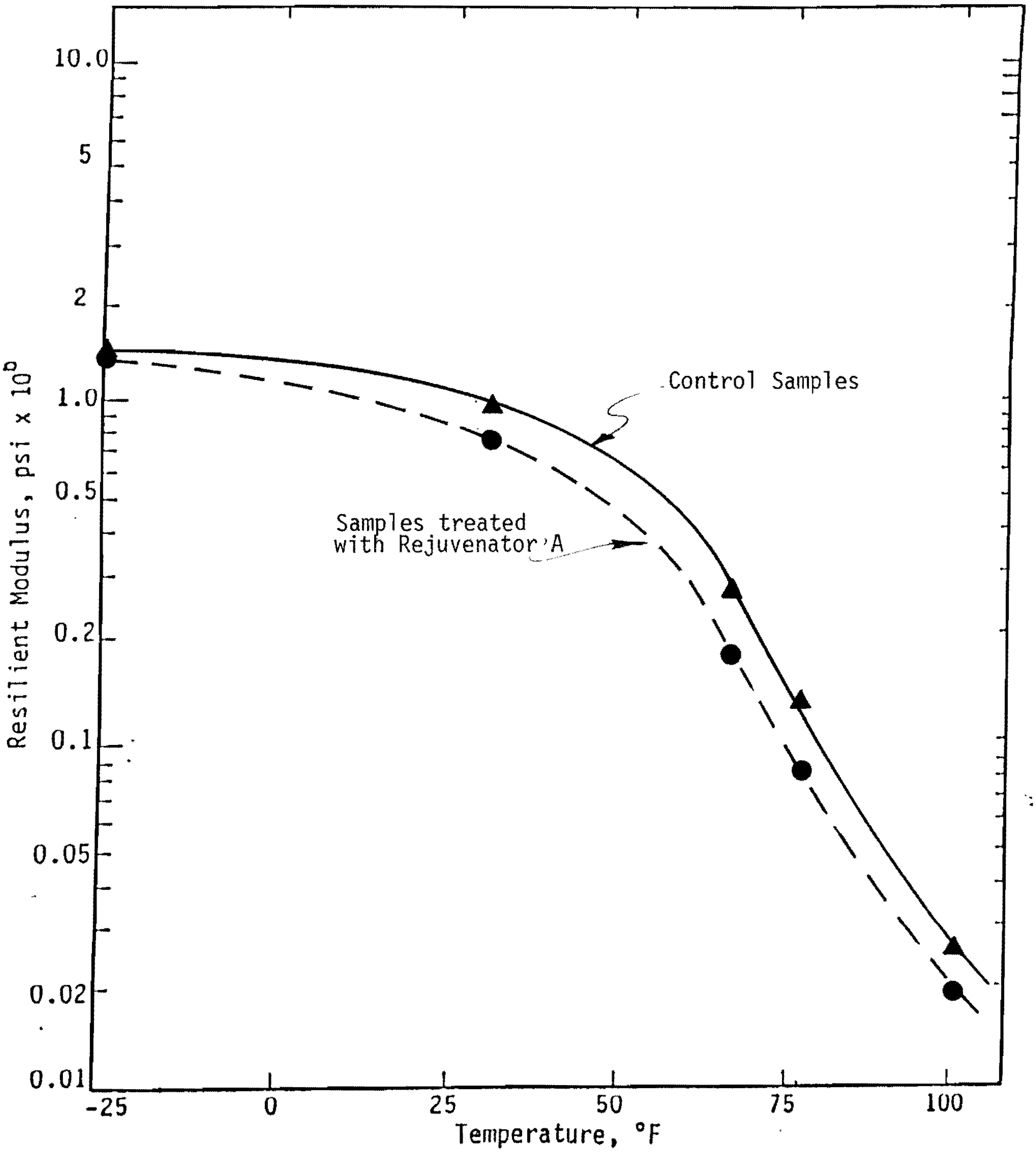


Figure 23. Resilient Modulus versus Temperature for Rejuvenated and Control Asphalt Concrete Samples.

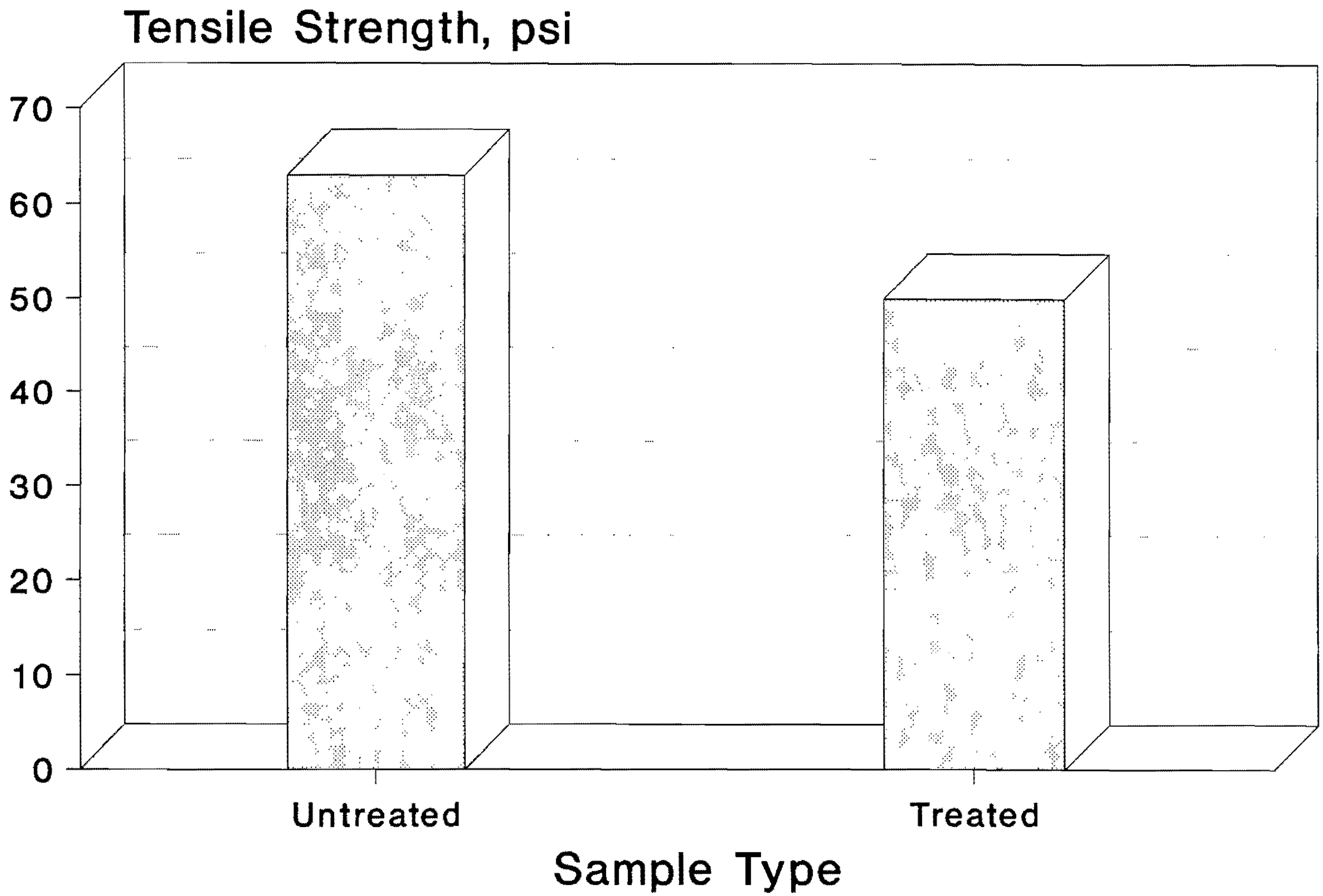


Figure 24. Tensile Strength of Rejuvenated and Control Asphalt Concrete Samples.

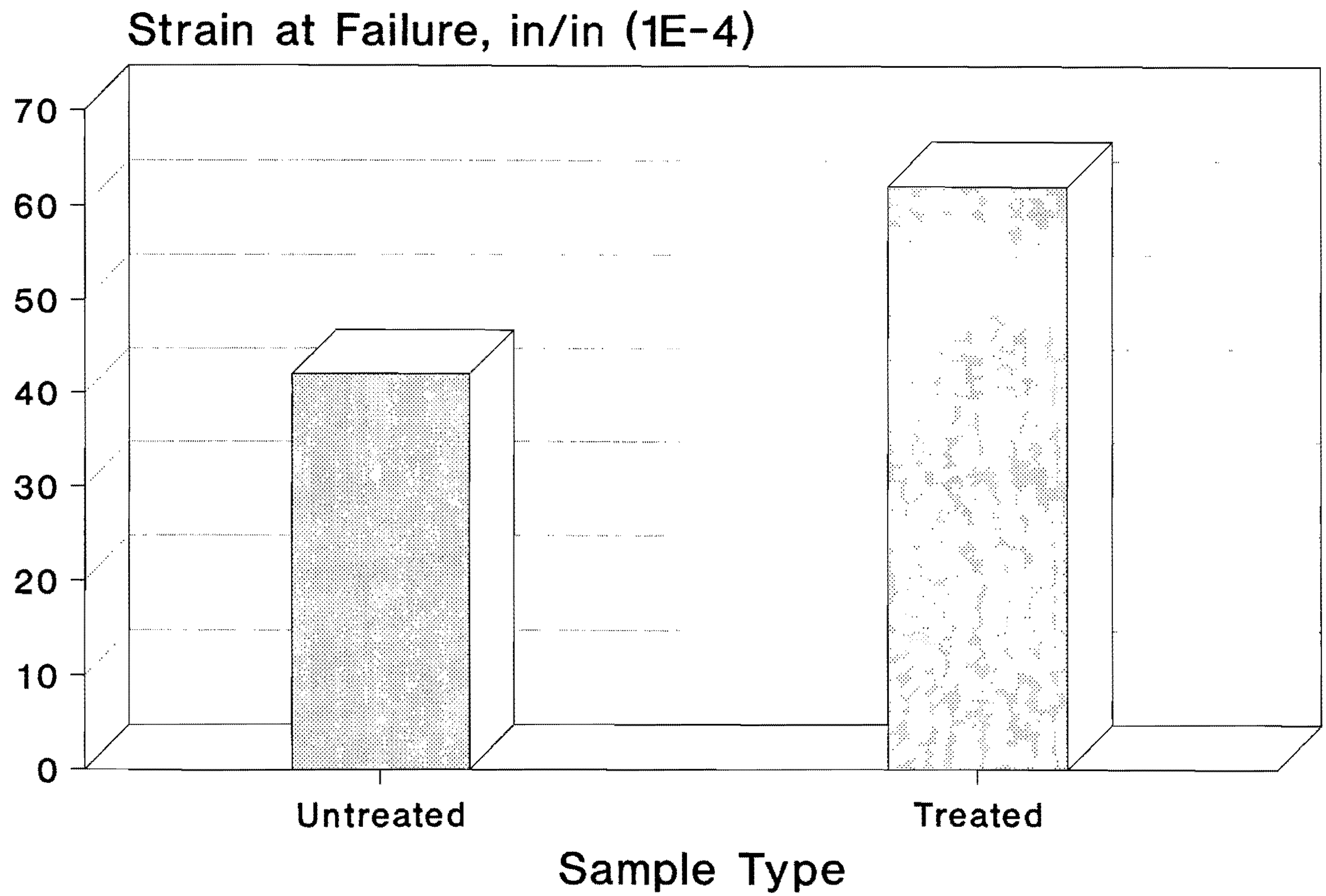


Figure 25. Tensile Strain at Failure for Rejuvenated and Control Asphalt Concrete Samples.

Table 23. Properties of Mixtures Treated With Rejuvenating Agents and Exposed to 140°F for Six Weeks.

Mixture Type	Air Voids, percent	Resilient Modulus, psi x 10^3	Tensile Strength, psi	Strain @ Failure, in/in
Texaco Control (unaged)	6.5	430	210	0.0021
Texaco Control (aged)	6.3	642	251	0.0021
Texaco + Rejuvenator A	6.8	535	236	0.0025
Texaco + Rejuvenator B	6.7	526	206	0.0029
Texaco + Rejuvenator C	6.7	574	228	0.0025
Exxon Control (unaged)	6.2	392	205	0.0028
Exxon Control (aged)	6.2	626	228	0.0024
Exxon + Rejuvenator A	6.2	536	174	0.0028
Exxon + Rejuvenator B	6.4	482	160	0.0031
Exxon + Rejuvenator C	6.1	610	210	0.0025
Fina Control (unaged)	6.4	376	197	0.0023
Fina Control (aged)	6.0	540	227	0.0021
Fina + Rejuvenator A	6.1	520	216	0.0025
Fina + Rejuvenator B	6.5	500	190	0.0028
Fina + Rejuvenator C	6.6	550	220	0.0022

Resilient Modulus. Resilient moduli data are shown in Figure 26 for the Texaco, Exxon, and Fina mixtures. Rejuvenators A and B caused a significant decrease in resilient modulus from the corresponding aged control samples for the Texaco and Exxon mixtures. The Fina mixtures showed very little reduction in resilient modulus with any of the rejuvenators.

Indirect Tension. All three rejuvenators for each asphalt mixture type caused decreases in tensile strength from the corresponding aged controls. (See Figure 27.) Again, the mixture properties of the Fina samples were less affected by the rejuvenators than both the Texaco and Exxon mixtures. Strain at failure is shown in Figure 28. While all the rejuvenators caused some increase in the strain at failure, or flexibility, rejuvenator B showed the highest increase in strain at failure for every asphalt mixture type. These data indicate that even though the rejuvenator only penetrates about 3/8 inch, it does have an effect on the measured stiffness properties of the mix.

FIELD EVALUATION

A rejuvenating seal was constructed near San Antonio on US 87 from FM 1628 to the Wilson County Line in August of 1990. The rejuvenator was sprayed onto the pavement at a rate of 0.06 gallons per square yard and allowed to penetrate into the surface for 45 minutes to one hour prior to sanding. British Portable Skid Tests were made on the control surface which had no rejuvenator and compared to the rejuvenated surface. The control section had an average skid number of approximately 59. Immediately prior to sanding the rejuvenated surface, the skid number on the rejuvenated section was about 23. Two hours after the surface had been sanded the skid number was up to 49, and at 24 hours the skid number was back to its original skid resistance of 60. Sanding the surface in this manner appears to be very effective in keeping the skid resistance at a safe level.

A pavement evaluation performed four months after construction of the rejuvenated seal showed no obvious difference in performance

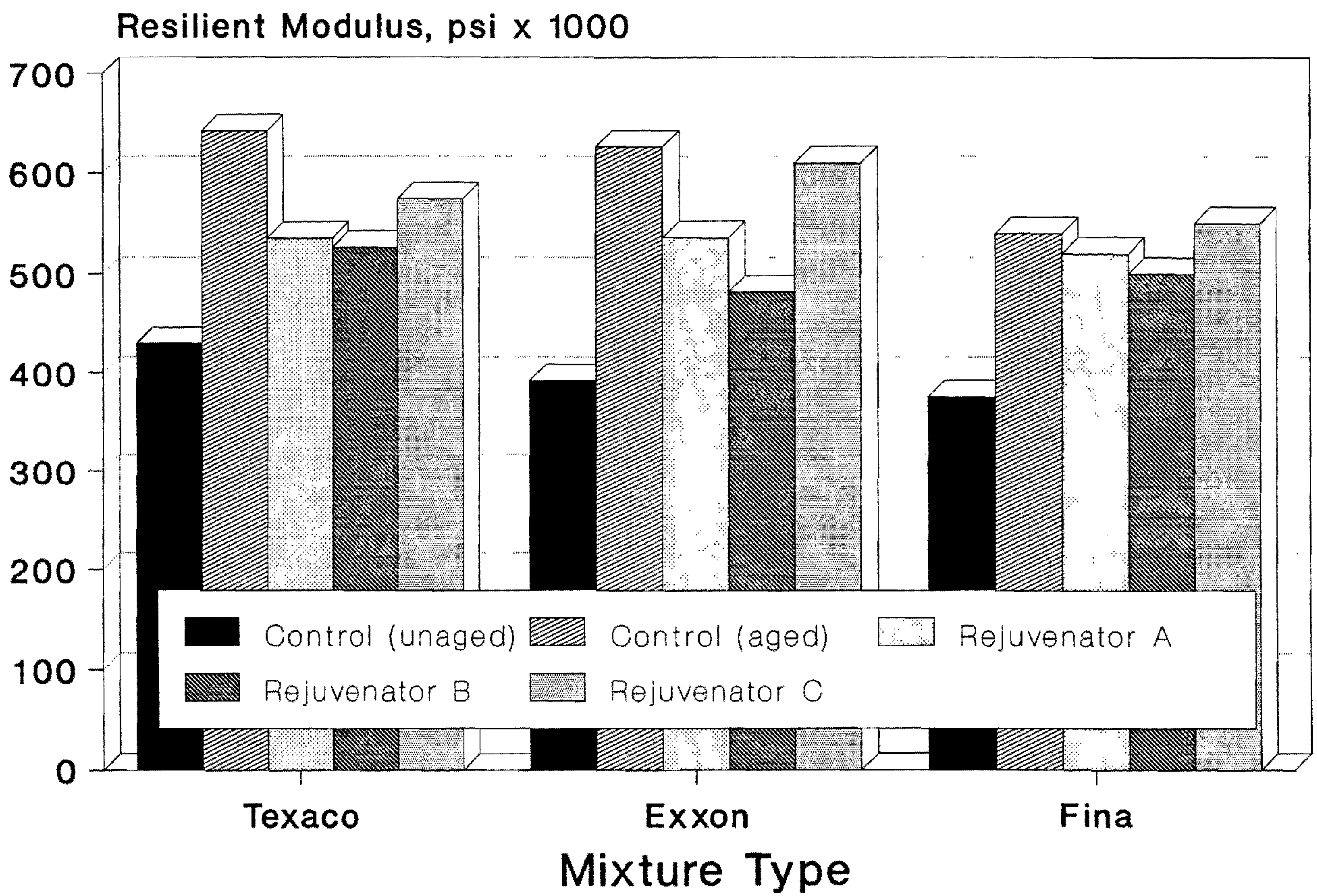


Figure 26. Resilient Modulus for Rejuvenated and Control Asphalt Conrete Samples.

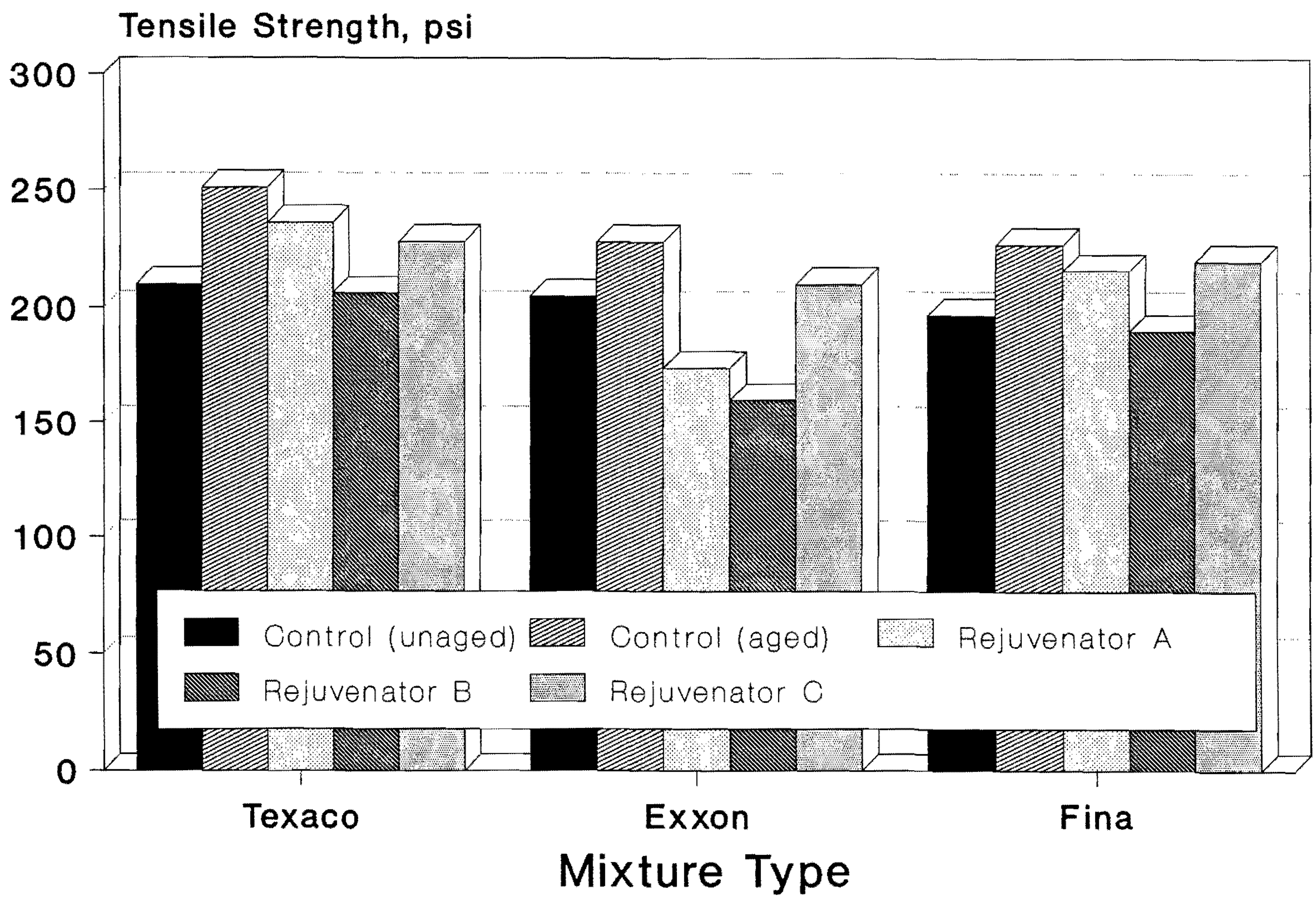


Figure 27. Tensile Strength of Rejuvenated and Control Asphalt Concrete Samples.

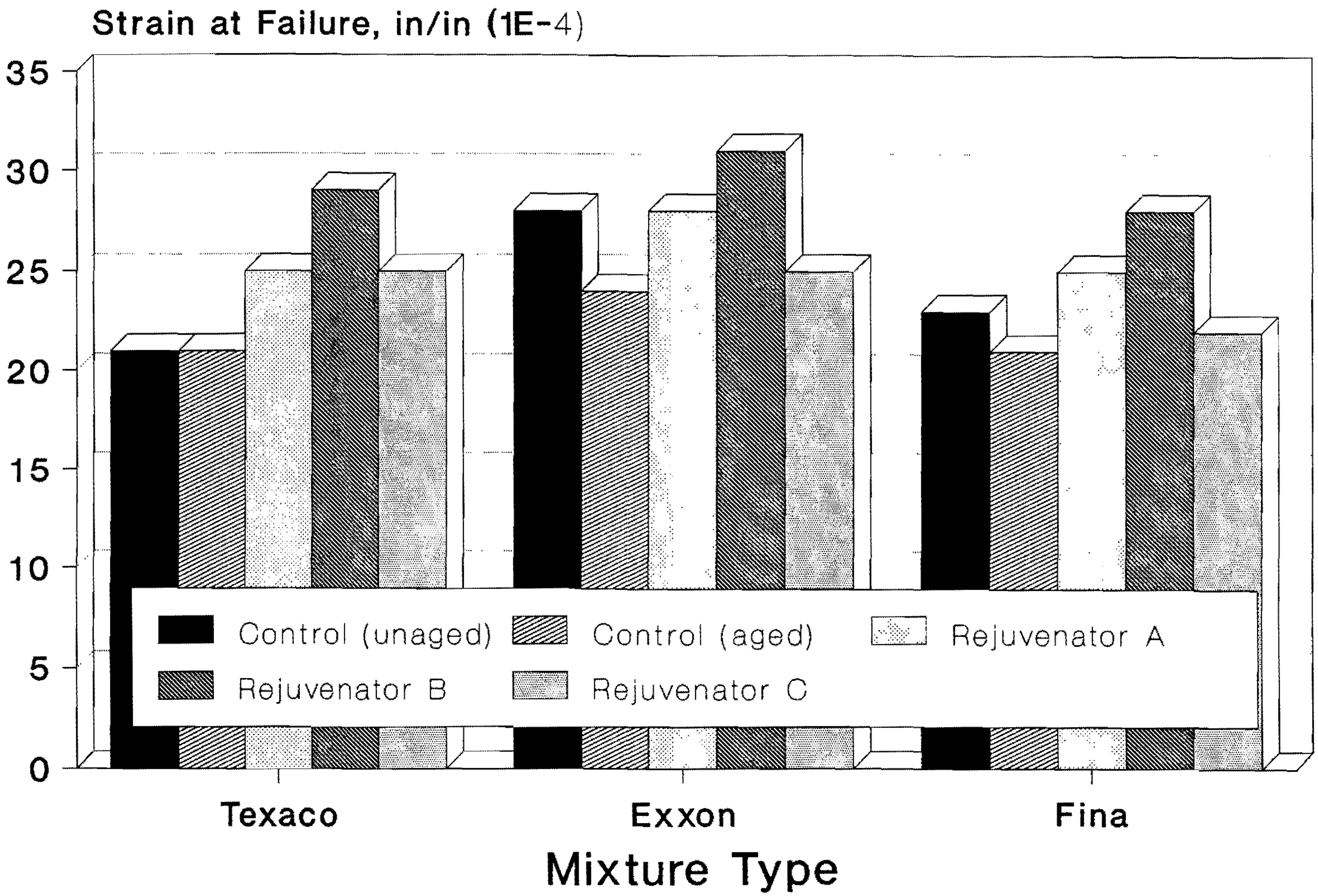


Figure 28. Tensile Strain at Failure for Rejuvenated and Control Asphalt Concrete Samples.

in the treated versus untreated sections. Cracking was measured at the time the seal was placed and was approximately the same at the time of the first evaluation.

DESIGN APPLICATION QUANTITIES

A guideline for determining appropriate application quantities was developed by the Utah Department of Transportation and is presented in Appendix C (13).

COST-EFFECTIVENESS OF FOG SEALS AND REJUVENATORS

Because of the many factors influencing the life of any pavement surface, it is very difficult to assess the cost-effectiveness of fog seals and rejuvenators. Fog seals and rejuvenators are applied to pavement surfaces in attempt to extend service life, but the actual life extension realized by these maintenance treatments is difficult to accurately estimate.

As seen from the data presented earlier, there is no doubt that fog seals can stop the aggregate loss on a chip seal which was constructed with an inadequate quantity of binder and can, therefore, extend the life of that chip seal. A fog seal applied at a residual binder rate of 0.05 gallons per square yard was estimated to cost $.10 per square yard, in place. Materials costs were estimated from actual bid prices and districts were contacted to obtain estimates of manpower, equipment charges and production rates. A conventional chip seal, in place, costs approximately $.50 per square yard (obtained from construction bids in 1989) (<u>12</u>). These costs were used to calculate equivalent uniform annual cost using the following formula:

$$A = \frac{P\,[\,i * (1 + i)^n]}{[(1 + i)^n - 1]}$$

where,

A = equivalent uniform annual cost,

P = initial construction cost,

i = interest rate, and

n = pavement life in years.

It must be kept in mind that the annualized cost is based on initial construction cost only with an effective interest rate of four percent (interest rate with inflation accounted for). It does not include any user costs or expected maintenance costs.

It is commonly reported that a conventional chip seal will last seven years in Texas. A fog seal is not expected to extend the life of a chip seal beyond what is normal. It is used to extend the life of an underdesigned chip seal <u>to</u> what is normal. The equivalent uniform annual cost of a conventional chip seal is \$.083 per square yard. A single application of a fog seal increases its uniform annual cost to \$.10 per square yard. When fog seals are applied in several applications, the cost increases accordingly. Therefore, if a second application of a fog seal was made soon after the first, the equivalent uniform annual cost would increase to \$.117 per square yard. If a fog seal constructed during the first year can cause an inadequately designed chip seal to have a normal life, then it can be considered cost-effective.

It is even more difficult to assess the cost-effectiveness of fog seals or rejuvenators on asphalt concrete pavements. There is little evidence to support an actual pavement life extension caused by fog seals or rejuvenators on asphalt concrete pavements. However, there may be some advantage when used to correct specific surface problems such as ravelling. Using a cost of \$.10 per square yard for an emulsion fog seal as used previously, it was determined that if a fog seal can delay further rehabilitation by as much as 18 months, it would have an equivalent uniform annual cost slightly less than that of a chip seal.

Rejuvenating seals were estimated to cost approximately \$.15 per square yard. Actual bid prices from 1990 were used to estimate materials costs. A rejuvenator applied to an asphalt concrete surface would need to extend pavement life by approximately two years to have an equivalent uniform annual cost (\$.079) slightly less than that of a chip seal.

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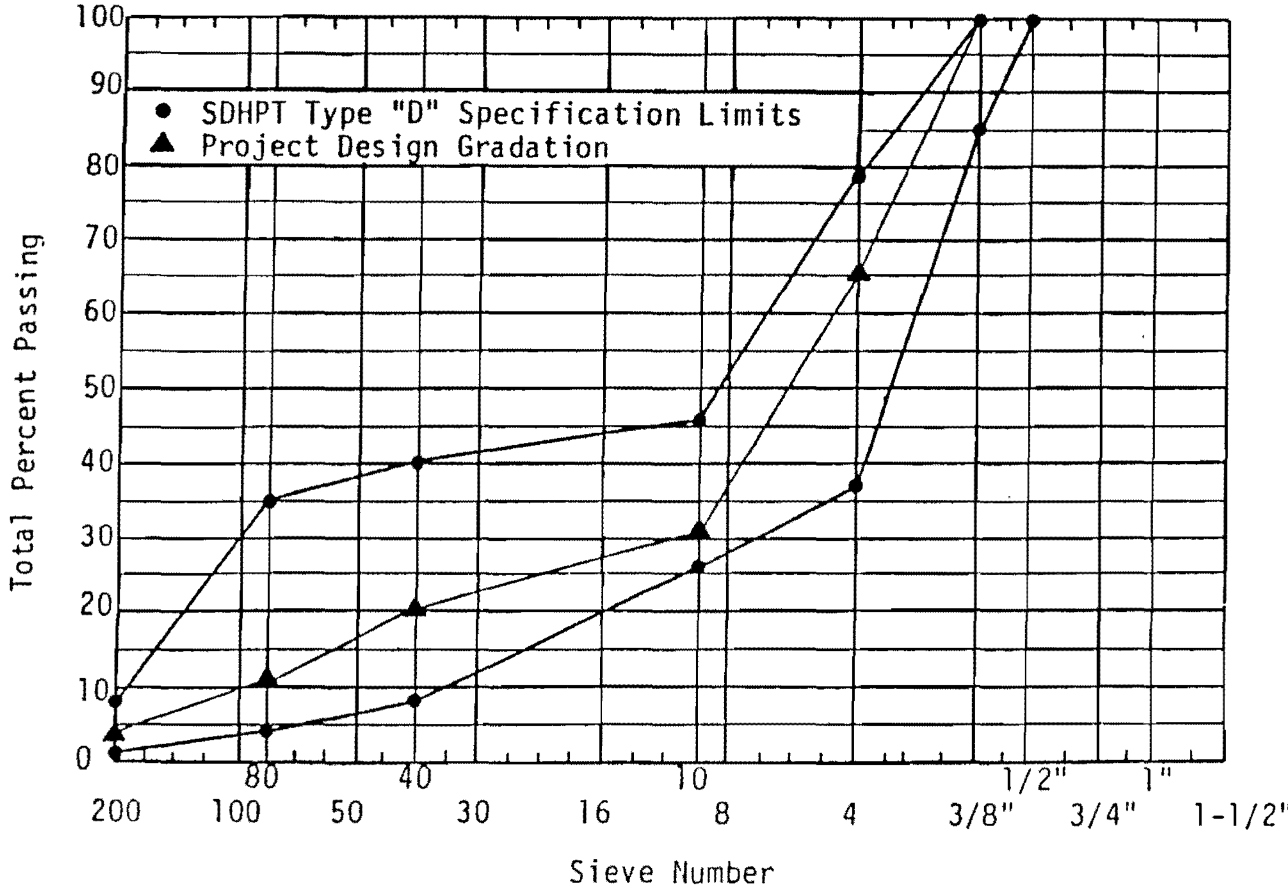
APPENDIX A

MISCELLANEOUS MIXTURE MATERIAL PROPERTIES



Design gradation specification limits for
pea gravel aggregate.

APPENDIX A MISCELLANEOUS MIXTURE MATERIAL PROPERTIES

Table A1. Individual aggregate gradations for washed pea gravel, washed sand, field sand, and limestone crusher fines.

	Washed Pea Gravel	Washed Sand	Field Sand	Limestone Crusher Fines
Sieve Size	Percent retained	Percent retained	Percent retained	Percent retained
#4	65.6	0.3	1.4	0.1
#8	31.6	13.1	1.1	6.2
#16	1.6	17.7	1.0	18.4
#30	0.4	18.4	0.4	16.1
#50	0	35.4	1.1	11.7
#100	0	11.9	44.8	10.4
#200	0	0.7	28.5	7.1
-#200	0.8	2.5	21.7	30.0
Percentage of each aggregate used in blend	50%	30%	10%	10%

Table A2. Bulk specific gravity, apparent specific gravity, and percent absorption for the pea gravel and combined fines.

	Pea Gravel	Pea Gravel	Combined Fines (washed sand, field sand, limestone fines)
Bulk Specific Gravity	2.575	2.529	2.584
Apparent (maximum) specific gravity	2.658	2.640	2.642
Absorption, percent	1.22	1.68	0.86

APPENDIX B

LABORATORY TEST DATA FOR REJUVENATED AND CONTROL ASPHALT CONCRETE SAMPLES

BRITISH PENDULUM TEST

Three Days After Treatment

*(TREATED SAMPLE)

	SAMPLE NO	TEST NUMBER 1	2	3	4	5	AVERAGE
Treated	*5-1	35	32	32	30	26	31
	*5-2	29	27	26	27	26	27
	*5-3	28	27	28	28	28	28
	*5-4	30	30	30	26	28	29
	*5-5	28	29	25	25	25	26
	*5-6	30	30	32	29	28	30
	*5-7	28	26	27	27	26	27
	*5-8	29	29	31	30	30	30
Untreated	5-9	47	42	45	45	44	45
	5-10	47	47	47	46	46	47
	5-11	50	48	50	49	49	49
	5-12	42	40	41	42	40	41
	5-13	42	41	40	42	41	41
	5-14	45	45	46	44	45	45
	5-15	45	46	43	43	40	43
	5-16	43	43	42	41	41	42

BRITISH PENDULUM TEST

Three Weeks After Treatment

TEST NUMBER

	SAMPLE NO	1	2	3	4	5	AVERAGE
	5-1	40	40	40	40	40	40
	5-2	40	40	40	40	40	
	5-3	40	40	41	42	41	40.8
	5-4	40	40	41	40	39	40
Treated	5-5	47	47	47	45	46	46.4
	5-6	49	49	48	48	48	48.4
	5-7	46	46	46	46	46	46
	5-8	43	42	43	43	43	42.8
	5-9	50	50	51	50	49	50
	5-10	46	46	45	44	44	45
	5-11	45	46	45	45	44	45
Untreated	5-12	47	48	47	47	47	47.2
	5-13	45	43	44	43	42	43.4
	5-14	46	45	45	45	44	45
	5-15	40	40	40	39	38	39.4
	5-16	42	42	42	41	41	41.6
	5-17	35	35	35	35	34	34.8

BRITISH PENDULUM TEST

Six Weeks After Treatment

		TEST NUMBER					
	SAMPLE NO	1	2	3	4	5	AVERAGE
	5-1	45	46	47	47	42	45.4
	5-2	45	45	45	46	50	46.2
	5-3	47	46	45	47	48	46.6
	5-4	48	48	48	49	50	48.6
	5-5	51	53	53	54	54	53
Treated	5-6	53	48	49	50	50	50
	5-7	48	48	49	49	50	48.8
	5-8	53	54	54	55	55	54.2
	5-9	41	41	42	42	42	41.6
	5-10	43	43	45	45	45	44.2
	5-11	45	46	46	46	47	46
	5-12	50	45	48	48	48	47.8
Untreated	5-13	50	51	48	51	52	50.4
	5-14	53	52	50	48	50	50.6
	5-15	52	50	51	53	52	51.6
	5-16	50	50	45	48	46	47.8

RESILIENT MODULUS

TEMPERATURE = 100°F

$$M_R = \frac{P\ (V + 0.2732)}{t\ (\Delta)} \qquad V = 0.35$$

SAMPLE NUMBER	P (LOAD) (LBS)	T HEIGHT (INCHES)	Δ DEF	M_R (PSI) # x 10^6	AVERAGE M_R # 10x10^6
	5.5		60	0.02106	
5-1	5.9	2.712	64	0.02118	0.0211
	6.4		40	0.0365	
5-10	6.4	2.725	46	0.0318	0.0341
	6.7		74	0.0206	
5-3	7.7	2.735	88	0.0199	0.0202
	6.6		51	0.0298	
5-11	6.3	2.7	60	0.0242	0.027
	6.0		81	0.0167	
5-4	6.0	2.753	76	0.0178	0.0172
	5.9		55	0.0245	
	6.4		74	0.0198	
5-12	6.4	2.72	60	0.0244	0.0229
	6.4		120	0.0122	
5-5	6.2	2.71	115	0.0123	0.0122
	6.0		85	0.0160	
	6.2		69	0.0204	
5-13	6.3	2.735	66	0.0217	0.0193
	6.0		84	0.0161	
5-6	6.1	2.761	77	0.01788	0.0169
	5.9		48	0.0282	
5-14	6.5	2.712	51	0.0292	0.0287
	6.5		63	0.0236	
	6.1		76	0.01839	
5-7		2.719	56		0.0209
	5.8		53	0.0250	
	5.8		45	0.0295	
5-15	5.8	2.721	54	0.0245	0.0263
	5.6		42	0.0306	
5-16	5.7	2.712	41	0.0318	0.0312

RESILIENT MODULUS

TEMPERATURE = 77°F

$$M_R = \frac{P\ (V + 0.2723)}{t\ (\Delta)} \qquad V = 0.35$$

SAMPLE NO	(P) LOAD (LBS)	(t) HEIGHT (INCHES)	(Δ) DEF.	M_R # x 10^6	AVERAGE
	34.8		73	0.1095	
	42.3		120	0.0810	
5-1	42.5		109	0.0895	0.093
	42.5		71	0.133	
	42.6		101	0.0942	
5-9	43.2		86	0.1122	0.1131
	42.4		107	0.090	
5-2	42.8		117	0.083	0.0865
	41.8		59	0.162	
5-10	42.8		65	0.150	0.156
	42.1		135	0.071	
	42.2		122	0.0788	
5-3	41.8		125	0.0761	0.0753
	42.2		72	0.1352	
	41.8		79	0.1221	
5-11	41.6		70	0.1371	0.1314
	41.9		81	0.1170	
	41.5		103	0.0912	
5-4	43.8		110	0.0901	0.0994
	42.7		75	0.1304	
	42.3		90	0.1016	
5-12	41.6		79	0.1206	0.1195
	42.9		132	0.074	
	42.9		160	0.0616	
5-5	41.5		152	0.0627	0.066
	40.9		98	0.0950	
	39.3		82	0.1092	
5-13	41.2		99	0.0948	0.0996
	40.1		126	0.0718	
	40.8		140	0.0837	
5-6	40.7		118	0.0778	0.0777
	39.3		65	0.1389	
5-14	39.3		66	0.1368	0.1378
	39.2		79	0.1137	
	39.1		73	0.1246	
5-7	39.2		95	0.0945	0.1109
	39.0		52	0.1717	
	38.7		66	0.1342	
5-15	40.2		62	0.1485	0.1514
	39.8		106	0.0838	
	38.7		129	0.0670	
5-8	39.4		126	0.069	0.0732

Temperature 68°F $M_R = \frac{P\ (V + 0.2732)}{E(\Delta)}$ ASP.=0.35

Sample NO.	(P) LOAD (LBS)	(t) HEIGHT INCHES	(Δ) DEF	M_R $\#x10^6$	AVERAGE
	50.9		49	0.1480	
	50.9		58	0.2016	
5-1	51.5		70	0.1690	0.1728
	53.5		47	0.2542	
	51.9		55	0.2107	
5-9	51.7		50	0.2309	0.2319
	47.3		55	0.1955	
5-2	52.1		62	0.1910	0.1932
	47.5		32	0.3394	
5-10	47.4		36	0.3011	0.3202
	50.0		58	0.1964	
	49.9		68	0.1672	
5-3	49.3		62	0.1811	0.1815
	47.7		39	0.2823	
5-11	50.8		42	0.2791	0.2807
	50.3		51	0.2232	
5-4	48.5		44	0.2495	0.2363
	52.6		43	0.2770	
	51.3		42	0.2798	
5-12	50.5		46	0.2515	0.2694
	52.8		68	0.1785	
	51.1		75	0.1566	
5-5	49.6		75	0.1520	0.1623
	48.5		50	0.2210	
	52.8		50	0.2451	
5-13	52.2		49	0.2427	0.2362
	48.5		60	0.1825	
5-6	51.7		63	0.1852	0.1838
	52.7		37	0.3273	
	50.5		40	0.2901	
5-14	49.6		36	0.3166	0.3133
	49.7		49	0.2324	
	52.5		47	0.2560	
5-7	51.5		54	0.2185	0.2356
	52.2		41	0.2915	
	50.4		38	0.2815	
5-15	49.6		40	0.2840	0.2856
	49.2		66	0.1671	
	53.1		76	0.1560	
5-8	52.2		77	0.1514	0.1518

RESILIENT MODULUS

Temperature = 32°F

$$M_R = \frac{P\ (V + 0.2723)}{t\ (\Delta)}$$

Asp. = 0.35

SAMPLE NO.	(P) LOAD (LBS)	(t) HEIGHT INCHES	(Δ) DEF.	M_R #x10[6]	AVERAGE
	87.2		20	1.001	
	86.6		23	0.8652	
5-1	86.5		23	0.8642	0.9101
	86.7		20	0.9856	
5-2	86.3		22	0.8918	0.9387
	87.8		29	0.6898	
5-3	85.8		24	0.8146	0.7522
	86.5		19	1.0434	
5-7	86.0		19	1.0374	1.0404
	87.6		20	0.9783	
5-9	86.5		22	0.8782	0.9285
	86.8		17	1.1677	
5-10	87.6		18	1.1129	1.1403
	87.0		20	1.004	
5-11	88.0		19	1.069	1.0365
	87.1		19	1.0503	
	86.3		21	0.9415	
5-12	86.2		18	1.0972	1.0296
	89.5		24	0.8575	
	86.3		24	0.8269	
5-5	87.2		25	0.802	0.8288
	86.5		19	1.0373	
	88.4		20	1.0071	
5-13	87.0		19	1.0433	1.0292
	87.1		24	0.8215	
5-4	88.1		24	0.8309	0.8262
	87.1		18	1.1119	
5-14	86.9		16	1.2480	1.1799
	87.9		19	1.0638	
	87.5		24	0.8384	
5-6	85.5		21	0.9362	0.9461
	88.6		18	1.1273	
5-15	87.2		17	1.1748	1.1510
	87.4		24	0.8134	
	88.0		24	0.8190	
5-8	86.2		25	0.7701	0.8008

RESILIENT MODULUS

Temperature = -26°F

$$M_R = \frac{P(V + 0.2732)}{t\ (\Delta)} \qquad V = 0.35$$

Sample No	(P) LOAD (LBS)	(t) HEIGHT (INCHES)	(Δ) DEF.	M_R # x 10^6	AVERAGE
84.9	13		1.500		
5-1	83.0		11	1.7338	1.6169
	82.3		12	1.3865	
	81.9		14	1.3067	
5-9	82.8		14	1.3210	1.3865
	82.8		14	1.3446	
	82.8		15	1.2550	
5-2	82.9		16	1.1780	1.2592
	83.1		14	1.3574	
5-10	81.4		13	1.4319	1.3946
	83.1		13	1.4655	
5-3	82.0		11	1.6986	1.5820
	81.5		13	1.4470	
5-11	82.5		13	1.4647	1.4558
	81.8		13	1.4243	
5-4	82.1		13	1.4296	1.4269
	84.3		13	1.4857	
5-12	83.3		14	1.3632	1.4244
	81.1		12	1.5541	
5-5	81.8		13	1.4469	1.5005
	81.6		13	1.4302	
	84.3		15	1.2805	
5-13	82.4		13	1.3411	1.3506
	83.1		14	1.3397	
5-6	82.9		14	1.5365	1.3381
	81.7		12	1.5645	
	82.4		14	1.3524	
5-14	82.6		13	1.4660	1.4589
	81.8		12	1.5623	
5-7	83.5		12	1.5948	1.5785
	82.8		13	1.4587	
	85.3		12	1.6280	
5-15	83.2		14	1.3611	1.4826
	81.3		12	1.5133	
5-8	81.3		11	1.5509	1.5821

TENSILE PROPERTIES at 77°F

	SAMPLE NO	TENSILE STRENGTH PSI	STRAIN @ FAILURE in/in	SECANT MODULUS PSI
Treated	5-2	46.3538	0.012871	3601.3293
	5-3	52.6908	0.003779	13940.5807
	5-4	48.8067	0.005474	8915.8688
	5-5	46.9595	0.005959	7879.944
	5-6	45.5387	0.004705	9677.8889
	5-7	57.3168 Avg. = 50	0.004133 Avg. =0.0062	13866.8219 Avg. = 9,600
Untreated	5-9	49.2182	0.003945	12473.9757
	5-10	63.2589	0.003086	20496.6478
	5-11	62.8367	0.004356	14422.5435
	5-12	64.1768	0.004884	13139.6724
	5-13	59.7514	0.005599	10671.2764
	5-14	60.9154	0.004197	14513.2743
	5-15	72.9052	0.003709	19653.964
	5-16	72.2476	0.003935	18359.6197
		Avg. = 63	Avg. = 0.0042	Avg. = 15,500

APPENDIX C

UTAH DEPARTMENT OF TRANSPORTATION

SQUARE-YARD METHOD TO DETERMINE

REJUVENATOR APPLICATION RATES (13)

Utah Department of Transportation
Square-Yard Method to determine the
Rejuvenator Application Rate

Equipment recommended for the square yard method is as follows:

1. Metal square yard mask.
2. Electric airless sprayer with wide fan nozzle.
3. Small portable generator, fuel can and extra fuel.
4. 1000 ml graduate cylinder to measure the quantity of rejuvenator to be applied on the square yard area, and for preparation of rejuvenator requiring dilution prior to application.
5. Samples of rejuvenators from suppliers.
6. 5 gallons of water or diluent for the rejuvenators.
7. Approved cleaning solvent for the airless sprayer, and for clean up.
8. Notebook and/or data sheets to record the location of tests, application rates, and rejuvenator used.
9. Vehicle to transport equipment and personnel to the roadway for testing.
10. Appropriate barricades, warning flashers, and personal safety equipment for vehicles, test spots, and personnel.
11. Pavement marking paint to identify test spots as to date applied, rejuvenator used, dilution (if any), and application rate.

12. Sand, if it is to be used along with an appropriate means of measuring 0.5 to 3 pounds in 0.5 pound increments.

Use of this equipment is mostly self-explanatory. The procedure briefly is; after the square yard mask is placed on the pavement, the airless sprayer is charged with the exact amount of rejuvenator to be applied. The rejuvenator is then uniformly sprayed over the square yard area. After application, the rejuvenator is allowed to penetrate and cure, which can take from one to four hours depending on climatic conditions, texture, age, and porosity of the pavement. Sand, if it is to be used, should be uniformly spread over the test at this time. Two to three test patches should be applied at rates varying not less than 0.03 gallons per square yard. During the application process technicians should observe for under or over application. The test spots, after curing, should also be observed for under or over application <u>before</u> they are sanded. After the test spots are subjected to vehicular traffic they should be and evaluated at least once more to pick the optimum application rate.

Once the test patches have cured, and the correct application rate determined, the Utah Department of Transportation may also check skid resistance. The British Pendulum Tester, and ASTM E303-83 are utilized. UDOT also checks skid resistance using the ASTM E274-85 lock wheel test vehicle at 40 mph. Verification before and after rejuvenation, and on the test patches, assures the highway engineer of success with rejuvenators without loss of adequate skid resistance.