SD91-03-F

SD Department of Transportation
Office of Research

Asphalt Surface Treatment Performance

Study SD91-03
Final Report

Prepared by
ERES Consultants
8 Dunlap Court
Savoy, Illinois 61874-9501

June, 1992

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July 27, 1992

Mr. David Huft
South Dakota Department of Transportation
Office of Research, Room B-116
700 Broadway Avenue East
Pierre, SD 57501-2586

Dear Mr Huft:

Thank you for your review of the revised draft report for project SD91-03. We are pleased that we were able to satisfactorily incorporate the suggested changes and focus to better suit your needs. Enclosed are 25 copies of the Final Report for Project SD91-03, Asphalt Surface Treatment Performance, incorporating the final changes as suggested by your July 11, 1992 letter.

In response to the question regarding the climatic zones, the zones were determined based on the annual average mean temperature as reported by the Agricultural Experiment Station at the South Dakota State University. Though moisture and temperature will influence the life of a pavement, we felt that the temperature would play a more important role over the life of the surface treatment, and during construction. Thus, the annual average mean temperatures were used to establish the North to South climatic zones. A long term pavement performance investigation would benefit from an East to West moisture zone analysis. However, because the focus of this analysis was on design and construction of the surface treatment, we do not believe that a further or different climatic breakdown would yield substantially different results.

We have enjoyed working with you and your staff and look forward to working with you in the future. Please let us know if we may be of further service.

Sincerely,

Samuel H. Carpenter

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16. Abstract

Seventy individual surface treatment projects throughout the state of South Dakota were surveyed to determine the current condition and extent of problems with surface treatments in South Dakota. These projects were one to two years old, and included 7 contractors, 11 aggregate sources, 5 asphalt sources, and covered a wide range of ADT. The following eight distresses were noted: loss of aggregate, streaking, flushing, rutting, fatigue cracking, longitudinal cracking, edge cracking, and transverse cracking.

Asphalt surface treatment design concepts were reviewed. Several currently implemented design procedures were described and contrasted with South Dakota's current design procedure. The Pennsylvania DOT's graphical design procedure was recommended for adoption.

The field survey data was analyzed to determine performance correlations. Asphalt application rate and aggregate gradation properties were the most important variables influencing performance. It was recommended that more care be given to monitoring these variables in the field.

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EXECUTIVE SUMMARY

SURFACE TREATMENTS: PERFORMANCE IN SOUTH DAKOTA

SDDOT Contract:
SD91-03

JUNE 1992

INTRODUCTION

There is a growing reliance on surface treatments as a valuable maintenance tool to maintain the serviceable condition of many pavements. This increased reliance has led to a heightened awareness of the performance of these seals. These concerns led the South Dakota Department of Transportation to initiate a project to survey typical surface treatment projects throughout the State, analyze the findings, and report the results. The following items were to be discussed:

- Determine the current condition and extent of problems with surface treatments in South Dakota.
- Evaluate the current design procedure in South Dakota and recommend an improved procedure, if needed.
- Recommend a survey procedure that can be used by South Dakota in the future to survey their surface treatments.
- Conduct field surveys and interviews with field personnel.
- Determine what materials, design procedures, or construction activities are influencing the performance of the surface treatments in South Dakota, and recommend changes where necessary.

Twenty three contracts with seventy individual projects were included in this study. These projects were surveyed using a procedure developed by the Ontario Ministry of Transportation in Canada for their surface treated roads. This comprehensive procedure provides a tool for evaluating the total condition of a roadway, and is recommended for future implementation if South Dakota chooses to continue to survey their surface treated pavements. These seventy projects were one to two years old, and included 7 contractors, 11 aggregate sources, 5 asphalt sources, and covered a wide range of ADT and truck traffic.

Eight distresses in varying levels were found on all projects. These distresses included loss of aggregate, streaking, flushing, rutting, fatigue cracking, longitudinal cracking, edge cracking, and transverse cracking. This data was collected at each mile marker for the first 500 feet to provide an average indication of distress over the length of the project. Where localized differences were seen, they were surveyed also and noted.

Asphalt surface treatment design concepts were discussed and design procedures from the Asphalt Institute, Pennsylvania DOT, and the Texas DOT were described to illustrate how they consider the design variables that can affect surface treatment performance. These are contrasted with the current South Dakota process which is strictly a table providing an asphalt and aggregate application rate for several typical aggregate gradations. South Dakota has no formal design procedure that provides for localized conditions to be evaluated in a uniform manner. It was recommended that the Pennsylvania DOT procedure be considered for adoption as it is a graphical procedure, and has been developed for conditions similar to South Dakota's.

The analysis of the survey data examined the development of loss of aggregate, streaking, and flushing, which are the distresses related to surface treatment design and construction. Less than 8 (eight) percent of the projects exhibited distress levels near maximum, which is not unusual for a treatment with a life of 5-7 years. There does not appear to be any exceptional problems with the surface treatments. There were differences between the contractors to the extent that the best could be statistically separated from the worst, but the contractors with intermediate distress values could not be differentiated. This was also true for aggregate sources, while asphalt suppliers could not be differentiated.

The materials did not show a distinct influence on performance. It was felt that combinations of aggregate types and emulsion types could cause performance problems. Limestone aggregates with CRS-2 emulsions and siliceous aggregates with AE 150S emulsions could present problems if not constructed properly. The data from the seventy projects surveyed did not indicate higher distresses with these combinations. The limestone aggregates did not indicate higher distresses than the siliceous aggregates, with both aggregate types exhibiting failed projects.

The most important variables were asphalt application and aggregate gradation properties. There were significant differences between specified properties and the properties recorded during construction. This was most apparent in the gradation values. Variations here can have distinct influences on performance if they are not accounted for in the design process. The most significant differences were found in the aggregate gradations. Not every project had field measurements available for analysis, which complicated the analysis. Because of the similarity in ages, which produced similar levels of deterioration over the projects, performance prediction models could not be developed. The individual models for each contractor do provide some general indications of performance, but the limits of the database restrict predictions.

While specific problems were not noted in the construction or performance, several recommendations have been made resulting from the surveys and analysis. A design procedure should be implemented to provide a consistent means of proportioning asphalt and aggregate related to the pavement conditions. A simplified survey procedure should be implemented to develop more substantive data for a more detailed analysis in the future. A great deal of effort to modify construction procedures does not appear warranted presently because no severe problems were detected during the surveys conducted. More care should be given to field quality control, which while generally sufficient, should be improved to provide more frequent equipment calibrations and measurements of asphalt and aggregate application rates on an individual project and specific location basis.

TABLE OF CONTENTS

List of Tables

List of Figures

CHAPTER 1

INTRODUCTION

SURFACE TREATMENTS

Surface treatments are defined as application of asphalt to the surface of the pavement with or without an application of aggregate. A number of surface treatments fall into this category:

- Fog Seals
- Slurry Seals
- Aggregate Seals
  - Single or multiple layers
- Open Graded Friction Course
- Sand Seals

These surface applications perform specific functions on the surface of the pavement. The aggregate seal surface treatment reduces the infiltration of moisture, and the associated moisture related damage, such as crack pumping, pothole development, alligator cracking, stripping, and transverse cracking. When properly designed and constructed, it restores surface friction to a worn pavement surface. The treatment protects the surface from further detrimental effects of weathering, ravelling, and asphalt aging. Other benefits can include restoring nighttime delineation between the mainline pavement and the shoulder, improving surface drainage, and providing aesthetic improvements to the pavement surface.

In this study, the single layer aggregate seal will be studied. This surface treatment is often referred to as a chip seal or sand seal depending on the gradation of the aggregate. In this study, the chip seal and sand seal will be both be referred to as a surface treatment or chip seal for ease of communication, without obscuring the differences between the two. At the appropriate time, the distinctions will be clearly made to assist in the analysis and project descriptions.

Aggregate surface treatments being evaluated here are used as a routine maintenance application to extend the life of the pavement. Depending on the characteristics of the pavement and the loading conditions, high quality surface treatments are expected to last at least five years, and probably should average more than seven years of life. If this minimum service life is not being obtained, there could be problems in one or more of several important areas:

- Surface Treatment Design
- Material Properties
- Construction

These three areas which may contribute to failure will be evaluated in an attempt to identify the causes of early failures of surface treatments in South Dakota. Recommendations to address the problems identified will also be made.

PROJECT OBJECTIVES

The driving force behind this project was the question at the South Dakota Department of Transportation (SDDOT) whether their aggregate surface treatments are performing up to expectation. There was, however, no data to verify the performance capabilities of the treatments. The objectives of this project can be stated as follows:

- Determine the extent of the problem of poor performing surface treatments in South Dakota.
- Identify factors which affect surface treatment performance.
- Develop recommendations for materials and construction methods that will result in improved surface treatment performance.
- Develop criteria for an objective and repeatable procedure for evaluating current condition of surface treatments.
- Develop rational, scientific means of predicting the future performance of surface treatments.
- Develop a comprehensive design procedure for future surface treatment projects.

PROJECT APPROACH

To accomplish the objectives the following tasks were specified:

- Conduct literature review to establish current technology in use on surface treatments.
- Collect current information from South Dakota concerning their surface treatment construction and design.
- Develop criteria to quantify chip seal performance.
- Inspect and evaluate past surface treatment projects in South Dakota.
- Interview project personnel.
- Visit current construction projects.
- Analyze data collected.

The following chapters describe the procedures used to survey the surface treatment projects, the data collection efforts, a review of currently available surface treatment design procedures, construction considerations, data analysis, economic implications, and the conclusions and recommendations based upon the analysis.

CHAPTER 2

DATA COLLECTION

INTRODUCTION

This chapter describes the steps required to collect data from the selected surface treatment projects in South Dakota. Site selection is also discussed. The development of the survey procedure to be used is presented and modifications to fit the procedure to South Dakota are presented. The collection of field and office data are presented, and the database is discussed.

LITERATURE SEARCH

Prior to starting the data collection efforts, an extensive literature search was conducted to provide a complete understanding of how the design has developed over the years. Much effort has been expended in the past, and much is being conducted at present, on the design, construction and evaluation of surface treatments. Much of the earlier work still provides the basis for currently implemented design and construction practices of standard surface treatments. An annotated bibliography resulting from the literature search may be found in Appendix A. The relevant works are referenced where appropriate to the presentation in the individual chapters.

SURFACE TREATMENT SITES IN SOUTH DAKOTA

Chip and sand seals are a common type of surface treatment in South Dakota, as typically 400 miles of pavements are sealed each year.

Of all of the surface treatments applied in 1989 to 1990, a list of twenty-three general chip seal projects consisting of 70 individual surface treatment projects was furnished by the SDDOT for use in this study. Projects constructed in 1989 and 1990 were selected on the basis of equal geographical representation. Relatively new projects were selected for examination in this study so that the effects of age and weathering would not be the overwhelming distresses studied in the evaluation. A general project was defined by the SDDOT as a contract project. Within each contract project, different routes or locations on the route were constructed by the same contractor and are appropriately considered individual project sites. Table 1 shows the projects included in the study and Figure 1 shows their locations.

Table 1. Project definition.

Proj. No.	Highway	Length, mi	Year Const.	Seal Type	From	To	From, MRM	To, MRM
1	44	15.12	1990	Chip	SD 50	US 281	312.88	327.88
	50	9.19	1990	Chip	Near I 90	N. of Chamberlain	222.26	231.45
	50	31.81	1990	Chip	I 90	SD 44	241.61	273.42
	1804	3.81	1990	Chip	Near Missouri River	SD 50	86.01	89.82
2	18	6.7	1990	Chip	Near I 29	SD 11	439	445.70
	19	6.97	1990	Chip	SD 42	I 90	65.50	72.47
	44	10.49	1990	Chip	SD 19	SD 17	395.82	406.31
	115	2.97	1990	Chip	I 29	Near Dell Rapids	104.57	107.54
3	25	25.16	1990	Sand	Roslyn	Hillhead	193.00	219.00
	45	18.01	1990	Sand	SD 20	Ipswich	159.32	177.33
	239	7.32	1990	Sand	SD 10	N. to Long Lake	188.00	195.32
	253	10.01	1990	Sand	US 12	Hosmer	172.91	182.92
4	19A	7.79	1990	Chip	Centerville	SD 19	25.65	33.44
	46	21.14	1990	Chip	SD 50	SD 25	297.36	318.50
	103	5.73	1990	Chip	SD 46	Hudson	380.27	386.00
5	10	22.01	1990	Sand	US 83	Eureka	203.22	225.24
	12	9.35	1990	Sand	Watauga	McIntosh	121.00	130.35
	12	10.52	1990	Sand	E. of McLaughlin	W. of Mobridge	171.00	181.52
	47	12.27	1990	Sand	N. of SD 253	Eureka	235.00	247.27
	63	2.22	1990	Sand	SD 12	North	251.78	254.00
	212	27.95	1990	Sand	Red Elm	Eagle Butte	127.00	154.95
	1804	17.97	1990	Sand	US 12	N. of Mobridge	355.50	373.47
6	28	11.02	1990	Sand	Carpenter	Willow Lake	295.98	307.00
	37	12.87	1990	Sand	N. of Huron	SD 28	133.00	145.87
	212	3.00	1990	Sand	Raymond	East	335.00	338.00
	212	6.25	1990	Sand	Redfield	East	307.73	314.00
	281	12.55	1990	Sand	Near Redfield	S. of Mellette	154.45	167.00
7	14	13.05	1990	Sand	Near Blunt	Around Harrold	254.00	267.05
	14	36.63	1990	Sand	Near SD 63	Pierre	190.22	226.85
	73	23.81	1990	Sand	I 90	N. of US 14	78.19	102.00

Table 1. Project definition (continued).

Proj. No.	Highway	Length, mi	Year Const.	Seal Type	From	To	From, MRM	To, MRM
8	53	8.39	1990	Sand	MP 75	I 90	75.00	83.39
	248	13.03	1990	Sand	Vivian	Presho	225.33	238.36
	248	38.39	1990	Sand	Belvidere	Draper	175.41	213.80
9	47	17.4	1990	Sand	I 90	SD 34	70.07	87.47
10	22	13.41	1990	Sand	Near Hazel	US 81	333.44	346.85
	25	5.01	1990	Sand	Near Claire City	ND State Line	236.45	241.46
	28	21.10	1990	Sand	SD 25	US 81	319.91	341.01
	106	5.15	1990	Sand	Near Claire City	Near Hammer	332.50	337.65
11	79	14.00	1989	Chip	N. of Fairburn	S-E of Rapid City	51.00	65.00
12	12	0.5	1989	Sand	US 83 Exit	East	214.00	214.50
	12	0.48	1989	Sand	SD 20	East	181.52	182.00
	63	0.53	1989	Sand	SD 12	South	251.25	251.78
	63	7.00	1989	Sand	BIA 8 by Missouri River	North	145.00	152.00
	1806	3.68	1989	Sand	US 12	South	359.75	363.43
13	1804	16.17	1989	Chip	W. of Agar	N. of US 212	292.16	311.97
14	11	8.00	1989	Chip	SD 38	South	64.00	72.00
15	38	8.17	1989	Chip	SD 11	Toward MN	375.35	383.52
16	18	17.05	1989	Chip	US 81	SD 19	402.77	419.82
	37	17.18	1989	Chip	SD 50	US 18	24.44	41.62
	50	11.00	1989	Chip	Avon	Tyndall	343.00	354.00
	81	11.88	1989	Chip	N. of Yankton	SD 46	3.41	15.29
17	12	3.07	1989	Sand	W. of Bowdle	Bowdle	230.00	233.07
	12	14.97	1989	Sand	Bowdle	Roscoe	233.07	284.04
	37	10.12	1989	Sand	SD 10	ND Border	233.51	243.63
	37	28.00	1989	Sand	Turton	Groton or US 12	180.43	208.43
18	79	10.98	1989	Chip	Near Newell	SD 168	133.02	144.00
19	12	12.50	1989	Chip	Near White Butte	W. of Thunder Hawk	80.5	93.00
20	14	12.56	1989	Sand	E. of Quinn	W. of Philip	123.14	135.70
	34	18.56	1989	Sand	E. of Pierre	W. of Stephan	227.00	245.56
21	44	39.66	1989	Sand	US 83	Near Witten	200.74	240.40

Table 1. Project definition (continued).

Proj. No.	Highway	Length, mi	Year Const.	Seal Type	From	To	From, MRM	To, MRM
22	14	1.58	1989	Chip	I 29	East	422.42	424.00
	22	13.33	1989	Sand	Near Clear Lake	MN State Line	370.57	383.90
	28	18.99	1989	Sand	US 81	I 90	342.01	361.00
	101	3.22	1989	Sand	SD 22	North	85.50	88.72
	212	7.00	1989	Chip	W. of Watertown	Watertown	368.00	375.00
	218	8.54	1989	Sand	I 29	East	357.54	366.08
23	28	17.98	1989	Sand	E. of Hitchcock	W. of Carpenter	278.00	295.98
	34	12.44	1989	Sand	E. of Pierre	SD 47	245.56	258.00
	45	6.90	1989	Sand	SD 34	North	81.10	88.00
	212	9.20	1989	Sand	Zell	Redfield	297.08	306.28

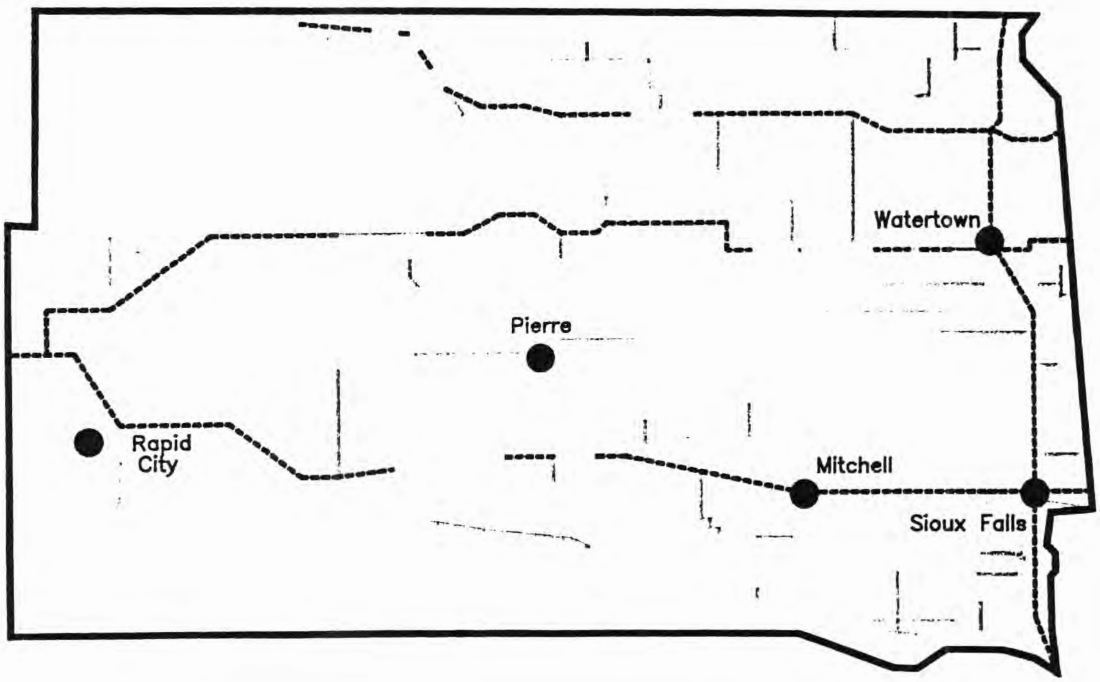

Figure 1. Chip seal project locations.

FIELD SURVEY PROCEDURE

Based on the literature reviews and discussions with various State DOT personnel, it was decided to evaluate the projects using the procedure outlined in a report developed for the Ontario Ministry of Transportation entitled "Manual for Condition Rating of Surface-Treated Pavements."[1] This procedure has recently been adopted by the Strategic Highway Research Program to evaluate surface treated pavements. The procedure was modified slightly for the South Dakota project to include drainage conditions.

The rating scheme developed for Ontario is based on a rater evaluating the ride quality and the extent and severity of the pavement surface distress. The ride evaluation keeps an indication of the pavement's functional condition, and the distress evaluation gives an indication of the pavements structural condition.

Evaluation of pavement condition first involves determining the section boundaries for the roadway based on uniformity of the overall surface condition. If distinctive differences in the performance of the roadway are observed, the roadway section should be subdivided into two or more appropriate sections. Minimum section lengths of 1 mile are suggested.

The second step is to determine the pavement ride quality by driving over the section at the posted speed limit. The ride quality is subjectively rated from 1 to 10, with 10 to 8 being excellent and 2 to 0 being very poor.

The third step involves driving over the pavement slowly to assess distress manifestations. Each type of distress is evaluated in terms of its density (extent of occurrence) and severity. Two or three stops per section are recommended to examine distress type and severity. Steps 4 and 5 involve recording the observations and assigning a pavement condition rating based on the observations.

The Ontario Ministry of Transportation's procedure provided the framework which was used to structure the survey procedure used in South Dakota.

Inspections of the 23 surface treatment contracts (70 project sites) were performed during July and August, of 1991. Each project was subdivided into sections to allow between one-third to one-half of the project being surveyed. Each section was located at the Mile Reference Marker (MRM), spaced over the length of the project. The distress survey was performed on the initial 500 ft of each section. Extra sections were added as necessary to include any concentrations of distress which were out of the ordinary. These locations were noted during the drive over the project, and were included when it became obvious that the characteristics of the pavement had changed.

The section length and pavement width were determined with a measuring wheel. The overall condition and drainage characteristics were then recorded. Next, each of two surveyors recorded the distresses that were observed, and estimated the severity levels present for each distress, and the area associated with each distress. The average value for each surveyor was recorded for that section. Rutting measurements were taken with a 3-ft straightedge and ruler at 100 ft intervals in both wheelpaths.

Eight different distress types were noted throughout the 70 project sites with the severity varying from slight to severe. The distresses noted and their definitions are given here[1]:

- *Loss of cover aggregate* - The whipping off of cover aggregate under traffic from a surface-treated pavement, leaving only the asphalt.
- *Streaking* - Alternating lean and heavy lines of asphalt running parallel to the centerline of the road.
- *Flushing* - Free asphalt migrating upward to the pavement surface. More likely to occur in the wheel paths, especially during hot weather.
- *Rut depth* - Longitudinal depressions left in the wheel tracks after repeated load applications resulting from compaction and pavement deformation under load, and pavement material shoving sideways.
- *Transverse cracking* - Cracks follow a course approximately at right angles to the pavement centerline. Full width transverse cracks tend to be regularly spaced along the length of the road while half width transverse and part width transverse occur at shorter intermediate distances.
- *Longitudinal cracking* - Cracks follow a course approximately parallel to the direction of travel and are situated at or near the center of the wheel paths, centerline, mid-lane, etc.
- *Edge cracking* - Cracks are parallel to and within 1 ft of the pavement edge and are either straight and continuous or consist of crescent shaped cracks in a wave formation.
- *Alligator cracking* - Cracks forming from a network of multi-sided blocks resembling the skin of an alligator. The block size can range from a few inches to about 1 ft.

Reference 1 should be consulted for definitions on the severity level and units of density measurement. The first three distresses are distinctly surface treatment distresses, while the remaining five are structural, and related to the pavement structure and condition prior to the application.

During the field survey, the method of measuring the density of the flushing distress was modified. In the manual, the density is taken as the flushed area divided by the wheel paths area. During the field survey it was difficult to estimate the wheel paths area and it was determined that the density be taken as the flushed area divided by the total pavement surface area. This is a more practical approach as excess asphalt sometimes extends beyond the wheelpaths. With this measurement procedure the area coverage would have a normal upper limit of 50 percent assuming 3 foot wide wheelpaths on a twelve foot lane, although a larger area can occur.

The ride quality determination was not performed on the pavements surveyed as a part of this study. The purpose of this study is to assess the performance of the surface treatments and investigate areas for improvement. Ride quality is an important factor for use in scheduling major rehabilitation, but provides no direct relationship with short term surface treatment performance.

A summary of the field survey results is shown in Table 2. Figure 2 shows the number of projects exhibiting each of the distresses and the severity of the distress. As can be seen, transverse cracking and longitudinal cracking are evident on almost all of the projects. It can also be seen that loss of aggregate, streaking, and flushing is common. Very few projects show edge cracking or alligator cracking.

The graphs in Figure 3 show the number of projects affected by the individual distresses and the severity levels and the percent area affected. The graphs illustrate that the majority of the distresses observed are low or slight in severity and that the area affected is generally small. There are five projects exhibiting high severity loss of aggregate, three project exhibiting high severity streaking, eight exhibiting high severity flushing, six exhibiting high severity longitudinal cracking, ten exhibiting high severity transverse cracking, and two exhibiting high severity alligator cracking. However, only a small percentage of the projects' area is effected. Project 8 Highway 248, from Belvidere to Draper, exhibits the greatest degree of loss of aggregate. Project 12 Highway 1806, Project 13 Highway 1804, Project 14 Highway 11, and Project 15 Highway 38 show a relatively greater amount of streaking than the other projects. While project 5 Highway 212, Project 11 Highway 79, and Project 16 Highway 81 show a relatively greater amount of flushing than the other projects. Potential differences between these projects will be discussed in the data analysis section of the report.

OVERALL CONDITION RATING

Many highway agencies use overall pavement condition ratings to evaluate that pavement's ability to serve its intended use, both structurally and functionally. The summarization of the distresses and riding quality are generally combined into an overall rating to chart the progression of distress and the performance of the pavement. The rating schemes have generally been developed for asphaltic-concrete or portland cement concrete pavements. There has been no generally accepted rating scheme specifically developed for surface treated roads.

The approach taken to develop a rating procedure that is useful in planning maintenance or rehabilitation of a pavement is a complicated process. It first

Table 2. Summary of distress survey.

Proj. No.	Highway No.	Length mi.	No. of sections surveyed	Distress Type (%)								Ditch Line Depth, ft
				Loss of Cover Aggregate	Streaking	Flushing	Rutting	Longitudinal Cracking	Transverse Cracking	Edge Cracking	Alligator Cracking	
1	44	15.12	5			S21,M5	4/16	S4	S85		S1,M1	4
	50	9.19	3		S27,M1		2/16		S19			5
	50	31.81	8	S.5			2/16	S1	S15			5
	1804	3.81	2	S25	S35	M5	3/16					6
2	18	6.7	2		S50	S6	4/16		S15			4
	19	6.97	2	M8	S18,M5,H8		1/16		S30			5
	44	10.49	3	S2	S30	S1	3/16		S26			5
	115	2.97	2		S35		2/16			S28		7
3	25	25.16	6	S2	S11		4/16	S20,M1	S27,M4			11
	45	18.01	4		S48		2/16	S14	S26,M5			8
	239	7.32	3	S13,M5			1/16	S18	S34,M25			8
	253	10.01	4	S14,H1			4/16	S1	S16,M10			6
4	19A	7.79	2		S25	S3,M.5,H.5	3/16		S18,M10			10
	46	21.14	5	S1	S6		3/16		S19			5
	103	5.73	2		S75		2/16		S15			5

Table 2. Summary of distress survey (continued).

Proj. No.	Highway No.	Length, mi.	No. of sections surveyed	Distress Type (%)								Ditch Line Depth, ft
				Loss of Cover Aggregate	Streaking	Flushing	Rutting	Longitudinal Cracking	Transverse Cracking	Edge Cracking	Alligator Cracking	
5	10	22.02	5	S6		S20	3/16	S13,M2	S44,M19,H4			7
	12	9.35	3			S15,M.5,H.5	2/16	S12	S31,M3			6
	12	10.52	3	S10	S3		2/16	S17	S17,M5			6
	47	12.27	4	S2			3/16	S22	S37,M8			6
	63	2.22	1	S3		S35,M1	3/16		S26			10
	212	27.95	7			S25,M17,H14	5/16	S1	S30			7
	1804	17.97	6	S16,H6	S7	S3,M.2	4/16	S14	S33	S2		8
6	28	11.02	3	S2			4/16	S17,H2	S15,M3,H28		S0.25	5
	37	12.87	3		S43		4/16	S5,M3	S29			6
	212	3	1		S50		1/16	S20	S25,M5			8
	212	6.25	2		S20		2/16	S8,H13	S37,M3			7
	281	12.55	4		S6	S23	3/16	S3,M4,H10	S33,M15,H8			8
7	14	13.05	3	S4			1/16	S6	S37			6
	14	36.63	7		S1	S22,M6,H1	4/16	S.5,M1	S24			6
	73	23.81	6			S14,M13,H6	7/16	S1	S22			10
8	53	8.39	4	S8			6/16	M19	M20	S8,M5	H1	7
	248	13.03	5	S15,H2.5			3/16	S16	S16,M6	M6	S1,H1	7
	248	38.39	7	S20,M4,H2		S.2,H.2	3/16	S51,M4	S54,M4			8

Table 2. Summary of distress survey (continued).

Proj. No.	Highway No.	Length mi.	No. of sections surveyed	Distress Type (%)								Ditch Line Depth, ft
				Loss of Cover Aggregate	Streaking	Flushing	Rutting	Longitudinal Cracking	Transverse Cracking	Edge Cracking	Alligator Cracking	
9	47	17.4	4	S13,H2			2/16	S8	S27			5
10	22	13.41	3		S48		3/16	S18	S28,H2			7
	25	5.01	2	S3		S28	2/16	S2	S32		S1	5
	28	21.10	5		S8		4/16	S12	S45			9
	106	5.15	2	S9			2/16	S5	S17			6
11	79	14	4			S19,M40	2/16	S2	S13			6
12	12	0.5	1				2/16	S10,M10	S20,M20			4
	12	0.48	1			S10	2/16		S50			6
	63	0.53	1	S20	S50	S20	3/16	S20	S80			0
	63	7	3	S17	H17	S7,M7	3/16		S29			6
	1806	3.68	2	S8	S13,M65		3/16	S2	S13		S5	6
13	1804	16.17	5	S17	S26,M10		1/16		S16			9
14	11	8	3	S5	S48,M17		3/16	S2	S21			5
15	38	8.17	4		S53,H13		3/16	S9	S34			3
16	18	17.05	4		S35,M9	S14	5/16	S9	S47,M13	S5	S1,M8	5
	37	17.18	4		S8	M1,H.2	3/16	S1	S23			6
	50	11	4		S48	S14	3/16	S7	S40			5
	81	11.88	3			S15,M35	4/16	S12,M5,H2	S22,M15, H10	S13,M7		13

Table 2. Summary of distress survey (continued).

Proj. No.	Highway No.	Length, mi.	No. of sections surveyed	Distress Type (%)								Ditch Line Depth, ft
				Loss of Cover Aggregate	Streaking	Flushing	Rutting	Longitudinal Cracking	Transverse Cracking	Edge Cracking	Alligator Cracking	
17	12	3.07	2		S40,M5	S10	4/16	S28,M5	S53,M35			6
	12	14.97	3		S32	S18	3/16	S7,M13	S27,M34,H3			6
	37	10.12	3		S7	S30	3/16	S8,M7	S17,M15			8
	37	28.00	6		S76	S3	4/16	S3,M2	S16,M6			6
18	79	10.98	3		S15	S15,M.5	5/16	S2	S3,M3			4
19	12	12.5	4		S29		2/16	S6,M5	S31,M1,H8			7
20	14	12.56	3	S10			3/16		S36			6
	34	18.56	5	S19	S6		1/16		S25	S4		6
21	44	39.66	5	S12			2/16	S8,M1	S12	S1		10
22	14	1.58	1	S15		S20	6/16		S40,M10,H10			6
	22	13.33	3	S2			3/16	S15	S50			11
	28	18.99	4		S25		6/16	S50	S76,M2			6
	101	3.22	1	S2			3/16	S6	S32			5
	212	7	3		S35		4/16	S39,H7	S39,H10			7
	218	8.54	3				3/16	S27	S77			6
23	28	17.98	4	S5,M5	S34		5/16		S12,M20			8
	34	12.44	3	S18	S17	S11	3/16	S23	S69			7
	45	6.9	3	S12	S50	S.5,H4	1/16	S33	S53,M1			5
	212	9.2	3	S2	S41		2/16	S10,M5,H7	S30,M15,H25			6

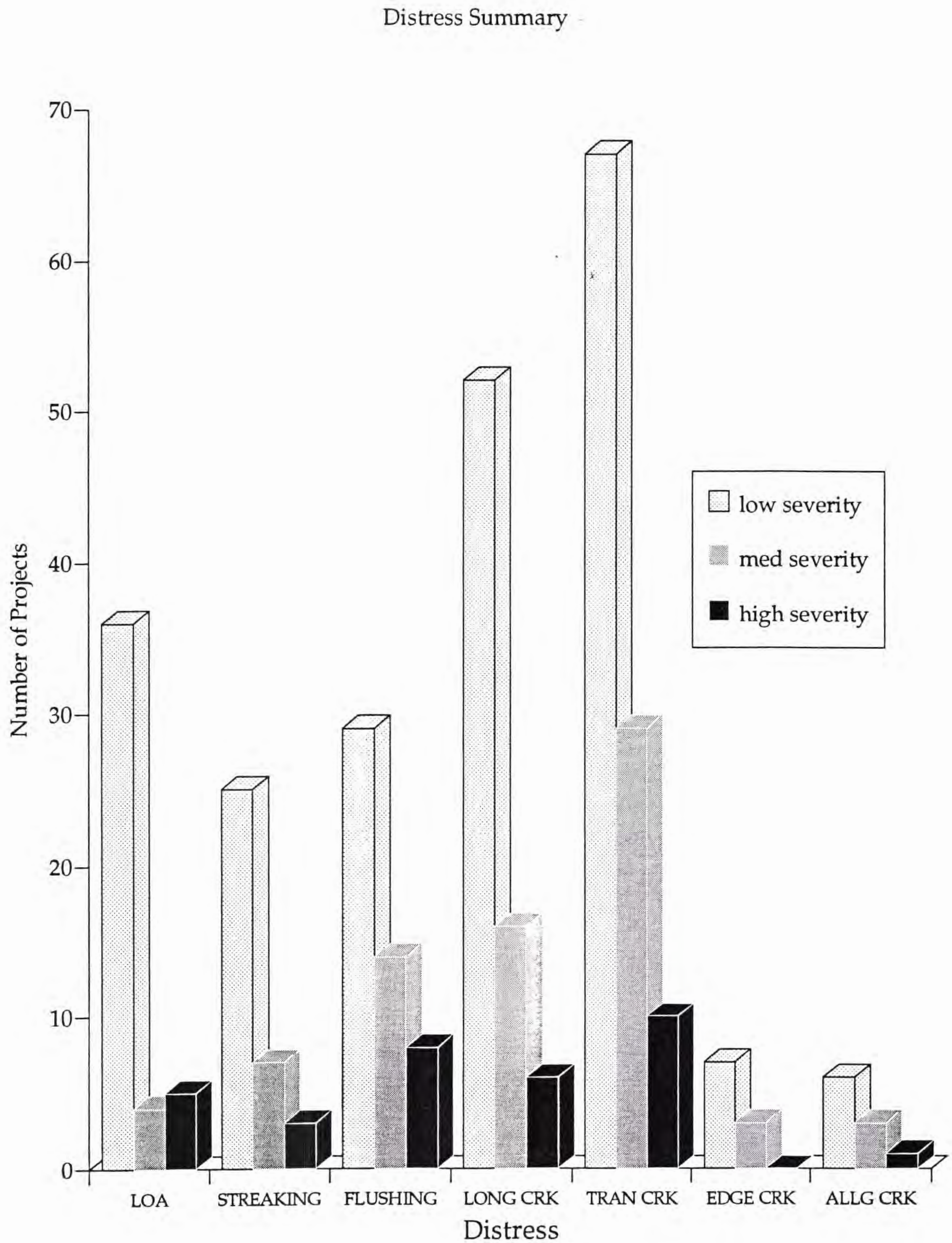

Figure 2. Distress summary.

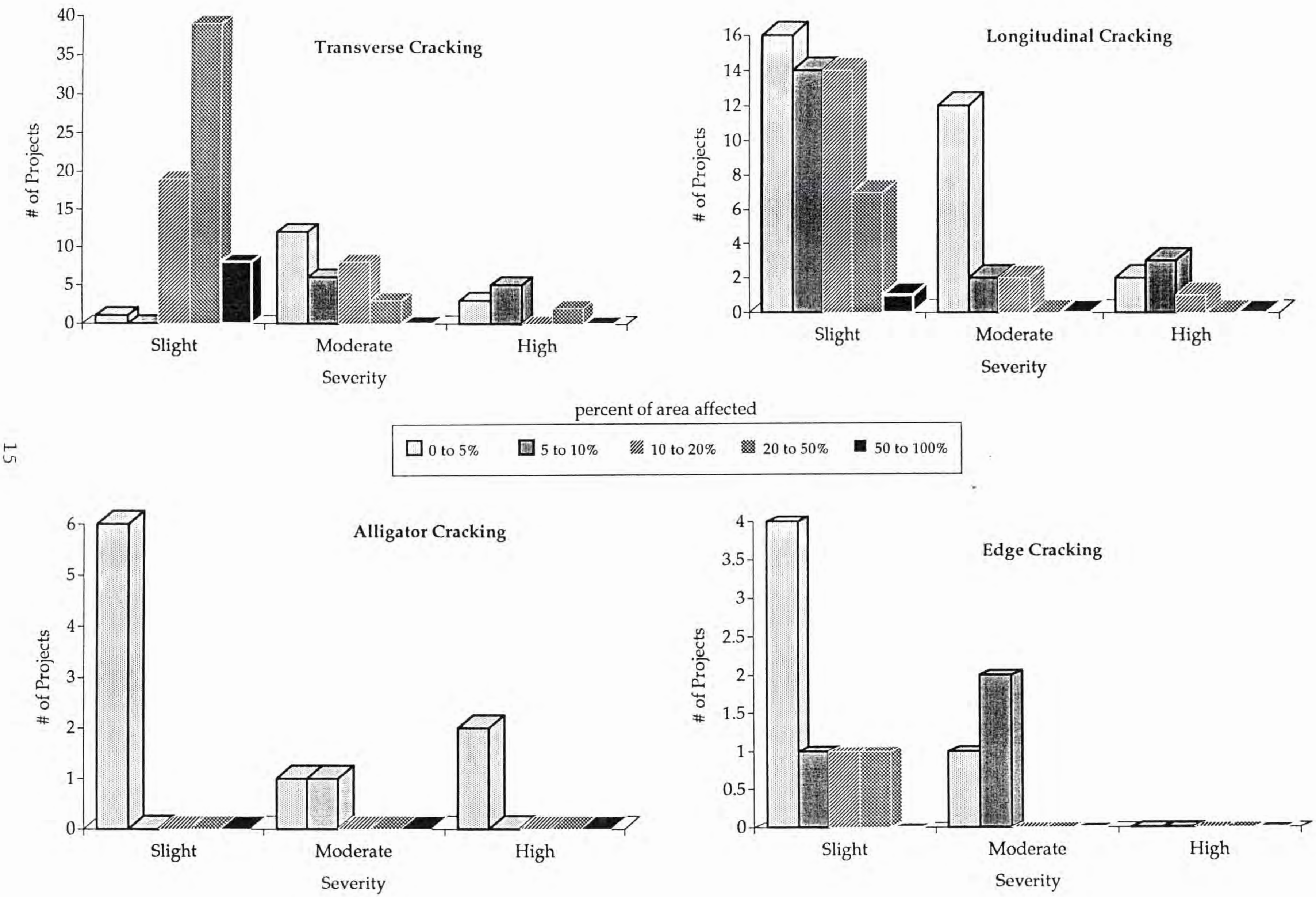

Figure 3. Distress summary by individual distresses.

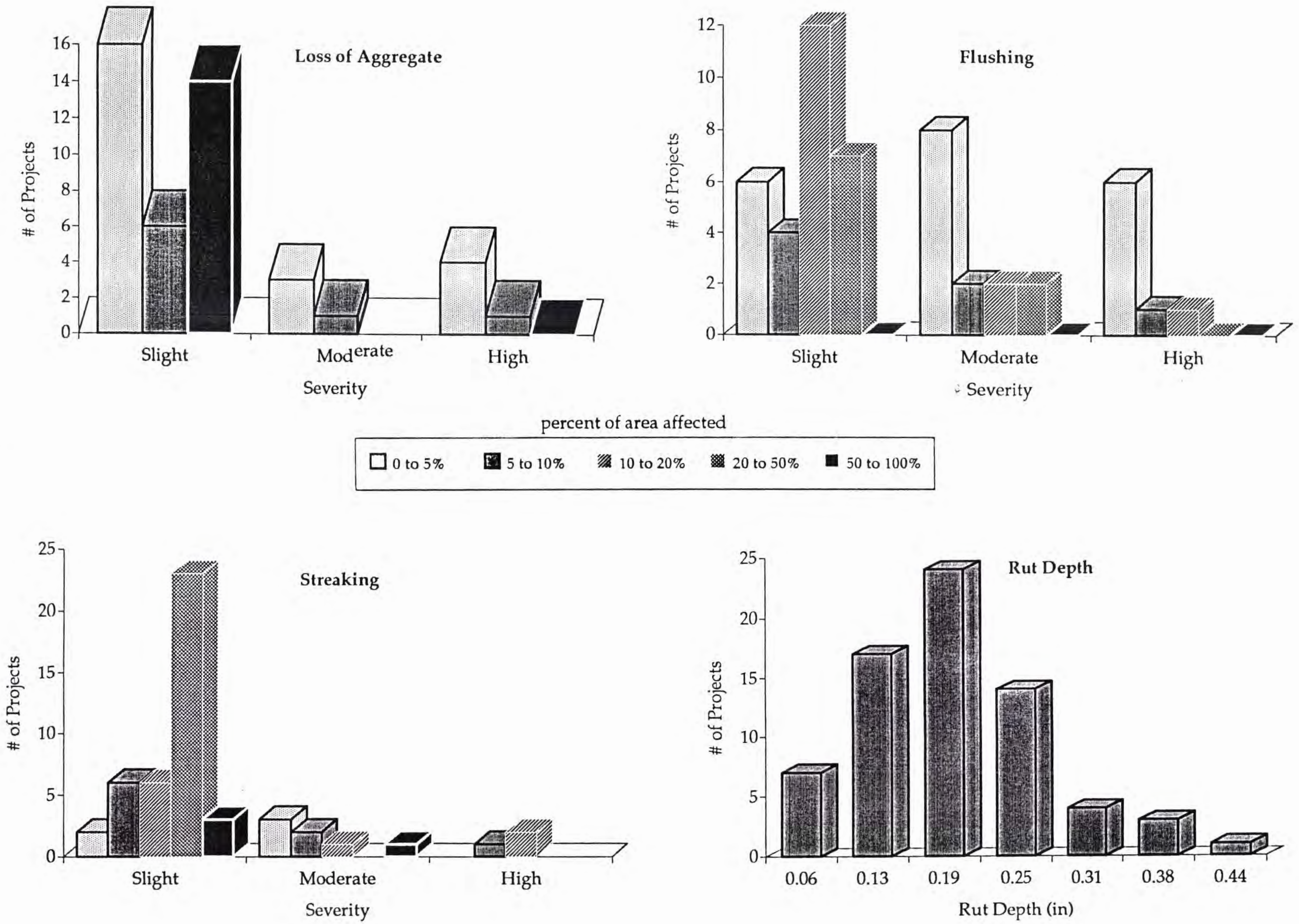

Figure 3. Distress summary by individual distresses (continued).

involves establishing a precise method of surveying pavements, including many pavements of varying ages and conditions. Next, these pavement sections are evaluated by experienced engineers to establish the pavements' condition relative to the level of maintenance or rehabilitation which would normally be performed on these pavements. Next, the pavements are ranked in order of the engineers' rating of relative state of disrepair, and the distress data is analyzed to produce a numerical calculation that ranks the pavements in the same order as the engineering panel. This then provides a consistent procedure for distress surveys and analysis that models engineering judgement.

This approach was used to develop the AASHTO PSI equations which model the PSR value assigned to a pavement by an individual riding the pavement and assigning a number from 0 to 5, representing the ride quality of the pavement. The Pavement Condition Index (PCI) was developed in this same manner.

Because the pavements evaluated for this project are relatively new and in good condition, developing an overall rating scheme from just this data would be inappropriate. A rational rating scheme may be developed if more information on the condition of a broader spectrum of surface treatment pavement sections is available.

FIELD SITE VISIT

In addition to the field surveys, project personnel visited a chip seal construction project in July 1991 on SD 14 East of Winner. During the visit, the following items were noted:

- The asphalt emulsion is sprayed using the double lap technique.
- There was considerable delay (approximately 10 minutes) between the asphalt and aggregate applications.
- Four compaction passes are made using pneumatic tired rollers.
- The application rates of asphalt and aggregate were within specifications.
- The machinery used in construction was not calibrated for this project at this time.

Conversations with field personnel indicate that the procedures followed on this project are similar to those followed on most projects. No specific comments regarding problems with construction were mentioned.

OFFICE VISIT

ERES personnel met with two South Dakota DOT personnel involved with the design of chip seal projects to discuss their chip seal mix design procedure, construction specifications, and quality control requirements. The findings of this interview are discussed in the appropriate sections relating to design, construction and quality control. In general, SDDOT expressed satisfaction with their design procedure, specifications, and quality control requirements. However, the interviewees were concerned about the uniformity or quality of surface treatment construction.

In addition to the interview, the SDDOT was asked to provide additional information not collected during the field survey and on the initial inventory. This information included the condition of the pavement prior to the treatment, ADT and percent truck volume, aggregate gradation and quality, asphalt emulsion spray and aggregate spread rates and variability, and any construction or weather-related problems. Data regarding the time between surface treatments, ADT and truck volumes, aggregate gradations, and average asphalt spray rates was available. Limited information was available on construction or weather-related variability.

DATABASE

The field survey, design, and construction data were entered into a database using SQLWindows. The database provides an easy means of extracting data for analysis. Data elements for each section surveyed included in the data base are: project number, road number, length of the section, ditch line depth, design asphalt application rate, actual asphalt application rate, asphalt type, asphalt producer, design aggregate application rate, aggregate type, aggregate source, aggregate gradations, aggregate type (siliceous/limestone), contractor, average daily traffic, average number of trucks, month and year of construction, last year of seal prior to present treatment, climatic zone, and the individual distress amounts and severity.

As mentioned earlier, 70 projects were surveyed. Tables 3, 4, and 5 present a partial inventory of the data which is useful for reference purposes, and to illustrate the cross section of data available in the projects included. Table 3 shows the number of projects by year constructed, aggregate type, asphalt type, and ADT. All of these projects are relatively new: 32 were constructed in 1989 and 38 were constructed in 1990. There are approximately twice as many sand seals constructed as chip seals. AE 150S is used more often than CRS-2. While the AE 200S is used by many of the counties, only one project in this study used an AE 200S emulsion. Though the western part of the state uses limestone aggregates frequently, only five projects in this study used limestone aggregate. The average age of the existing surface at the time of application of the surface treatment is seven years, which may indicate a relatively long life is being obtained from these surface treatments.

Table 3. Partial summary of other project variables.

		No of Projects
Year Constructed	1989	32
	1990	38
Aggregate Gradation	1B	26
	2A	22
	2B	22
AC Type	CRS-2	17
	AE 150S	52
	AE 200S	1
Aggregate Type	Limestone	5
	Siliceous	65
ADT	≤100	4
	101≤250	2
	251≤500	19
	501≤1000	22
	>1000	23

Table 4 shows the ditch line depth data summary. An inadequate ditch line depth may effect the drainage of the pavement section and contribute to a weak subgrade or base.

Table 4. Ditch line depth.

	Ditch Line Depth (ft)										
	0	3	4	5	6	7	8	9	10	11	13
No of Projects	1	1	4	14	23	10	8	2	4	2	1

Table 5 shows that the majority of the projects (77 percent) were constructed by three contractors. The remaining 23 percent or the projects were constructed by four other contractors.

Table 5. Number of projects by contractor.

Contractor	No of Projects
Asphalt Surfacing Co.	17
Bituminous Paving	3
Border States Paving	2
Davis Co.	5
Hills Materials	15
McLaughlin and Schultz	22
WYCO Construction	6

SUMMARY

Seventy individual projects were surveyed using a standard procedure developed by the Ontario Ministry of Transportation. This procedure is recommended as it will provide a repeatable method of assessing the condition of surface treated roads without requiring extensive training of field personnel. The data collected was placed in a database for easy analysis and retrieval. The initial inventory of the database provides a preliminary breakdown of the distribution of data. This helps indicate where potential descriptors of performance differences may be found. They provide the starting point for separating the database for analysis.

The description of performance of these surface treatments requires knowledge in the design of a surface treatment to illustrate how each component works in combination with the other components. These components, how they are considered in the design, how they are altered during construction, and how the material properties may be influenced during the manufacturing process are fundamental parameters which must be investigated to illustrate where performance differences arise from.

CHAPTER 3

DESIGN AND CONSTRUCTION CONSIDERATIONS

GENERAL DESIGN PHILOSOPHY

The principal objective in the design of a surface treatment is to select the relative proportions of the aggregate and asphalt binder such that the surface treatment will provide a durable long lasting surface for the intended design period. This proportioning comes entirely from the volume of voids in the aggregate after it is placed on the pavement surface. The volume remaining in the aggregate layer must be filled with the asphalt binder to provide a depth of embedment to the aggregate of approximately 70 percent. It is accepted that the voids in the aggregate develop as discussed below, and as illustrated in Figure 4. When the aggregate is first spread, it has some 50 percent voids in the layer of aggregate. After rolling, this void space is reduced to 30 percent of the total layer volume. Continued traffic can reduce this void space to 20 percent. It is this final void space, somewhere between 30 and 20 percent, depending on the traffic, that must be partially filled with the asphalt binder to bind the aggregate to the underlying roadway surface. If too much asphalt binder is present for the aggregate, flushing will occur. If not enough asphalt binder is present, there will not be sufficient binder to hold the aggregate and loss of aggregate will result.

Any factor that changes either the total volume of the layer being constructed or the amount of asphalt binder in the constructed layer will be made evident by a change in the performance of the finished surface treatment. These factors can occur in the aggregate gradation which will alter the dimensions, the asphalt composition, the texture of the original roadway surface, the level of traffic, or the construction procedure itself. Each of these factors will be discussed in the following sections to provide an understanding of how they interact to alter the performance of the constructed surface treatment. The determination of the variability in these properties in the surface treatments evaluated in this study will provide data to analyze performance differences. This discussion will also provide support of elements which must be present in a design procedure that can consider all elements which might impact performance of the finished surface treatment.

AGGREGATE

Good quality aggregate must be used for surface treatments. In general, cover aggregates should be hard, tough, clean, and dry fragments of stone, that have been produced either from quarried rock, or from clean, hard gravel.[2] In addition to the quality, the shape, gradation, and maximum size of the aggregate are important factors to consider.

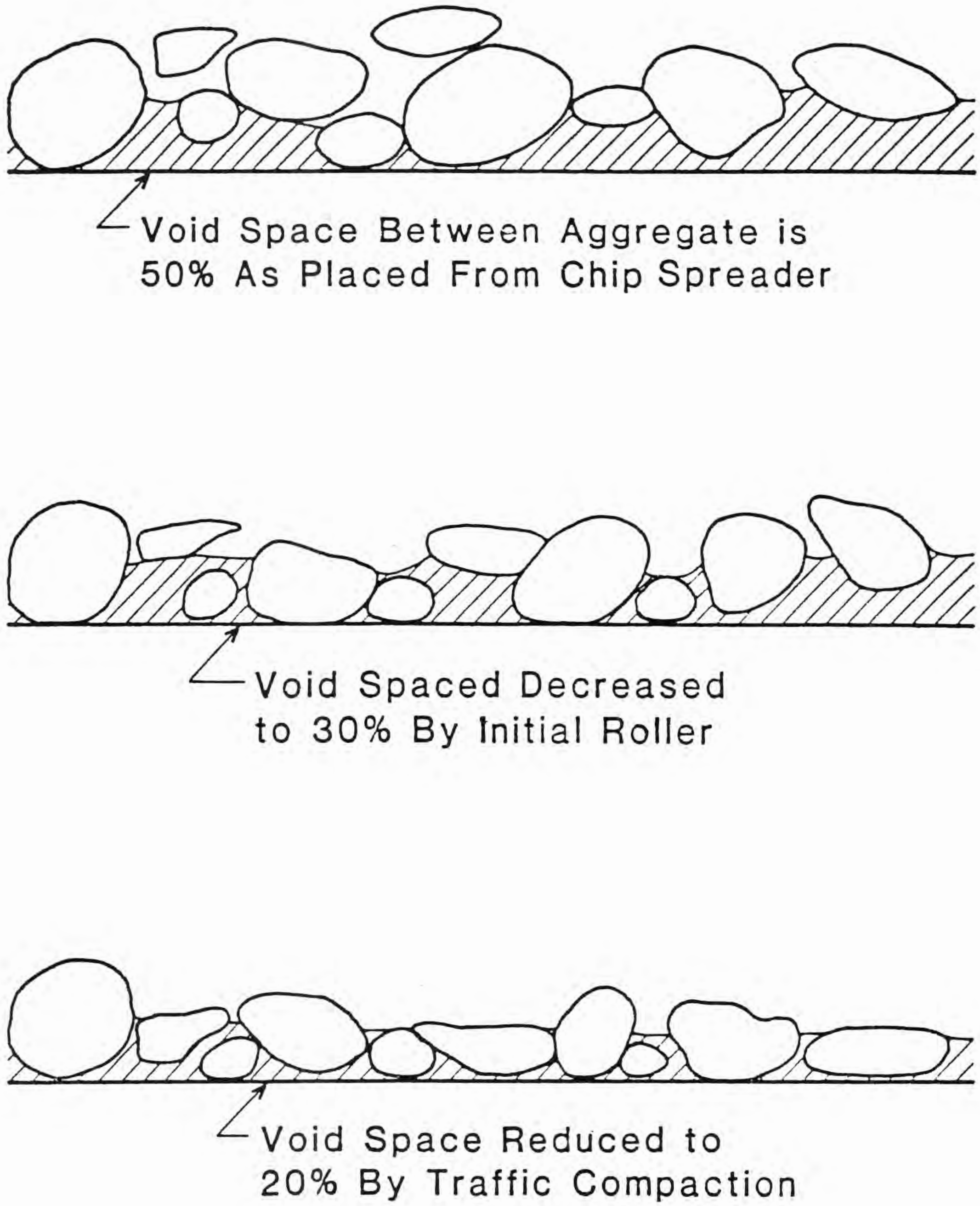

Figure 4. Change in voids in a surface treatment.

The optimum particle shape for cover aggregate is approximately cubical or equi-dimensional. This shape of aggregate is stable under the compactive efforts of the traffic. Aggregates that are elongated with one thin dimension can be reoriented by traffic until the aggregate particles are lying on their flattest sides with their smallest dimensions vertical to the surface. This overall average of the smallest dimension of the particles in a representative sample of the cover aggregate is referred to as its average least dimension (ALD). This dimension cannot be determined from a standard sieve analysis when the aggregate particles are elongated, and requires special testing.[3] The importance of the ALD of the cover stone is illustrated in Figure 5. Both aggregates shown in the diagram are 0.5 inch in sieve size. However, because the aggregate in the top diagram is cubical, its ALD is 0.5 in. In the bottom diagram, because the aggregate consists of elongated flat particles, its ALD is 0.2 inch. It can be seen that to fill the void space in the top aggregate it will take more asphalt than to fill the void space in the bottom aggregate. It can also be seen that with the eventual orientation of the particles due to traffic, more of the top cover aggregate would be required to obtain a surface treatment one stone thick. Obviously, the variation in the ALD of the aggregate requires corresponding changes in the quantities of asphalt binder and cover aggregate being applied. An acceptable design procedure must allow for these corrections to be determined, and used in the selection of design quantities of asphalt and aggregate.

The majority of surface treatments are done using a uniformly graded aggregate which results in one particle size dominating the material. A uniform gradation is one in which 80 percent of the material is retained on the next smaller sieve. At times a more well-graded material has been used which requires a slightly different parameter to be used. The spread modulus is another means of expressing the median aggregate size (D_{50}) of a well graded aggregate. The graph in Figure 6 illustrates the selection of the ALD size of an aggregate. The effect of elongated particles is lessened for these well graded materials, but it should be evaluated for every aggregate.[4] If possible, well graded aggregates should be avoided.

The selection of the maximum size of aggregate is based on several considerations. Observations in the field indicate that surface treatments employing large size cover aggregate perform better than those employing small size aggregate. There are two reasons for this. First, the larger cover aggregate requires more asphalt and the thicker asphalt provides a more effective seal. Secondly, there is a larger factor of safety in terms of gallons per square yard with regard to the application of either too much or too little asphalt with the use of the large aggregate. Consequently, the margin of safety against bleeding or flushing caused by too much asphalt or the loss of cover aggregate due to not enough asphalt is greater with the large aggregate. In addition, the large aggregates provide longer service life and are frequently used for high traffic volume areas. The major disadvantages of the large aggregate are the requirements of more asphalt binder to fill the voids in the cover aggregate, greater tendency to damage vehicles, and the associated tire noise.

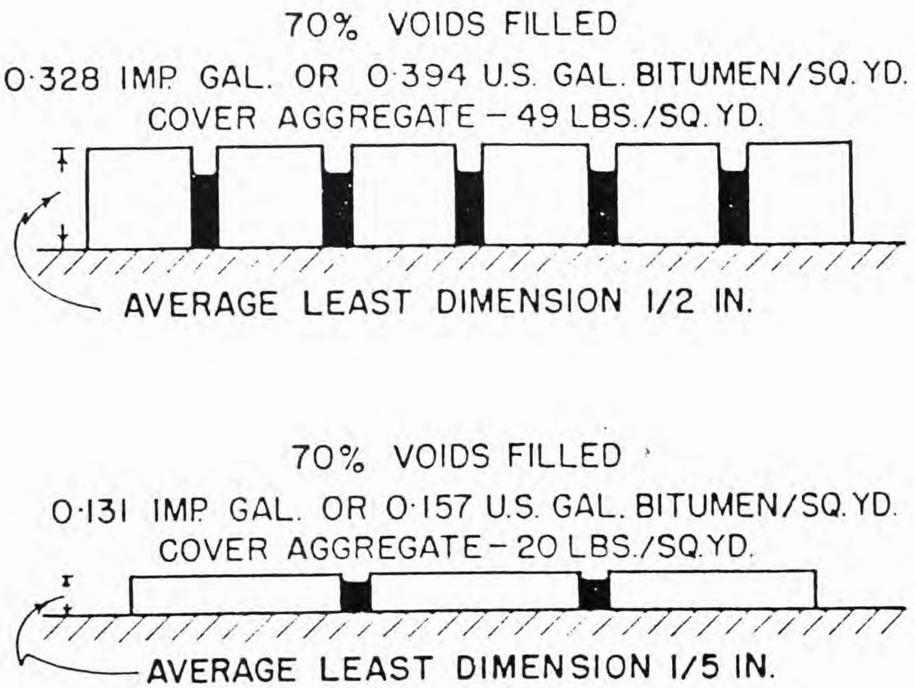

Figure 5. Influence of the average least dimension.

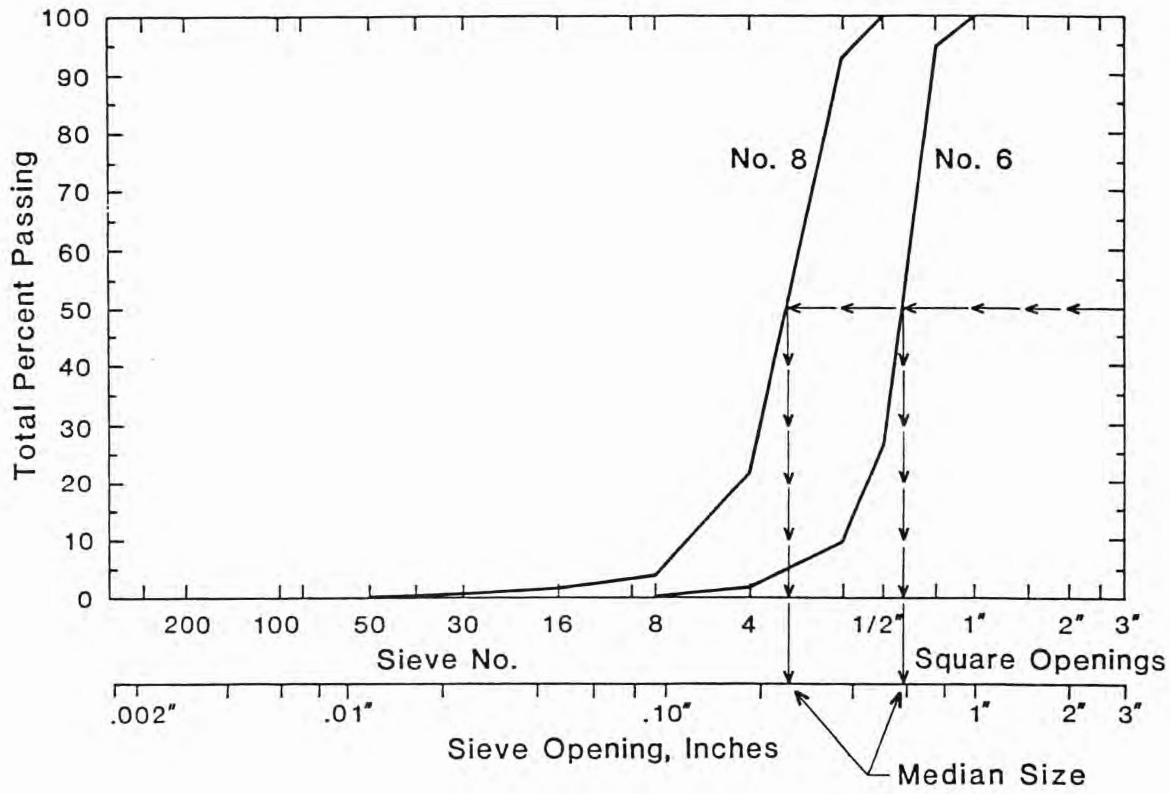

Figure 6. Typical gradations with median size indicated.

Cleanliness of the aggregate is very important for obtaining good, rapid adhesion between the aggregate and the asphalt binder. The presence of fines, or large amounts of fine particles in the aggregate severely alters the amount of asphalt required for a good chip seal. The higher the amount of fines, the higher the quantity of asphalt required for proper bonding. The presence of dust on the particles inhibits the development of proper adhesion between the aggregate and the asphalt binder. The recommended maximum level of minus #200 material is 1 percent.(5)

Many agencies precoat the aggregate with a thin film of asphalt binder to promote rapid adhesion. Because precoating the aggregate promotes the development of rapid wetting and good adhesion, it enables the use of more viscous asphalt binders and construction under less favorable conditions.

ASPHALT BINDER

AMOUNT

The important requirement of the asphalt-aggregate combination is to ensure the proper embedment of aggregate into the asphalt layer. This means that the asphalt binder must fill the void space in the aggregate, and any factor which changes this void space, or reduces the amount of asphalt available for aggregate embedment, creates a problem which should be considered in the design phase of the project. Further, these quantities must be noted and observed in the field to ensure uniformity within the project.

Traffic

The level of traffic on a pavement alters the final voids in the aggregate layer which alters the required amount of asphalt required to hold the aggregate. As mentioned previously, this traffic continues to seat the aggregate and orient the particles. A high number of vehicles will seat the aggregate more deeply and reduce the available air voids more than a low number of vehicles. Deep-seated aggregates will require a reduced amount of asphalt binder to achieve proper embedment compared to the same aggregate seated lightly under a relatively low number of vehicles. The same asphalt amount and the same aggregate will perform very differently on pavements with very different traffic levels.

Residual Factor

Because the final embedment is determined by the amount of asphalt cement remaining in the surface treatment after the emulsion water or the cutback solvent has evaporated, the relative amounts of asphalt cement and liquids must be known. This adjustment must be made to determine the proper application rate of emulsion or cutback to be used which will result in a residual binder content sufficient for proper embedment.

Aggregate Absorption

Absorption of asphalt into the aggregate is normally small, and not generally accounted for in the design procedure. However, if absorptive aggregate is used, the amount of asphalt should be adjusted to compensate for the absorption. Precoated chips can reduce the amount of absorption slightly.

Existing Surface

The condition of the existing pavement prior to the application of the surface treatment influences the amount of asphalt free for aggregate embedment. If the surface is old, oxidized, or porous, it will absorb the asphalt taking it away from the aggregate. This removes the asphalt from the aggregate in the surface treatment, increasing the likelihood of aggregate loss. Likewise, if the pavement surface is flushed with an excess of asphalt, this asphalt will combine with the asphalt sprayed, and will be available for embedment of the aggregate and produce a flushed surface treatment.

TYPE

All asphalt binders have been used for surface treatments. Soft viscosity grade asphalt cements have been used for newer high volume installations, and cutbacks have been used for many years. Emulsions are the choice for most surface treatments today. Emulsions provide the excellent properties to satisfy the requirements of the binder, namely:

- At the time of application, the binder must be fluid to wet the surface and aggregate, promoting good adhesion between binder, aggregate, and pavement surface.
- The binder must cure and gain sufficient viscosity to hold the aggregate and resist the tendency of traffic to pull the aggregate out.

These characteristics are provided by the emulsion water, and the properties of the base asphalt cement used in the emulsion. The properties of the base asphalt are obtained when the emulsion breaks or sets and the asphalt recombines.

Success with any aggregate-emulsion combination depends greatly on the electrical surface charges of the asphalt and aggregate. The probability of good adhesion is increased if the charges are opposite. The predominating charge on the aggregate surface determines whether anionic or cationic emulsion will produce the best results. Siliceous aggregates should normally be used with cationic emulsions (CRS-2), while carbonate aggregates should normally be used with anionic emulsions

(AE 150). It must be stressed that even with these general recommendations that good surface treatments can be constructed with mismatched materials if construction practices are tightly controlled.

Najafi, Johns and Viana's survey of chip seal coat practices of various states in the United States found that many states use at least one type of cationic emulsion.[4] Anionic emulsions, including high float emulsions, were used by 46% (of the 35 states surveyed) of the states. A more recent trend in the surface treatment area is the use of polymer modified emulsions.[2]

CURRENT IMPLEMENTED DESIGN PROCEDURES

In determining what if any changes may be required for South Dakota's chip seal design procedure it is helpful to review the design methods used by other state agencies. Despite the availability of numerous design procedures, many agencies determine the material quantities by experience and or precedent, as is the case in South Dakota. In terms of design factors, most states using a formalized design process consider average daily traffic, surface condition, and emulsion application temperature in their design procedures. Two other factors frequently considered are the aggregate Flakiness Index, (an indication of the proportion of elongated particles present in a gradation) and aggregate wastage or whipoff.

Early work in the United States by Kearby and McLeod has greatly influenced many of the current design procedures. The Asphalt Institute Method, the Texas Department of Highways and State Transportation Method, and the Pennsylvania Department of Transportation Method are based on the findings of their early research.

THE ASPHALT INSTITUTE METHOD

The Asphalt Institute method uses the existing pavement condition, loose unit weight of cover aggregate, bulk specific gravity of cover aggregate, ALD of cover aggregate, wastage factor, average daily traffic, and multiplying factors based on experience with local conditions to determine the design aggregate and asphalt application rates.[3]

The following equations are used to determine the quantity of cover aggregate and emulsified asphalt in a surface treatment.

Cover Aggregate	*Emulsified Asphalt*
$C = M[46.8(1-0.4V)HGE]$	$B = K[(2.244HTV + S + A)/R]$

where

C = cover aggregate application, lb/yd^2.

V = void in the cover aggregate in loose condition, V= 1-[W/(62.4G)], percent, expressed as a decimal.

W = loose unit weight of cover aggregate, lb/ft, AASHTO Method T 19 (ASTM Method C 29).

G = bulk specific gravity of cover aggregate, AASHTO Method T85 (ASTM Method C 127).

H = average least dimension (ALD) of cover aggregate, in.

E = wastage factor to allow for cover stone loss, due to whip-off and unevenness of spread.

M = a multiplying factor that must be evaluated by experience with local conditions of climate, traffic, cover aggregate, etc., and may have a value greater or less than 1.0, which is its normal value.

B = emulsified asphalt application, gal/yd^2.

H = average least dimension of cover aggregate, in.

T = traffic factor.

S = correction, gal/yd^2, for texture of surface on which surface treatment is to be placed.

A = correction, gal/yd^2 for absorption of asphalt into cover stone (disregard except for obviously porous stone).

R = residual asphalt in emulsion, percent, expressed as a decimal.

K = a multiplying factor that must be evaluated by experience with local conditions of climate, traffic, cover aggregate, etc., and may have a value greater or less than 1.0, which is its normal value. However, experience has shown that for emulsions in colder northern areas, "K" can have a value of about 1.2.

Reference 3 or Appendix B should be consulted for the traffic factor and correction values.

TEXAS STATE DEPARTMENT OF HIGHWAYS AND PUBLIC TRANSPORTATION (TSDHPT)

Cover Aggregate

S = 27W/Q

Asphalt

A = 5.61E (1-(W/(62.4G))) T + V

where

S = quantity of aggregate required, yd^2/yd^3.

W = dry loose unit weight, lbs/yd^3.

Q = aggregate quantity determined from board test, lbs/yd^2.

A = asphalt quantity, gals/yd^2 @ 60^{0}F.

E = embedment depth, in, E = ed.

where e = aggregate embedment, percent.
d = average aggregate or mat depth, in, $d = 1.33Q/W$.
G = dry bulk specific gravity of aggregate.
T = traffic correction factor.
V = correction factor for surface condition.

The residual asphalt quantity calculated using the above equation is then modified to correct for the amount of volatiles or water present in the asphalt material and time of placement and temperature of asphalt during placement. Reference 6 or Appendix B should be consulted for guidelines on determining embedment depth and correction factors.

PENNSYLVANIA DEPARTMENT OF TRANSPORTATION METHOD

The PennDOT procedure uses the existing pavement condition (flushed, smooth nonporous, slightly porous, slightly pocked, or badly pocked), median aggregate size (D_{50}), average daily traffic, aggregate whipoff factor (10 or 20 percent), the type of emulsion used, and type of aggregate used (limestone, gravel, or slag) as the variables necessary to calculate the application rates. Temperature corrections for asphalt application rates are suggested.

The equations used in designing the asphalt application rate and the aggregate spread rate have been consolidated into a graphical procedure. The nomographs used in this procedure are shown in Appendix B.[7] These nomographs represent the inclusion of all the design parameters discussed earlier.

SOUTH DAKOTA DESIGN PROCEDURE

The procedure used by South Dakota to select amounts for their surface treatments is shown in Table 6. Two types of seals, chip and sand, are used. Gradation 2A is used for chip seals and gradations 1B and 2B are used for sand seals. Two main types of emulsions, CRS-2 and AE 150 S, are used. CRS-2 is a cationic rapid setting, recommended for siliceous aggregates, and AE 150 S is a high float anionic medium setting, recommended for carbonate aggregates. AE 200 S is sometimes used by the counties. The decision to use either a chip seal or sand seal is made in the Region based on field observations and experience. Application rates for both the asphalt and aggregate are based mainly on experience. For example, when designing a sand seal using aggregate gradation 1B, the eastern part of the state generally specifies an asphalt application rate of 0.24 gal/yd^2 and an aggregate application rate of 22 lb/yd^2, while the western part of the state specifies an asphalt application rate of 0.26 gal/yd^2 and an aggregate application rate of 24 lb/yd^2. The difference in asphalt quantity for a particular gradation derives from the surface characteristics of the two types of aggregates generally used, limestone and quartzite.

The quartzite aggregate does not absorb as much asphalt as the limestone. The eastern part of the state generally uses high quality quartzite; the central part of the state uses siliceous aggregates; the western part of the state uses limestone. The sand seals are all siliceous.

Table 6. South Dakota surface treatment mix design.

Aggregate Type	Design AC Application Rate (gal/yd^2)	Aggregate Application Rate (lb/yd^2)
1B (Sand Seal)	0.24	22
	0.26	24
2A (Chip Seal)	0.27	24
	0.28	26
2B (Sand Seal)	0.24	22

The gradation requirements for the aggregates used for surface treatments are given in Table 7.

A comparison of the values of asphalt and aggregate quantities required by the various design procedures is shown in Table 8. As can be seen, the design quantities for the asphalt binder and the cover aggregate vary 0.1 gal/yd^2 for the asphalt, and 12 lbs/yd^2 for the aggregate. In this comparison, where required by the design procedure, the asphalt binder was assumed to have a residual factor of 0.68, the loose unit weight of the aggregate to be 85 lb/ft^3, an aggregate whipoff factor of 10 percent, and correction factors to be 1.0. Corrections for temperature have not been applied.

Table 7. South Dakota surface treatment aggregate gradations.

Requirement	Type 1		Type 2	
	A	B	A	B
Processing Required			Crush	Crush
Passing 3/4" Sieve				
Passing 5/11" Sieve				
Passing 1/2" Sieve				100
Passing 3/8" Sieve	100	100	100	30-90
Passing No. 4 Sieve	80-100	45-90	20-70	0-50
Passing No. 10 Sieve	55-90	0-20	0-20	0-15
Passing No. 40 Sieve	5-45	0-4	0-4	0-5
Passing No. 200 Sieve	0-7	0-4		
Plasticity Index, Max.	3	3		
L.A. Abrasion Loss, Max			40	40
Soundness Loss, Max			12	12
Foot Notes			1&2	1

1. At least fifty (50) percent of material retained on the No. 4 sieve shall have two (2) or more fractured faces produced by crushing.
2. A tolerance of three (3) percent in the amount passing the maximum size screen will be permitted providing all material passes a screen having one-fourth (1/4) in. larger openings.

Table 8. Comparison of design procedures

Proj #	Highway		Design Procedure			
			South Dakota[1]	Asphalt Institute	Texas	Penn DOT
13	1804	AC (gal/yd^2)	0.28	0.33	0.25 to 0.30	0.38
		Agg (lb/yd^2)	26	18	20	17
5	1804	AC (gal/yd^2)	0.24	0.30 to 0.31	0.23 to 0.28	0.25 to 0.26
		Agg (lb/yd^2)	22	17	20	10
2	18	AC (gal/yd^2)	0.27	0.24	0.18 to 0.21	0.27
		Agg (lb/yd^2)	24	17	20	17
17	12	AC (gal/yd^2)	0.26	0.20 to 0.21	0.15 to 0.19	0.21 to 0.23
		Agg (lb/yd^2)	24	20	20	14

1. No adjustments for residual asphalt content or aggregate whipoff have been applied.

In general, the SDDOT criteria calls for a higher asphalt and aggregate application rate, even if a certain amount of whipoff is allowed for (the SDDOT AC application rate must be adjusted for residual asphalt content for comparison). It should also be noted that the SDDOT design procedure does not allow for adjustments for traffic, aggregate ALD, or surface condition of the existing pavement, except for any adjustment field personnel may apply.

CONSTRUCTION CONSIDERATIONS

The proper choice of materials and their appropriate quantities is as important as the proper construction techniques, and while not a part of the design procedure they are just as important. The objective during construction is to apply the design or specified quantities accurately and uniformly to the road surface in such a manner as to result in a long lasting seal coat. Climate and weather, preparation of the existing surface, construction equipment, construction operations, and traffic control during and immediately following construction influence the performance of the seal coat.

WEATHER

Seal coats constructed during warm, dry weather are less likely to develop problems because construction problems are ameliorated by the weather. During warm weather, traffic will provide good embedment of the cover aggregate into the asphalt binder, minimizing time delay problems. Low humidity may result in a decreased set time. A slight wind may speed the set of the asphalt binder. However, high winds may distort the distributor spray pattern, making it impossible to obtain uniform asphalt coverage. Many states set minimum temperature and cutoff construction dates for these reasons.

SURFACE PREPARATION

Before a seal coat is constructed, the existing surface should be adequately repaired and cleaned. This includes patching potholes or sealing large cracks and sweeping with a power broom. A slightly wet surface is acceptable if an emulsion is used, but not if a cutback or asphalt-cement is used. If the surface is extremely porous, or oxidized, a prime coat should be considered.

EQUIPMENT

The equipment used for the construction of a surface treatment includes the asphalt distributor, aggregate spreader, and rollers. The equipment and its operation are important in determining the quality of the resulting surface treatment.

The asphalt distributor must be able to apply asphalt uniformly across and along the roadway at the specified rate. It is important to calibrate the equipment before the job begins. This calibration should include both total amount of asphalt applied and the variability across the supplication width. There are several acceptable methods of calibration. A test strip should be constructed and the application rates checked both longitudinally and transversely on the pavement. It is preferable to control the quantity of asphalt by synchronizing the distribution rate with the forward speed of the distributor rather than by gallons per minute. This would decrease the variation in applied rate due to small variations in forward speed of the truck due to changes in grade, etc.[6]

Two other very important features of the distributor include the spray bar height and spray nozzle angle setting. The angle of the nozzles controls the uniformity of the spray pattern and must be adjusted so that the spray fans will not interfere with each other. The recommended angle, measured from the spray bar axis, is 20^0 to 30^0.

The spray bar height must be set to provide uniform coverage. The best results are usually achieved with either a double coverage or a triple coverage. Figure 7 shows the effect of the spray bar height.

The asphalt binder in the distributor should be at a sufficiently high temperature to allow uniform application. Spraying asphalt binder that is too cold to enable uniform application is a common cause of streaking. Because spraying of emulsions will typically be done above 120 ^{0}F, the distributor must be capable of allowing the appropriate adjustments to be made to provide the desired application rate, specified at 60 ^{0}F.

The aggregate spreader must also apply a uniform aggregate cover at a specified rate. Spreaders range from the simple vane type attached to a truck tail gate to the highly efficient self-propelled type, all of which are capable of doing an acceptable job. The aggregate spreader must also be calibrated in a manner similar to that of the distributor using a test strip.

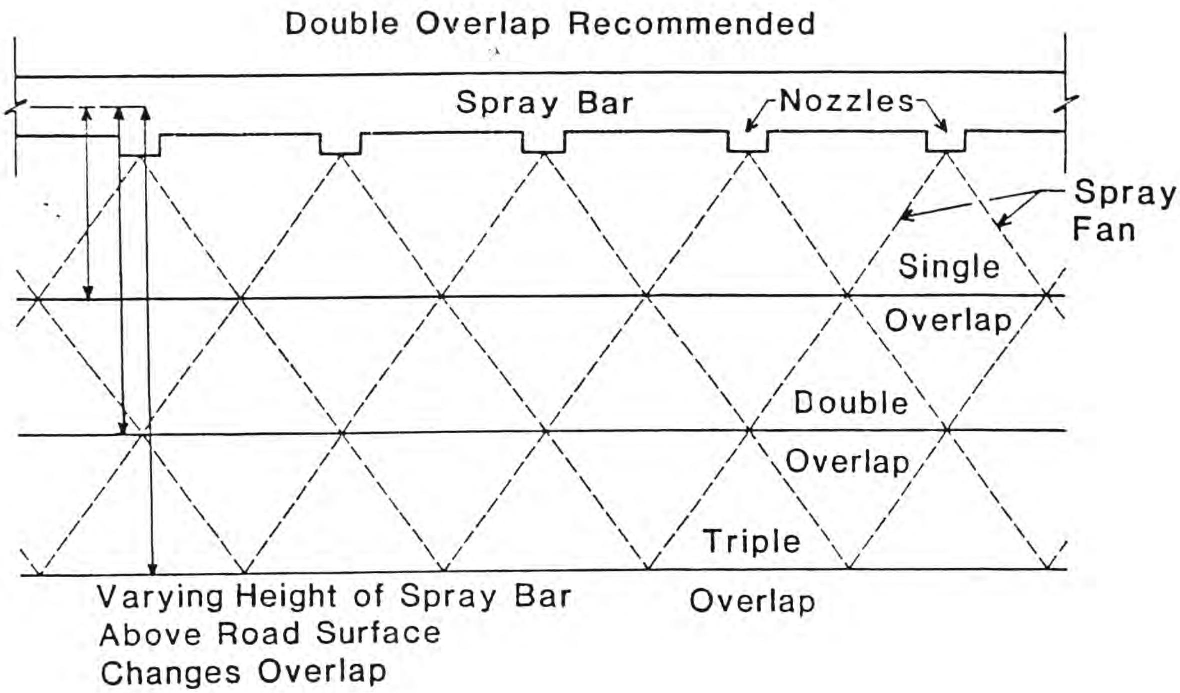

Figure 7. Spray bar height adjustments.

CONSTRUCTION SEQUENCE

Timing of the aggregate spread can influence the quality of construction, with long term performance implications. Ideally, the aggregate should be spread on the asphalt immediately after the asphalt is applied. This provides for rapid wetting of the aggregate by the emulsion, and establishes good initial adhesion with the asphalt and each aggregate particle. If the aggregate is spread too late they will not be adequately glued to the asphalt. If an emulsion is being used, the aggregate must be spread before the emulsion has set. Once the emulsion sets, no bonding of aggregate and asphalt will take place. The aggregate must also be placed so that they aren't rolled, or turned over during spreading. This action reduces the amount of asphalt binder remaining on the roadway to bind the aggregate.

Another critical operation in the procedure is rolling to seat the aggregate in the asphalt and enhance bonding between the aggregate and the asphalt. The rolling should commence as soon as the aggregate has been applied. The first pass of the roller over the aggregate should be completed within a few minutes after the aggregate has been applied. This provides better embedment and enhances rapid wetting of the stone chips by the binder. A pneumatic wheel roller is recommended, though a steel wheel roller in conjunction with pneumatic tire rollers has also been effective. A steel wheel roller alone will ride on the high spots, crushing the aggregate and passing over the low spots.

The total operation of asphalt application, chip spreading, and rolling, must be completed as quickly as possible once it begins; there should be no delays between operations. If delays occur, the asphalt can set which can prevent the effective coating and bonding of the aggregate.

A number of considerations should be observed when opening a newly constructed surface treatment to traffic. During the first few hours after construction, the seal coat does not have high stability, and can be damaged by the disruptive forces of high speed traffic because the asphalt is continuing to set and gain strength. Because of this, traffic speeds should be kept low. During hot weather, the worst time of day to open a new seal coat to traffic is between mid-day and late afternoon. The high temperatures during these hours make the asphalt binder much more fluid and less able to hold the cover aggregate. It is recommended that high speed traffic be delayed until after dark.[4]

QUALITY CONTROL

While the successful construction of the surface treatment depends on the skill of the contractor and engineers, proper inspection is important to maintain control over what is placed. Variability in the materials being used and operational procedures can produce unsatisfactory performance in surface treatments, especially on higher traffic volume roads, and those roads where a longer than normal life is desired. There are two general options that can be followed to monitor construction. Quality control checks can be performed on either a total application basis which requires measurements to be taken after specific areas have been paved, or on a periodic basis which determines conformance at specific locations. Either procedure can provide information relative to quality of construction practices. It is important that quality control checks be a part of any construction procedure to ensure that the design quantities are actually being achieved on the roadway.

Total Application Basis

In this procedure, the area of surface treatment is recorded and the weight (or volume) is taken on the asphalt distributor before and after application. The weight of aggregate on the spreader is also taken before and after application. The application rates are determined by dividing the weight, or volume, by the square yards placed. This procedure requires the use of large scales which may not always be available, and it provides only an average for the particular length of placement, which may be of considerable length. It provides no indication of variability in the equipment which may occur during placement. It cannot be used to indicate whether equipment was out of adjustment and placing improper amounts across the width of the roadway.

This procedure is used by the South Dakota DOT. It relies on careful calibration of the equipment before the project begins, and the careful control of the contractor. Often times the asphalt distributor and aggregate spreader may be calibrated at the beginning of a contract, while several different projects may be constructed under this one contract, using only the one calibration. This can lead to problems on individual projects which cannot be determined until the project is completed.

Periodic Basis

This procedure provides for an immediate determination of application rates at any time during placement. Asphalt application rates can be determined using cotton pads of known size and weight (ASTM D 2995, "Standard Recommended Practice for Determining Application Rate of Bituminous Distributors"). These are placed on the roadway ahead of the distributor. They are reweighed after the distributor passes and the application rate can be determined. Some states use a geotextile square instead of the cotton pads. The same procedure can be used to measure the aggregate spread rate. Normally a one square yard board or burlap cloth or 22- by 22- in pan is placed ahead of the spreader. The cloth or pan is weighed after the spreader passes, and the application rate is calculated.

These determinations provide a quick means of monitoring construction and checking variability within a project. They can be used to determine uniformity of application across the width of the roadway. They allow a quick check on equipment settings to indicate if they are still within calibration. They are necessary when changing application rates from one project to another. On these projects where the amounts change based on the design procedure, it is not sufficient to rely on a one time calibration, and the manufacturer's settings on the equipment. The actual amounts must be checked. Based on detailed statistical analyses performed, replicate samples seem to be necessary to obtain reliable results. The geotextile method was determined to be sufficiently repeatable for use as a routine test procedure for checking emulsion application rates as long as three or more determinations are made for each test.[9]

SUMMARY

In this chapter the general design philosophy for constructing a well proportioned surface treatment has been presented.. The design philosophy remains the same regardless of the aggregate size, and applies equally to South Dakota's chip and sand seals. The volumetric proportions of aggregate, void space in the aggregate and the percentage of this void space filled by the asphalt will control the performance of the resulting surface treatment. Thus, any investigation of the performance of a surface treatment must include some measure of these parameters.

Design procedures currently implemented by several agencies were presented and included in an Appendix to allow further study. These design procedures all include the relevant parameters discussed, to some extent. It appears that the South Dakota selection procedure is set up to provide adequate amounts of asphalt and aggregate for the materials specified. The main problem with this form of a selection process is that there is no formalized guidance given for consideration of unusual situations which may exist on the roadway being sealed, or which may arise during construction as variable conditions are noted in the materials.

The procedures briefly mentioned here, and the PennDOT procedure in particular provide the means of evaluating construction, and performing an actual design of the surface treatment. They provide the means of adjusting designs using formalized procedures to supplement whatever engineering judgement is being applied. To obtain surface treatments with improved performance characteristics which will provide the longest service life before resealing, the design procedure used must be comprehensive in nature. Implementation of one of the accepted design procedures is recommended before improved performance can be obtained.

CHAPTER 4

ANALYSIS OF SURFACE TREATMENTS

INTRODUCTION

The pavement data collected and presented earlier represents information that should describe why different pavements perform better or worse than others. This data must be analyzed using a statistical approach to clearly demonstrate whether certain construction procedures or design variables produce a difference in performance in a predictable manner. This analysis first takes the form of regression analysis, which develops models that describe the appearance of distress in terms of the design and construction data. Another method of comparison which does not provide a predictive model, but which indicates which variables are important, is the t-test comparison. Both of these methods will be presented.

Of the eight distresses noted on the pavements surveyed for this project, three could be considered as resulting from, or attributable to, the surface treatment. These are:

- Loss of aggregate.
- Streaking.
- Flushing.

The remaining distresses are more appropriately related to the underlying pavement structure or drainage, and not directly to the presence of a surface treatment. These are:

- Rutting.
- Transverse cracking.
- Longitudinal cracking.
- Edge cracking.
- Alligator cracking.

A surface treatment will not remove rutting, nor will it retard the progression of rutting. While a surface treatment will cover any cracking present, it cannot eliminate or retard cracking from reappearing after the surface treatment is applied. Therefore, it would not be expected that surface treatment design or construction variables would relate very well with these distresses.

PERFORMANCE CHARACTERISTICS

Loss of aggregate results when the amount of asphalt binder is too small for the aggregate gradation being used, or when construction procedures produce poor bonding (such as late application of aggregate). Higher traffic levels could also interact to accelerate loss of aggregate. Streaking is primarily a construction problem with an improper height adjustment on the spray bar, clogged nozzles, or improperly adjusted nozzles. Flushing results primarily from an excess of asphalt binder for the aggregate gradation being used. Higher traffic levels would tend to embed the aggregate deeper into the asphalt binder, producing higher levels of flushing in pavements susceptible to this problem.

It is necessary to add calculated variables to the database to reflect the interaction of asphalt binder amount and aggregate size, which vary with the type of surface treatment. As discussed in the section on design philosophy, the asphalt fills the void space left in the layer formed by the aggregate, and this void space varies with different aggregate sizes. There are two calculations that can be done using the available data to provide insight into the proportioning of the constructed surface treatment. These are:

- Ratio of asphalt volume to ALD total layer volume.
- Ratio of asphalt volume to voids in aggregate layer.

The first calculation uses the measured ALD of the aggregate (D_{50}, assuming cubical aggregate, with no data to the contrary) to establish the volume of the aggregate layer, and the actual asphalt quantity to establish the volume occupied by the binder. Theoretically, the asphalt volume should occupy between 70 to 80 percent of the 20 to 30 percent voids assumed to be in the constructed layer, depending on traffic. This procedure assumes that the ALD obtained by using the D_{50} gradation value is valid and the aggregates are not elongated. Unless there are tests to the contrary, this assumption must be made. General field observations of the constructed surface treatments did not indicate excessive elongated particles.

The second calculation uses the aggregate spread rate in pounds and the actual asphalt application rate. Because most aggregates produce a loose density of 90 to 95 pcf, the aggregate spread rate can be used to calculate the volume occupied by the aggregate layer. The void space available for asphalt will be 20 to 30 percent of this layer volume. The ratio of asphalt binder volume to this void volume provides the ratio of voids filled, which should be around 0.7 to 0.8 for adequate embedment.

These two void values are estimates, but represent the combination of aggregate property and amount of asphalt binder placed in a manner that indicates something about the amount of embedment provided to the aggregate. They may relate better to distress than the aggregate and asphalt quantities considered separately.

The seven contractors, eleven aggregate sources, and five emulsion suppliers were identified and included in the database for analysis by the appropriate procedures. Dummy variables were used to avoid biasing the data. Each entity was given a value of 1 when they were present in a project, and a value of 0 when not present. The state was divided into three climatic zones based roughly on the annual average mean temperature. The Black Hills, which lie in zones 2 and 3, temperatures vary significantly from the mean temperature in zones 2 and 3. However, this was not a concern as only one project was constructed in that area. The climatic zones map is shown in Appendix D.

The data regarding ADT, application rates, aggregate gradations, and median aggregate size are given in Appendix D.

STATISTICAL ANALYSIS

The goals of a statistical analysis of a complex database such as the one assembled for this study is to establish trends in the performance data. These trends can then be analyzed and the influence of individual data elements can be established. The statistically relevant influence of each data element on the performance is the piece of information that will be used to support statements regarding specific elements in the construction of a surface treatment that should be changed to improve performance.

Such an analysis to establish performance relationships should be done blind. That is, any preconceived attitudes regarding relationships and their affect on performance must not be present in the analysis. These attitudes must also not affect the initial selection of projects for the database. An unintentional bias that includes more projects, selected to demonstrate particular problems felt to exist, will actually produce insupportable conclusions.

There are two procedures which provide statistically supportable inferences about the database. A regression analysis establishes which data elements most closely relate to and explain the performance variable. A ranking of this relationship can be obtained and a model that indicates the relative influence of the data elements is produced. This model can be used to demonstrate precise relationships between the individual data variables which can provide design information if the correlation of the model is high enough. This method of describing performance is preferred as it provides for a precise investigation of the interactions.

The second means of evaluating differences is to separate the database into distinct categories and compare the data elements in each category to establish if there is a statistically significant difference between the data elements. If there is a difference between each category, that particular variable can be said to impact performance, and should be a candidate for further study. This analysis does not provide a means of evaluating the impact of any variable on performance. It does not provide a tool which may be used as a design investigation tool. This analysis procedure merely indicates where potential differences exist.

The variables used in the analysis of the database are defined as follows:

LOAT	is the percent of surface area exhibiting any loss of aggregate.
FLUSHT	is the percent of surface area exhibiting any flushing.
STREAKT	is the percent of surface area exhibiting any streaking.

TRUCKS	is the number of trucks per day.
DALD	is the design value for the Average Least Dimension (D_{50}) of the specification gradation.
AALD	is the actual ALD determined from construction test records.
RALD	is the range in ALD determinations made during construction, low to high.
AGE	is the age of the surface treatment in years.
ETYPE	is 0 for the CRS-2 emulsion and 1 for the AE-150 emulsion.
ADT	is the average daily traffic count.
ZONE	is the climatic zone, 1, 2, or 3.
ACRATE	is the actual application rate of asphalt binder, gal/yd^2.
DRAC	is the design application rate of asphalt binder, gal/yd^2.
DRAGG	is the design application rate of aggregate, lb/yd^2.
VOIDSA	is the percent of aggregate layer volume occupied by asphalt binder.
VOIDSP	is the percent of voids occupied by asphalt binder.
AGTYPE	is the aggregate gradation classification, 1 or 2.
DATECON	is the days into the specified construction season at which time the surface treatment was constructed.

ANALYSIS OF CONSTRUCTION

As discussed earlier, the various types of surface treatments are designed using the same basic principles. It is common, however, to have different classifications of surface treatments. For South Dakota, these are the sand seal and chip seal, with the chip seal having the larger aggregate size. The application rate for the asphalt binder is established based on these specification aggregate gradation values with some allowance for aggregate absorption. It is interesting to see how closely these specifications were obtained in the field, and how actual applications may influence performance.

AVERAGE LEAST DIMENSION (ALD)

As mentioned earlier, the ALD of a well graded aggregate may be assumed to be the same as the median aggregate size D_{50}. Based on this, the specification ALD of the chip seal (aggregate type 2B) is 0.287 in, and the ALD for the sand seals are 0.181 in (aggregate type 2A) and 0.142 in (aggregate type 1B). The relation between the design ALD, and the as constructed ALD is shown in Figure 8. The surface treatments designated as chip seals (ALD = 0.287 in) were clearly built with aggregates significantly smaller than called for in the specification. The two gradations for the sand seals were slightly larger than the design ALD value. It is interesting to note that the chip seal aggregate was not significantly different from the small sand seal aggregate. Unless the application rates for the asphalt are altered significantly, this could result in distinct problems of flushing for the chip seals.

Figure 9 illustrates the correlation between the design application rate of asphalt and the design ALD. It is clear that the projects termed chip seal have not been designed as a chip seal with a large size aggregate, as the design application rate of asphalt is significantly less than that specified for the sand seals. Thus, these three surface treatments are not really as different as is indicated in their specifications. However, construction results, shown in Figure 10, indicate that there were some slight differences between the three designated surface treatments. The sand seals received asphalt application rates above and below the chip seal, which should translate into very different performance for the designated sand seals compared to the designated chip seals. The variability for similar sized aggregates is a question which should be addressed.

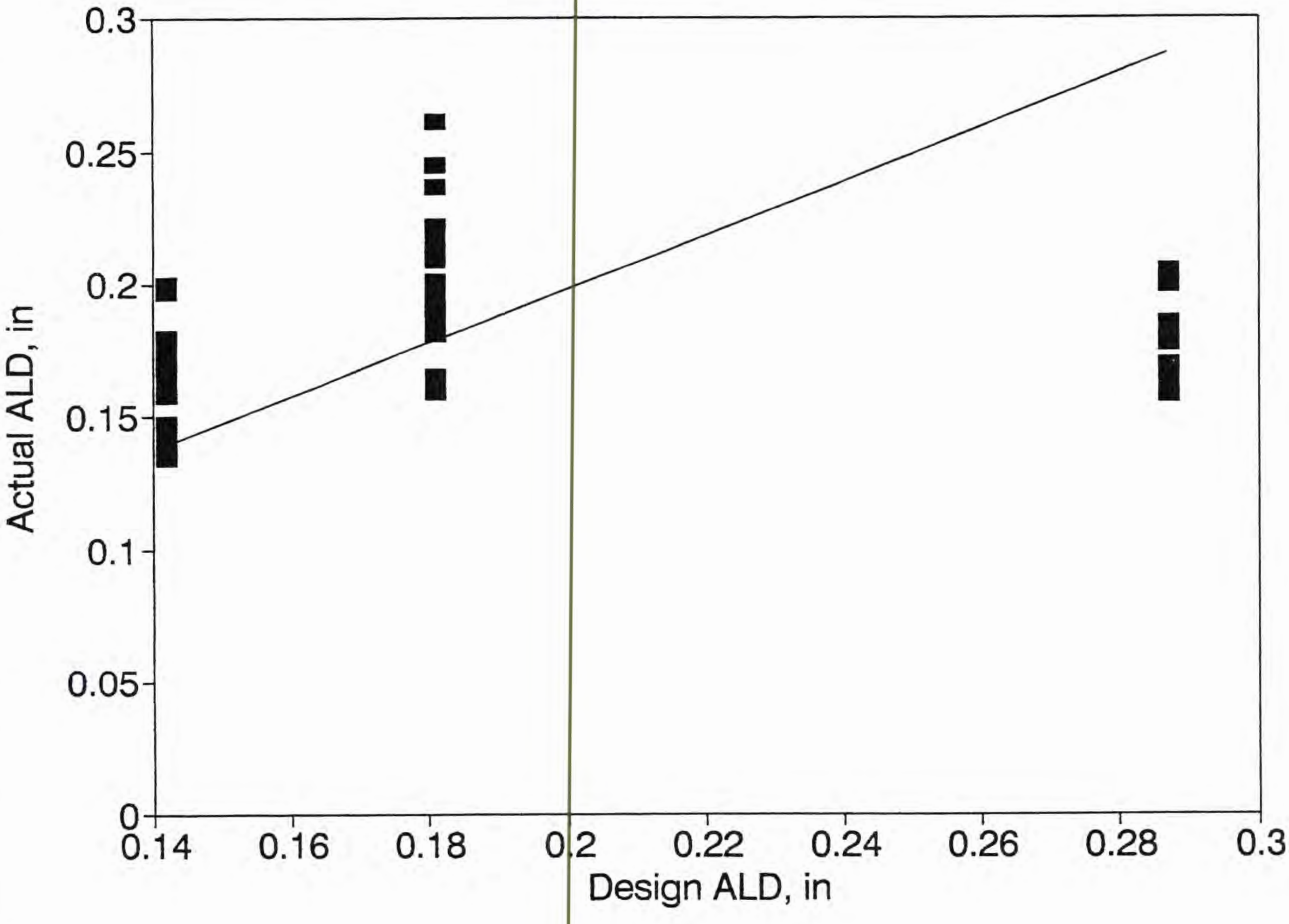

Figure 8. Relation between design ALD and as constructed ALD.

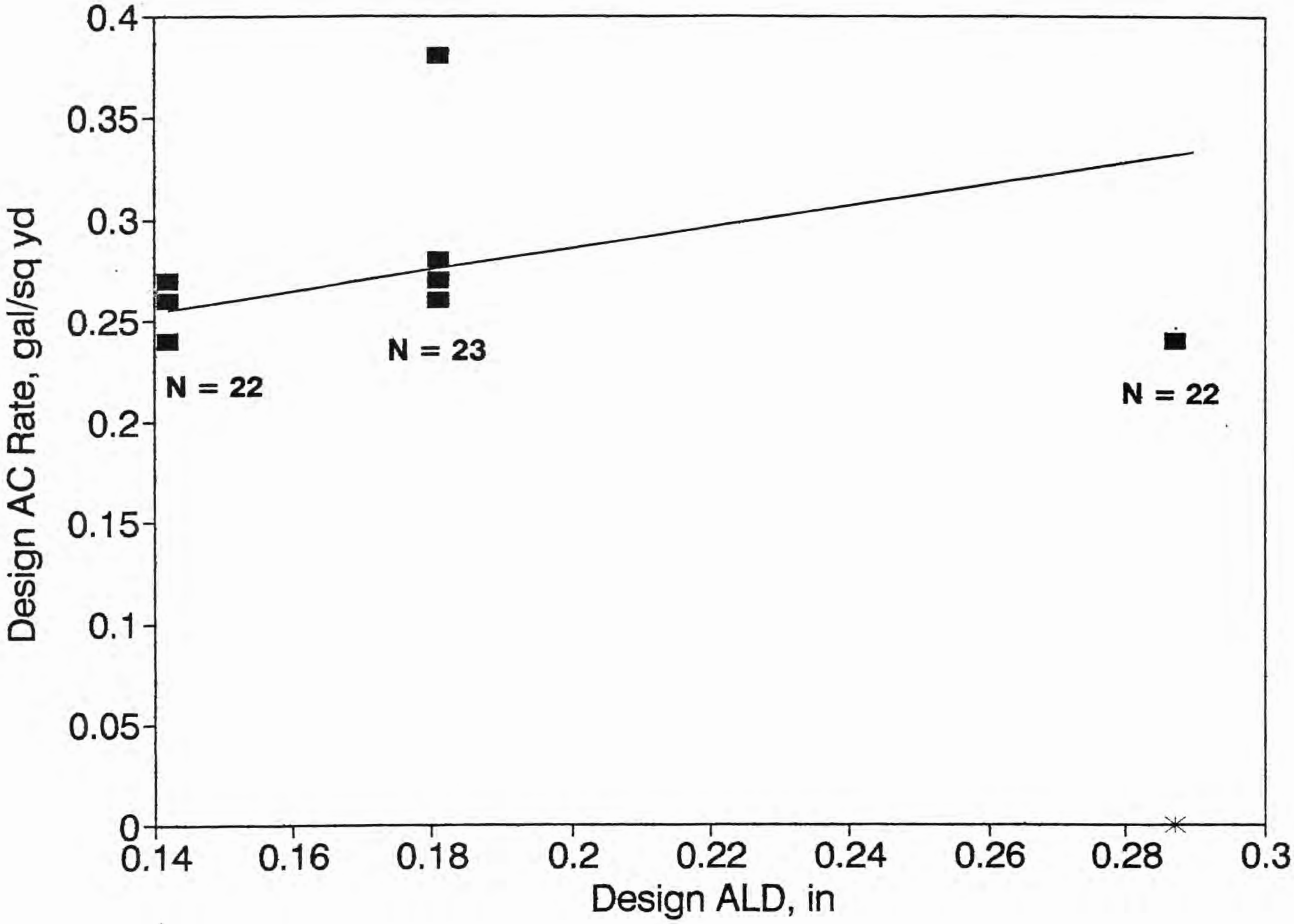

Figure 9. Correlation of design ALD and design asphalt rate.

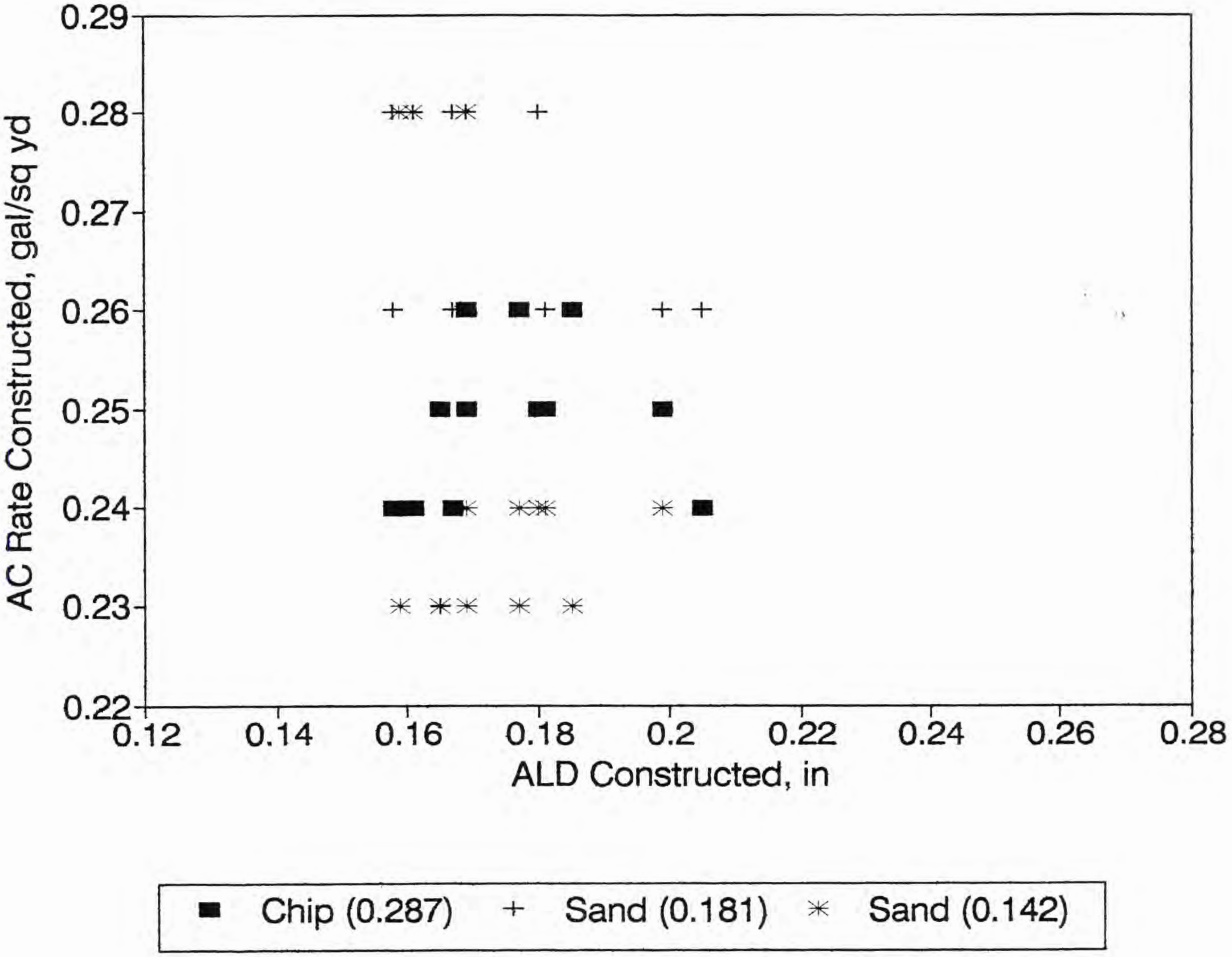

Figure 10. Correlation between as constructed ALD and asphalt rate.

The ability of the aggregate producer to maintain consistency in his gradation should be critical to the performance of the surface treatment. The variability in the ALD is indicated by the percent difference between the design ALD, and the as constructed ALD as shown in Figure 11. The trend is that the smaller the ALD, the larger the difference. Larger differences with smaller aggregates leads to large variations in the amount of voids filled with asphalt, resulting in over- or under-asphalting the treatment. This trend is uniform for all three designations. The position of the chip seal is questionable because the specification value of the ALD is questionable, as previously discussed. There are four projects of the sand seal designation, design ALD = 0.142, that fall outside of this trend which may indicate a problem.

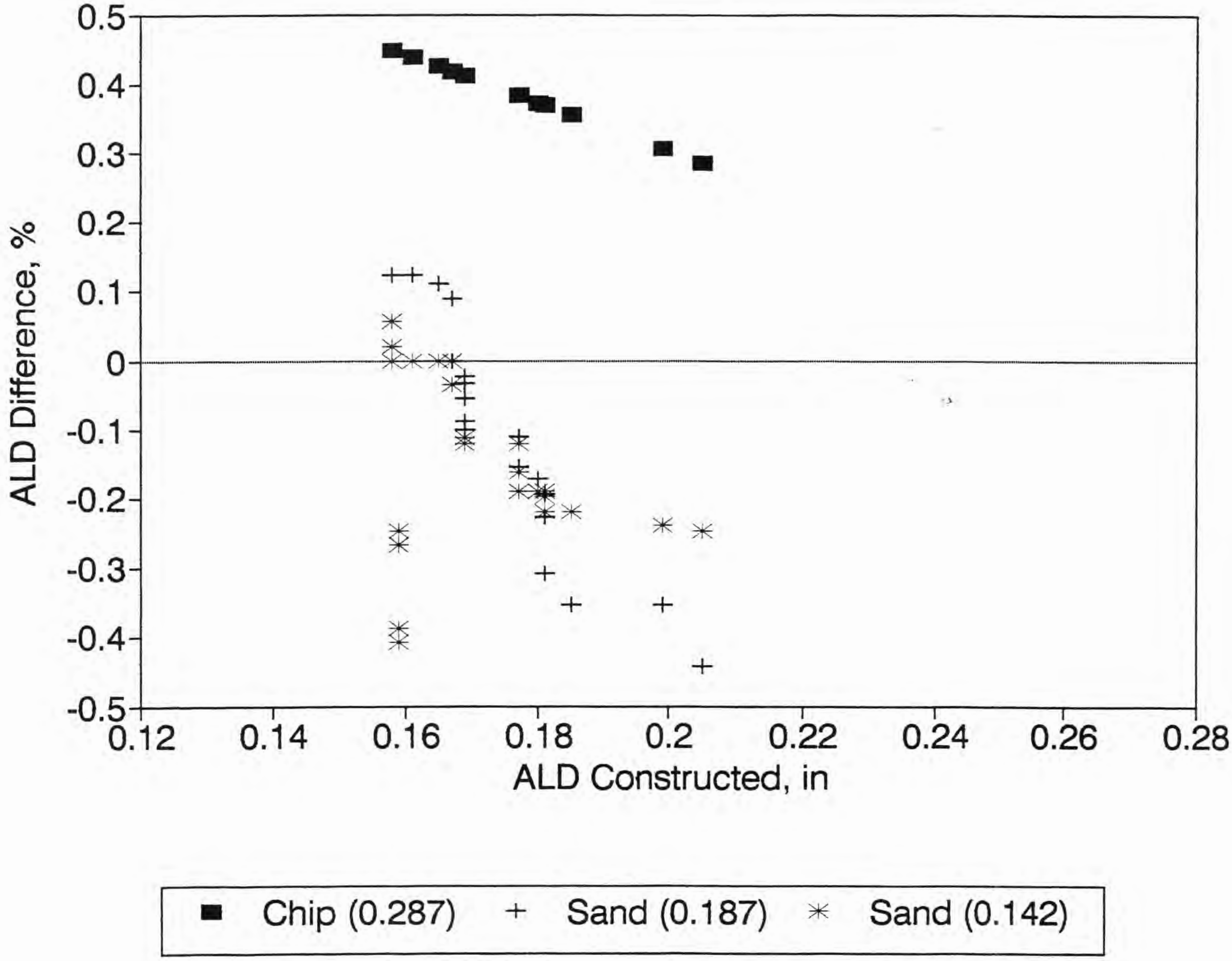

Figure 11. Relationship of as constructed ALD and ALD difference.

VOIDS FILLED WITH ASPHALT

The interaction of aggregate size and asphalt application rate is a crucial item to the performance of a surface treatment. If the amount of voids filled with asphalt is low, the treatment is more likely to develop loss of aggregate. If the amount of voids filled with asphalt is high, the propensity is for flushing to develop. For all aggregate sizes, this ratio of voids filled with asphalt should be a constant that changes only with level of traffic, aggregate absorption characteristics, or original surface characteristics. Aggregate gradation and asphalt application rate alter this value, which should normally be in the vicinity of 20 percent. Lower traffic levels could increase this range to just under 30 percent. Figure 12 indicates that the voids filled for the surface treatments surveyed were in this range. This figure also shows that the variability in aggregate production had an effect on this value with larger variability in the ALD (as shown by the range in test results during QA testing), producing a smaller percent of voids filled with asphalt. Thus, the degree of variability in aggregate gradation can interact with the asphalt added, and produce performance differences in the final product.

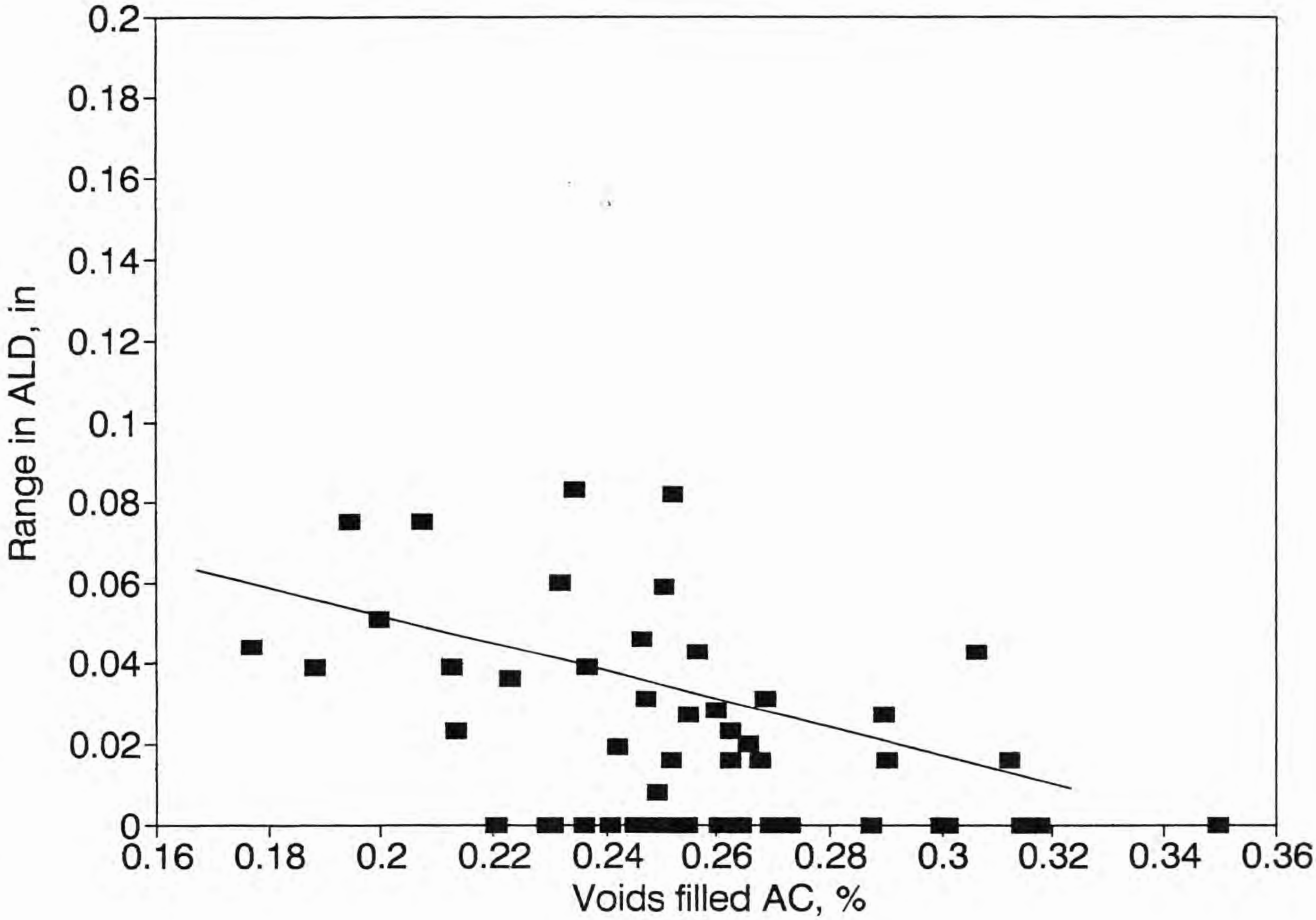

Figure 12. Change in voids filled with range in ALD measurements.

AGGREGATE TYPE

The majority of aggregates used were siliceous in nature. Only five projects were constructed using carbonate based aggregates. These five projects did not distinguish themselves from the overall data, but do require some individual discussion, which will be made when each contractor is discussed in the following sections.

This comparison of the construction parameters with asphalt and aggregate values indicates that the constructed surface treatments were quite different than specified. The differences did appear to produce two different treatments with asphalt application rate and aggregate sizes as indicated by the difference between the design ALD and the as-constructed ALD. The asphalt application rate also changed from what would normally be expected for a specified aggregate of the larger specification size, which is fortunate. The differences between specified and as-constructed treatments complicates a comparative performance analysis because quite often significantly different treatments are placed for specific reasons. The placement of a significantly different treatment than specified may indicate specific problems noted on the original pavement surface which necessitated the deviation from specifications. Significantly different surface conditions on the original pavement can produce significantly different design values, if a design procedure is used. If not, very different non-designed surface treatments can result with very little uniformity that could be discerned in a statistical analysis.

REGRESSION ANALYSIS

The regression analysis on the entire database did not provide any models suitable to describe the appearance of distress in terms of pavement variables. The best correlation coefficients were around 0.3, indicating that only 30 percent of the variability in the data could be explained. This develops from a distinct lack of variability in the data. This can be attributed to the relatively young age of the surface treatments, one and two years. The distresses have not progressed to the point where the small variability in the pavement data has produced significant differences. The presence of different contractors, aggregate sources, and asphalt suppliers did no enter into the relationships, most likely due to their being a high correlation between aggregate types, emulsion types, aggregate sizes, etc. and the contractor or supplier. The regression analysis excludes variables which are highly related (colinearity effects).

INDIVIDUAL CONTRACTORS

While the analysis of the complete database did not provide any statistical differences between contractors, there are differences, and each contractor produces a different surface treatment. The contractors in the database were separated and analyzed separately with the following results.

Asphalt Surfacing Company

There were 17 individual projects included for this contractor.

Loss of Aggregate

LOAT = - 0.02231(TRUCKS) + 0.005776(ADT) + 20.519(RALD) + 371.1(AALD) - 1.376(DRAGG - 0.1409(DATECON) - 103.22

R^2 (Correlation Coefficient) = 0.91 SEE (Standard Error of Estimate) = 1.03

Streaking

STRKT = 43.674(VOIDSP) + 0.006878(ADT) + 10.448(AGE) + 172.29(RALD) - 35.644

R^2 = 0.24 SEE = 25.44

Flushing

FLUSHT = - 1627.4(ACRATE) + 4.607(AGE) + 134.37(RALD) + 0.6813(DRAGG) - 0.6699(DATECON + 445.02

R^2 = 0.45 SEE = 11.75

McLaughlin & Schultz

There were 22 individual projects included for this contractor.

Loss of Aggregate

LOAT = 85.537(ACRATE) - 0.1076(TRUCKS) + 0.004724(ADT) -38.118(AALD) + 0.1601(DATECON) - 11.247

R^2 = 0.60 SEE = 5.25

Streaking

STRKT = 3906.3(VOIDSA) - 703.13(VOIDSP) + 15.25(ZONE) - 2260.5(ACRATE) + 0.0256(ADT) - 236.33(RALD) + 2981.9(AALD) - 129.3(AGTYPE) + 1180.3(DRAGG) - 0.07565(DATECON) - 1598.1

R^2 = 0.80 SEE = 12.71

Flushing

$$FLUSHT = -20.607(ZONE) + 0.1485(TRUCKS) + 0.02717(ADT) + 27.128(AGE) + 149.84(DALD) - 0.5339(DATECON) - 59.661$$

R^2 = 0.59 SEE = 14.03

Hills Materials

There were 15 individual projects included for this contractor.

Loss of Aggregate

$$LOAT = 0.03084(TRUCKS) + 245.73(RALD) - 572.29(AALD) + 172.35(DALD) - 0.2396(DATECON) + 60.634$$

R^2 = 0.93 SEE = 2.86

Streaking

$$STRKT = -1983.4(VOIDSP) - 34.021(ZONE) + 11222(ACRATE + 0.5003(TRUCKS) - 0.10341(ADT) - 29.003(AGE) + 902(RALD) - 9780.8(AALD) - 277.17(AGTYPE) + 1010.4(DALD) - 2.2267(DATECON) + 1071.3$$

R^2 = 0.99 SEE = 3.42

Flushing

$$FLUSHT = -1769.7(VOIDSA) + 501.94(VOIDSP) + 4.726(ZONE) - 2573.3(ACRATE) + 34.28(AGE) + 268.25(RALD) - 742.46(AALD) + 250.57(AGTYPE) - 1472.1(DALD) + 1.436(DATECON) + 596.69$$

R^2 = 0.98 SEE = 4.46

There were three projects constructed by this contractor that used a limestone aggregate. One project had no loss of aggregate or streaking, but 59 percent of the surface area was flushed after two years. This project had the highest ADT and number of trucks of the projects constructed by this contractor. It also had the highest asphalt application rate, with the largest ALD size. The other two projects had no flushing. Three projects exhibited this same level of flushing, with the other two projects using siliceous aggregates.

These three contractors accounted for 54 of the 70 individual projects included in this survey. Of the remaining contractors, two, Davis, and Wyco Construction were the only contractors having enough projects to perform a regression analysis, with 5 and 6 individual projects, respectively. The results for this regression are not as reliable as the regressions containing more projects, and must be interpreted accordingly. Border Construction had only two projects, which are of interest because both were constructed using a limestone aggregate.

Davis Company

There were 5 individual projects for this contractor.

Loss of Aggregate

$$LOAT = -0.02364(ADT) + 1.762(DATECON) + 2107(AALD) - 499.72$$

R^2 = 1.0 SEE = 0.03

Streaking

$$STRKT = 0.09182(ADT) - 0.7881(TRUCKS) + 20.811$$

R^2 = 0.81 SEE = 12.69

Flushing

$$FLUSHT = -11356(AALD) - 2856.7(VOIDSP) - 0.1068(TRUCKS) + 4139.4$$

R^2 = 0.92 SEE = 5.09

Wyco Construction

There were six individual projects for this contractor.

Loss of Aggregate

$$LOAT = 25.641(DALD) - 2.641$$

R^2 = 1.0 SEE = 0.0

Streaking

$$STRKT = 0.45745(DATECON) + 0.0342(TRUCKS) - 23.637$$

R^2 = 0.62 SEE = 12.56

Flushing

A model was not possible with the data.

Border States Paving

With only two projects included in the database, no regression analysis could be performed. These projects are of interest because they were constructed using limestone aggregates from the same source as used in Hills Materials project. These projects had no loss of aggregate, and averaged 22.2 percent streaking, and 10.0 percent flushing (one project with 20 percent). The project with no flushing had a very high ADT and TRUCKS count. The aggregate ALD size was similar to the Hills Materials project, as was the asphalt application rate, and emulsion type.

RANKING OF CONTRACTORS

Using the percent area covered by the distresses, each contractor could be ranked as follows, from highest distress to lowest distress present with the number of projects indicated in parenthesis.

Loss of Aggregate	*Streaking*	*Flushing*
Davis(5)	Bituminous Paving(3)	Bituminous Paving(3)
McLaughlin(22)	Asphalt Surfacing(17)	McLaughlin(22)
Hills Materials(15)	Border States(2)	Border States(2)
Wyco(6)	Davis(5)	Hills Materials(15)
Asphalt Surfacing(17)	McLaughlin(22)	Davis(5)
Bituminous Paving(3)	Wyco(6)	Asphalt Surfacing(17)
Border States(2)	Hills Materials(15)	Wyco(6)

Assuming uniform procedures were followed during construction, this ranking can indicate performance potential. Projects with high loss of aggregate should not develop high levels of flushing, and vice versa. This relationship is seen in the ranking with the exception being shown by McLaughlin & Schultz which had high levels of both distresses.

COMPARATIVE ANALYSIS

The development of regression equations from the total database did not provide a statistically significant relationship between the recorded distresses and the pavement variables. The reason for this can be seen in plots of the distresses as functions of the pavement variables. Figure 13 shows loss of aggregate as a function of several variables. Figure 14 shows streaking as a function of the variables it correlates most closely with. Figure 15 shows flushing as a function of several variables. These plots indicate that there is not a great degree of variability in the data and there is a large number of projects exhibiting no distress with the same level of pavement variables as the other projects.

In all likelihood this small degree of variability comes from the fact that the surface treatments are all rather young, only one and two years old. With an expected life of a surface treatment of 3 to 5 years the variability present in a young pavement will be small. This makes it difficult to separate the degree of influence provided by each individual pavement variable. This is seen in the fact that the analysis of individual contractors provided significantly better predictive models.

MATERIALS

Because the complete database did not indicate significant differences between the contractors, it is informative to examine the variables present for each contractor and compare them to see if there is any significant difference for each contractor. While statistical significance may not apply to this separation, it provides indications of where contractors may be performing their construction activities differently, and where material variability is coming from.

AGGREGATE SUPPLIERS

There are 12 aggregate suppliers, with three suppliers having multiple sources. The important variable for an aggregate in a surface treatment is the variability of the ALD, and the difference between the specified ALD and the ALD produced. The suppliers are shown here with the range in ALD and the percent difference in A:D (specified minus produced divided by specified). The order of ranking is given in parenthesis, with 1 indicating the worst value, and 12 the best. The ranking for ALD difference is based on absolute value as both positive and negative values indicate a potential for problems.

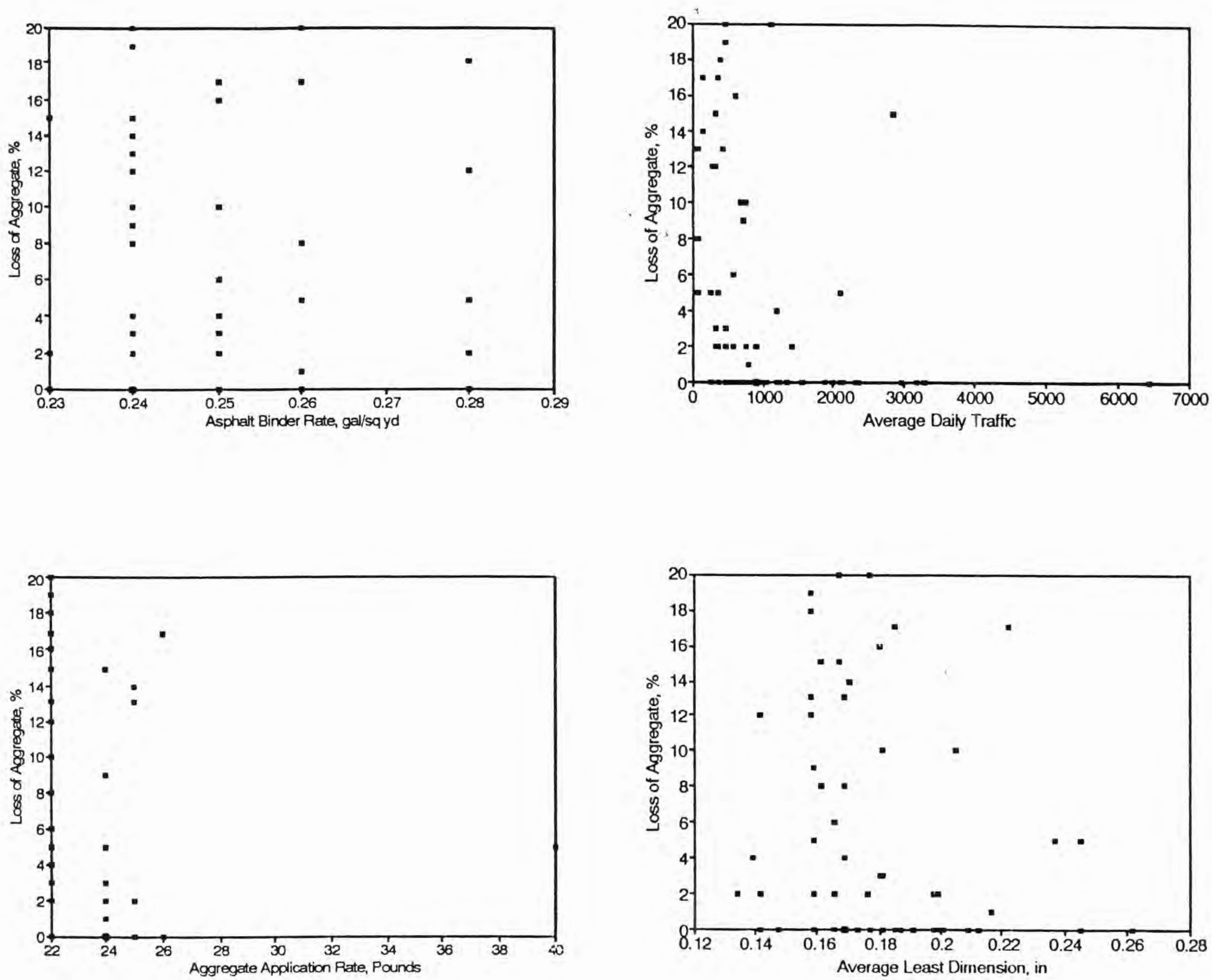

Figure 13. Loss of aggregate as a function of several variables.

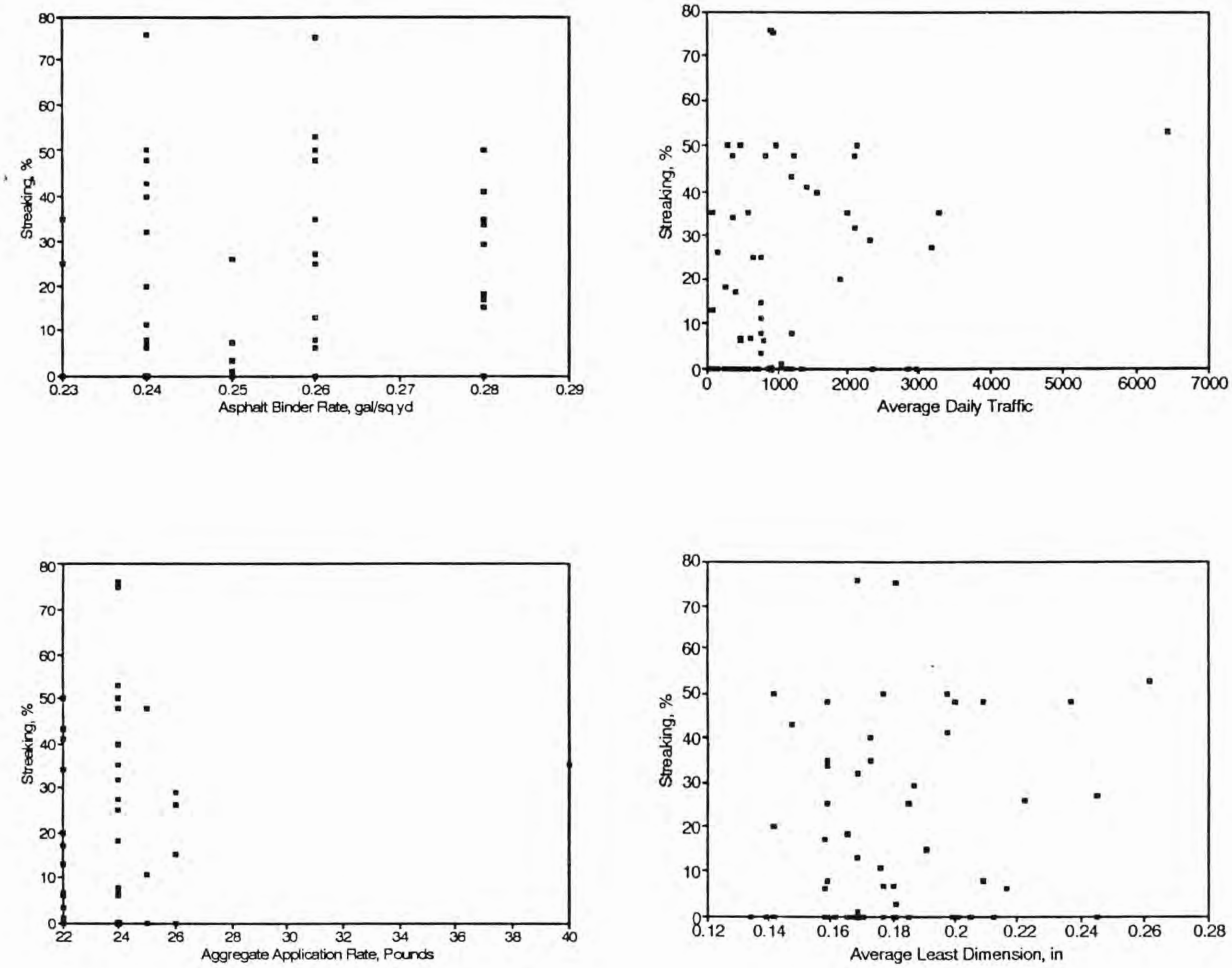

Figure 14. Streaking as a function of several variables.

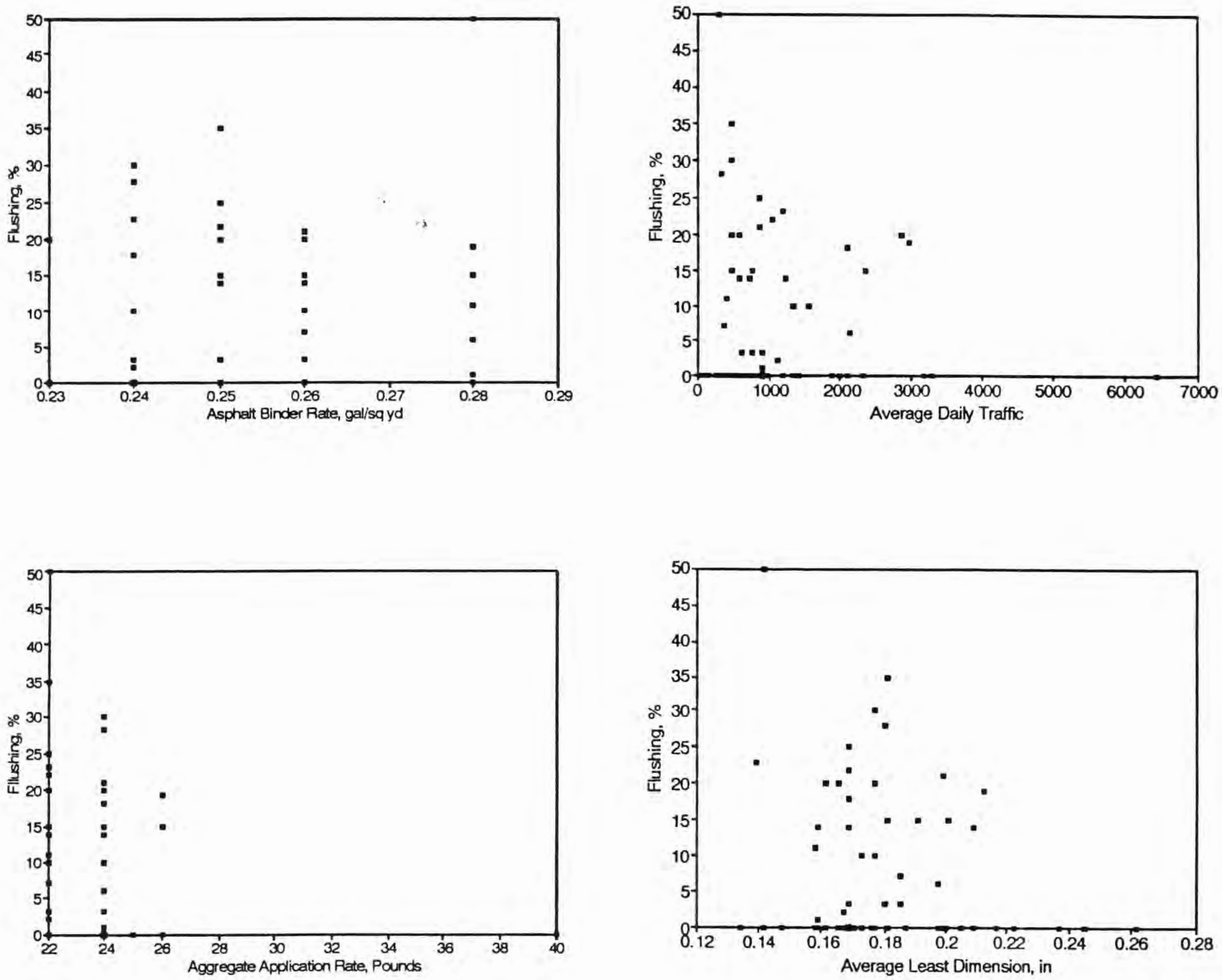

Figure 15. Flushing as a function of several variables.

Supplier	*Projects*	*ALD Dif, %*	*ALD Range*
Fisher	11	-.115 (10)	.022 (4)
Concrete Materials	7	-.076 (11)	.039 (3)
Jensen-Herried	14	+.297 (2)	.014 (6)
Everist	9	-.129 (9)	.014 (8)
ConAgra	5	+.009 (12)	.014 (7)
Birdsall, Blunt	8	+.426 (1)	.088 (10)
Dries	1	-.226 (4)	.051 (2)
Lakeview	2	-.204 (5)	.008 (11)
Thorpe	1	-.296 (3)	0.0 (12)
Local, Huron	4	-.155 (8)	.004 (8)
Const Materials	5	-.187 (7)	.021 (5)
Hills Materials	3	+.188 (6)	.053 (1)

It must be emphasized that some suppliers had only one or two projects in the database, and these comparisons of variability may not apply to their production on all projects. The positive ALD difference indicates that the specified ALD was larger than the ALD actually produced. A positive difference may indicate that the smaller aggregate would be susceptible to flushing, if the design asphalt rate were placed based on the larger aggregate size in the specification. In the above calculation, the largest positive values generally come from the chip seal projects where the specified ALD was 0.287 in, but the actual ALD produced was less. Because asphalt application rates were typically adjusted downward for these projects, there is not a clear connection between ALD difference, and ALD size directly with performance. Thus, performance cannot be inferred from only the ALD size differences, as construction practice differences of each individual contractor will interact with the aggregate material produced to exhibit difference performance. A negative difference in ALD would indicate that the aggregate produced is larger than specified, and could be a candidate for loss of aggregate unless the asphalt application rate were altered accordingly to maintain depth of embedment.

The occurrence of large ranges in the ALD as sampled on the pavement does indicate a material that has the potential to develop problems on the pavement, regardless of the contractor using the aggregate. Large variability means that there will be the potential for areas with small or large aggregates. Given a constant application rate of asphalt over the length of the project, the potential for distresses to develop will be greater. There will be no preference for one distress to develop over the other as loss of aggregate will develop where large aggregates are placed, and flushing will develop where smaller aggregates happen to be placed. There should be a correspondence between total distress and higher variability in aggregate ALD. One supplier had an ALD range greater then 0.04 and the total loss of aggregate and flushing was 29 percent. Three suppliers had an ALD range between 0.02 and 0.04 with an average total distress of 9.2 percent. Five suppliers had an ALD range between 0.0 and 0.02 with an average total distress of 7.8 percent. Three suppliers were not included in these calculations because they had a very limited number of projects (1 and 2). An improvement in aggregate variability can significantly reduce loss of aggregate and flushing, given standard contractor practices.

CONTRACTORS

McLaughlin & Schultz

McLaughlin & Schultz had the most projects in the database, 22. The 7.3 percent loss of aggregate and 11 percent flushing averages placed this contractor in the second worst position in terms of area distressed, and the highest total of both distresses. Streaking distress was in the best third of the grouping in position 5. The aggregate sources for these projects came from 7 different suppliers. The distresses present for each aggregate source are indicated here:

Supplier	*Loss of Aggregate*	*Streaking*	*Flushing*
Jensen, Herried(9)	8.4	1.3	15.6
Everist(2)	0	28	0
Birdsall, Blunt(1)	12	0	0
Dries(1)	17	36	0
Lakeview(1)	0	45	10
Local, Huron(4)	10.5	35.5	16.3
Constr. Mat'ls(4)	3.4	14.8	7

The Jensen and Local sources appear to cause the most widespread problem for this contractor. Streaking seems to be present for all projects which indicates it is not a material problem, but a construction problem. The trend for other aggregate sources appears to support the presence of flushing when loss of aggregate is low, and loss of aggregate when flushing is low. These projects were in zones 1 and 2 with one being in zone 3.

Asphalt Surfacing

There were 17 projects by this contractor with aggregates coming from three sources. The distresses are as follows:

Supplier	*Loss of Aggregate*	*Streaking*	*Flushing*
Fisher(9)	1.22	18.8	12.2
Conc. Mat'l(7)	2.1	38.9	1.6
Everist DR(1)	0	75	0

This contractor ranked in the sixth position with the second least amount of loss of aggregate and flushing, while he was second worst for streaking. The Everist DR aggregate appears to have contributed heavily to the streaking on one project. One project with the Fisher aggregate used an AE 150 emulsion, the remainder all used the CRS-2 emulsion. This project did not develop higher distresses, with the flushing being significantly below the average for the contractor. All of these projects were in zones 2 and 3.

Hills Materials

There were 15 projects by this contractor with aggregates coming from three sources. The distresses are as follows:

Supplier	*Loss of Aggregate*	*Streaking*	*Flushing*
ConAgra(5)	1.2	22.6	4.6
Hills-Wasta(2)	14.5	3	0
Hills Mat'ls RC(1)	0	0	59.0
Birdsall, Blunt(7)	9.67	2.0	20.0

This contractor ranked in the fourth position with average amounts of loss of aggregate and flushing. Projects showing low loss of aggregate had high flushing, and vice versa. The flushing for this contractor was high from one project, the Hills Materials RC aggregate, which was limestone. This project had the highest ADT and truck count. It was specified as a chip seal, but the ALD was only 0.21 in, not significantly higher than the average for Hills Materials aggregate. However, the asphalt application rate was significantly higher than for the other aggregates from Hills Materials, which could have contributed to the flushing. Four of these projects were in zone 3 with the remainder being constructed in zone 2.

Wyco Construction

There were six projects for this contractor. The aggregate was supplied by Everist from three pits. The distresses are as follows:

Supplier	*Loss of Aggregate*	*Streaking*	*Flushing*
Everist Brook(4)	1.0	6.2	0
Everist DR(1)	15	0	20
Everist Orto(1)	0	35	0

This contractor ranked best overall with the least total of loss of aggregate and flushing. The DR aggregate project used a CRS-2 emulsion, while all others used the AE 150 emulsion. These projects were constructed in zone 2.

Davis

There were five projects by this contractor, with the aggregates all coming from Jensen, Herried. The distresses are as follows:

Supplier	*Loss of Aggregate*	*Streaking*	*Flushing*
Jensen, Herried	9.0	17.0	8.8

This contractor ranked second worst with loss of aggregate and flushing. The ranking of this contractor with ALD range is confusing because there were no field data available to establish field variability. It is obvious that this contractor and aggregate will produce higher distresses than others. One project exhibiting the bulk of the distress was constructed very late in the construction season, near the first week of September, with 2 of the remaining 4 projects also being constructed in this time period. This would indicate that time of construction did not play an important role.

Bituminous Paving

There were three projects for this contractor, all supplied by a different aggregate supplier. The distresses are as follows:

Supplier	*Loss of Aggregate*	*Streaking*	*Flushing*
Constr. Mat'ls	0	76	3
Lakeview	0	32	18
Thorpe	0	7	30

This contractor had no loss of aggregate, but had the highest amounts of distress for streaking and flushing. This may indicate equipment problems during construction. This is especially suspected in the project with Construction Materials aggregate, as these distress levels are significantly higher than those for other contractors using this aggregate. The Thorpe and Lakeview aggregates were not used by enough contractors to make a comparison.

MISMATCHED MATERIALS

The importance of matching emulsion type and aggregate type was discussed earlier. The use of a cationic emulsion with a limestone and an anionic emulsion with a siliceous aggregate can cause problems if construction is not carefully monitored, and the different characteristics of setting and curing with each combination are not taken into consideration.

The limestone aggregate projects (5) were all constructed with the AE 150 emulsion, which is anionic. This aggregate-emulsion combination is compatible and should not cause construction concerns. One project exhibited excessive flushing, another exhibited excessive streaking, while none exhibited loss of aggregate beyond average.

Of the 53 projects constructed with an anionic emulsion, 48 were siliceous aggregates. The recommended combination would be the siliceous aggregate with a cationic emulsion, which was used in 17 projects. The 17 projects using the CRS-2 emulsion had lower loss of aggregate, and lower flushing. The streaking was significantly higher with this combination. No limestone aggregates were used with the CRS-2 emulsion for comparison. The data for this separation will be shown in a later section.

ASPHALT SUPPLIER

The asphalt emulsion supplier can impact the performance of a surface treatment if the residual asphalt in the emulsion varies from one supplier to another and no account is provided for in the design procedure. There were five asphalt suppliers included in the 70 projects. They are:

- Jebro
- Koch, MN
- Cenex
- Hills Materials
- Koch, ND

Jebro supplied all of Asphalt Surfacing projects, a total of 17. Koch, ND supplied Mclaughlin & Schultz, and Wyco projects, 13 and 6, respectively. Cenex supplied McLaughlin & Schultz, Bituminous Paving, and Border States projects, 9, 3, and 2, respectively. Hills Materials supplied all of Hills Materials projects, for a total of 15. Koch, ND supplied all of Davis Co. projects, for a total of 5. The contractors, Asphalt Surfacing and Hills Materials did very well using their single source of material. Bituminous Paving, Davis Co., and McLaughlin & Schultz were at the low end of the performance ranking using their asphalt. Wyco did best, using the same asphalt as McLaughlin & Schultz,

A comparison of the McLaughlin & Schultz projects which used both Koch MN, and Cenex shows a difference in projects between the two sources. The Koch ND projects demonstrated slightly more loss of aggregate, significantly more streaking, and significantly less flushing. This may indicate that the Cenex emulsion could have a slightly higher residual asphalt which will result in more asphalt being placed which would produce a surface treatment with a potential for flushing. The relative differences are such that the Koch ND material and the McLaughlin & Schultz construction techniques would be in the best group, while the Cenex emulsion in combination with the same construction procedures would be in the worst group.

EXCESSIVELY DISTRESSED PROJECTS

While none of the projects could be considered to have failed, as they are carrying daily traffic in a safe manner, there are several projects which have areas of distress which represent the maximum that can develop. For flushing, this is a 50 percent coverage. For loss of aggregate, this is larger, but 50 percent represents the area of the wheel paths. Four projects had flushing on 50 percent of the pavement, (1-Asphalt Surfacing, 2-McLaughlin & Schultz, and 1-Hills Materials), while no projects had loss of aggregate exceeding 50 percent coverage. Ten projects had streaking exceeding 50 percent coverage, (5-Asphalt Surfacing, 4-McLaughlin & Schultz, and 1-Hills Materials).

Another way to examine any potential differences is to separate the data into two parts, one containing the projects with distress, and one containing projects with no distress. The means of the individual project variables can be compared to determine if there are any differences between the two files. This comparison on the means can be performed using the t-test.

Loss of Aggregate

Table 9 contains the means and standard deviations for the pavement variables separated into sections containing projects with no loss of aggregate, and the projects which had a loss of aggregate. The differences which show up most clearly here are the average daily traffic (ADT) and number of trucks, which are higher for the sections with no loss of aggregate, indicating better embedment of the aggregate with the higher traffic. While the design ALD was higher for the projects with loss of aggregate, the actual aggregate used on the projects had an actual ALD that was smaller for projects with loss of aggregate. The difference in ALD between the two sets of projects is very small, and the application rate for the asphalt were very similar. Again, there could be no statistical significance placed on these differences. Only the presence of the trend can be noted.

Streaking

Table 10 contains the means and standard deviations for the pavement variables separated into sections containing projects with no streaking, and projects which had streaking. The streaking data showed less direct relationships with the construction variables, as might be expected. The traffic values are higher for the projects with streaking present, indicating that deeper embedment produced by more traffic tends to highlight the presence of asphalt binder more than when low traffic is present. The application rate of the aggregate was higher on projects developing streaking, but higher traffic levels may remove more aggregate at time of placement on these projects.

Table 9. Means and standard deviations for projects separated on loss of aggregate.

Pavement Variable	Loss of Aggregate Present		No Loss of Aggregate Present	
	Average	Std. Dev.	Average	Std. Dev.
Emulsion Type	0.86	0.35	0.65	0.49
Design Aggregate Application Rate	23.36	3.10	23.68	1.17
Aggregate Type	1.64	0.49	1.62	0.49
Design ALD	0.21	0.068	0.18	0.051
Actual ALD	0.17	0.0256	0.18	0.0260
Range in ALD	0.0190	0.0226	0.0179	0.0230
Age	1.42	0.50	1.50	0.51
ADT	631.9	572.4	1453.9	1193.3
Trucks	76.75	61.61	183.71	136.33
Actual Asphalt Application Rate	0.25	0.0149	0.25	0.0158
Zone	1.9	0.78	2.0	0.79
Asphalt Filled Voids	0.26	0.0365	0.25	0.0300
Percent Voids Filled	0.88	0.14	0.86	0.098
Design Asphalt Application Rate	0.25	0.025	0.26	0.0136
	N = 36		N = 34	

Table 10. Means and standard deviations for projects separated on streaking.

Pavement Variable	Streaking Present		Streaking Not Present	
	Average	Std. Dev.	Average	Std. Dev.
Emulsion Type	0.69	0.47	0.84	0.37
Design Aggregate Application Rate	23.95	2.91	22.97	1.22
Aggregate Type	1.56	0.502	1.71	0.461
Design ALD	0.180	0.0495	0.22	0.067
Actual ALD	0.180	0.0282	0.174	0.0225
Range in ALD	0.017	0.0213	0.0200	0.0245
Age	1.54	0.51	1.35	0.486
ADT	1199.7	1166.7	819.1	731.2
Trucks	148.6	132.9	103.7	89.49
Actual Asphalt Application Rate	0.256	0.0162	0.247	0.0129
Zone	1.9	0.78	1.9	0.81
Asphalt Filled Voids	0.27	0.0376	0.25	0.0279
Percent Voids Filled	0.88	0.137	0.86	0.102
Design Asphalt Application Rate	0.26	0.0241	0.25	0.0137
	N = 39		N = 31	

Flushing

Table 11 contains the means and standard deviations for the pavement variables separated into sections containing projects with no flushing, and the projects which had flushing. This data showed the least degree of variability with only marginally higher asphalt application rates and smaller ALD values being present on the projects that developed flushing.

Table 11. Means and Standard Deviations for Projects Separated on Flushing.

Pavement Variable	Flushing Present		No Flushing Present	
	Average	Std. Dev.	Average	Std. Dev.
Emulsion Type	0.724	0.455	0.780	0.419
Design Aggregate Application Rate	23.17	1.256	23.76	2.888
Aggregate Type	1.72	0.455	1.56	0.502
Design ALD	0.210	0.0629	0.192	0.060
Actual ALD	0.176	0.0175	0.178	0.0306
Range in ALD	0.0190	0.0244	0.0181	0.0217
Age	1.52	0.509	1.415	0.499
ADT	1066.8	744.0	1005.9	1169.5
Trucks	145.07	105.29	117.12	124.75
Actual Asphalt Application Rate	0.256	0.0150	0.249	0.0152
Zone	1.9	0.86	2.00	0.74
Asphalt Filled Voids		0.0289		
Percent Voids Filled	0.86	0.0606	0.88	0.147
Design Asphalt Application Rate	0.25	0.0148	0.26	0.0241
	N = 29		N = 41	

COMPONENT ANALYSIS

The data presentation comparing variables on projects with and without distress does not provide the ability to show the effects of variables such as emulsion type or aggregate type which were discrete variables, usually 0 or 1 depending on the material being used. The climate zone effect also could not be seen in the averages presented. To more clearly illustrate any effect produced in performance by these variables, the data was separated to provide means on the distresses developing with each component.

Emulsion Type

There were two general types of emulsions used, a cationic CRS-2, and an anionic AE 150S. The distress data for each emulsion is given in Table 12. The AE 150S emulsion produced more loss of aggregate and slightly more flushing, but significantly less streaking than the CRS-2. It is interesting to note that the CRS-2 emulsion was used only with aggregate type 2, while the AE 150S was used with both types of aggregate. The AE 150S emulsions are further broken down in Table 13 which shows the performance of this emulsion with the two aggregate types. Aggregate type 2 showed more loss of aggregate, while aggregate type 1 showed considerably more streaking with the AE 150S emulsion. The presence of flushing was similar for both aggregate types. It must be noted that one project was constructed with an AE 200 emulsion, which was included in the general AE classification. This one project, while being designed very differently from the others, was not constructed with different properties, and did not develop distresses above average.

Climatic Zone

The state was divided into three climatic zones as described earlier. The distresses developing in each zone are shown in Table 14. The general trends evident here show that loss of aggregate and flushing decreased from zone 1 to 2 to 3, while streaking increased from zone 1 to 2 to 3. It is interesting to note that construction procedures also varied by climatic zone. This data is shown in Table 15. Zone 3 used only the type 2 aggregate, with a predominance of the CRS-2 emulsion. Zone 1 used only the AE 150 emulsion with both aggregate types. Zone 3 had the highest traffic, with zone 1 being lowest. Zone 3 had higher application rates of asphalt binder and aggregate, reflecting the higher levels of traffic and a larger aggregate size as shown by the ALD values from the field. This data fits in with the previous observations regarding distress appearances in each zone. Flushing and loss of aggregate would be expected to be lower in zone 3. Higher streaking in zone 3 may be attributable to the use of only one aggregate type, although it once again must be stressed that no statistical separation could be made from the data collected.

Table 12. Variation in distresses as a function of emulsion type.

Pavement Variable	AE 150 S		CRS 2	
	Mean	Std. Dev.	Mean	Std. Dev.
Loss of Aggregate Low Sev	5.53	6.67	1.65	3.82
Loss of Aggregate Med Sev	0.264	1.095	0.471	1.94
Loss of Aggregate High Sev	0.255	0.959	0.0	0.0
Streaking Low Sev	14.53	19.62	25.18	23.71
Streaking Med Sev	0.415	1.67	1.88	4.58
Streaking High Sev	0.321	2.34	1.24	3.60
Flushing Low Sev	7.17	11.47	5.53	7.84
Flushing Med Sev	1.87	6.25	2.44	8.48
Flushing High Sev	0.604	2.23	0.041	0.128
	N=53		N=17	

Table 13. Variation in distresses for the AE 150S emulsion separated by aggregate type.

Pavement Variable	Aggregate Type 1		Aggregate Type 2	
	Average	Std. Dev.	Average	Std. Dev.
Loss of Aggregate Low Sev	3.38	5.24	7.59	7.32
Loss of Aggregate Med Sev	0.38	1.36	0.148	0.770
Loss of Aggregate High Sev	0.038	0.20	0.46	1.31
Streaking Low Sev	22.50	22.19	6.85	13.10
Streaking Med Sev	0.191	0.981	0.630	2.13
Streaking High Sev	0.00	0.00	0.630	3.27
Flushing Low Sev	6.65	12.83	7.67	10.22
Flushing Med Sev	0.00	0.00	3.67	8.45
Flushing High Sev	0.154	0.785	1.037	2.99
	N=26		N=27	

Table 14. Variations in distress for the climatic zones used in the analysis.

Pavement Distress	Climate Zone 1		Climate Zone 2		Climate Zone 3	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
Loss of Aggregate Low Sev	5.35	.603	4.63	.523	3.65	5.83
Loss of Aggregate Med sev	0.22	1.04	0.19	.96	0.60	1.96
Loss of Aggregate High sev	0.30	1.26	.074	0.38	0.23	.70
Streaking Low sev	14.87	21.36	16.85	18.75	20.05	24.06
Streaking Med sev	0.96	2.46	0.37	0.19	1.55	4.27
Streaking High sev	0.00	0.00	0.63	.27	1.05	3.33
Flushing Low sev	9.43	11.78	6.00	11.66	4.75	7.32
Flushing Med sev	1.00	3.64	1.15	3.06	4.33	11.48
Flushing High sev	0.83	3.05	0.41	1.37	0.14	0.45
	N=23		N=27		N=20	

Table 15. Variation in construction procedures for the climatic zones used in the analysis.

Variable	Climate Zone 1		Climate Zone 2		Climate Zone 3	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
DRAC	0.254	0.015	0.25	0.0126	0.27	0.029
ETYPE	1.00	0.00	0.889	0.320	0.30	0.470
DRAGG	23.39	1.469	22.89	1.155	24.500	3.777
AGTYPE	1.565	0.507	1.407	0.501	2.00	0.00
DALD	0.215	0.072	0.185	0.0628	0.202	0.0435
AALD	0.177	0.0132	0.167	0.0247	0.192	0.0315
RALD	0.0168	0.0187	0.0144	0.0199	0.0258	0.0288
AGE	1.435	0.507	1.519	0.509	1.400	0.503
ADT	776.4	98.8	1058.5	866.5	1287.1	1451.6
TRUCKS	102.9	75.9	128.7	109.8	158.5	157.8
ACRATE	0.249	.0101	0.250	.0186	.260	0.0298
ZONE	1.00	0.0	2.00	0.0	3.0	0.0
VOIDSA	0.25	0.0171	0.270	0.0373	0.244	0.0367
VOIDSP	0.853	0.0748	0.900	0.110	0.849	0.170
	N=23		N=27		N=20	

SUMMARY

The analyses presented in this chapter illustrate how the different design factors, contractors, and materials can impact performance of a surface treatment. While the statistics did not allow for a complete separation of these factors to support specific statements regarding construction or design, the comparisons do indicate areas where improvements may be found.

There appears to be discrepancies between the type of surface treatment called for in the specifications, and the surface treatment actually constructed. If the specified surface treatment is being applied for a particular problem on the old pavement, and the treatment is changed from a chip seal to a sand seal, this may produce different performance in the surface treatment compared to when the same treatment is applied to a different pavement. This should be investigated to determine why the changes were made.

The gradations produced by the aggregate suppliers meet the specification. However, there is a significant difference between the specification ALD, and the ALD produced. This can have an impact on the appropriate surface treatment asphalt and aggregate application rates, and emphasizes the importance of using actual production data as a final check on the design values which are based on specification values. If these changes are not made, significant problems can result. These problems result in the flushing or loss of aggregate that was observed on these projects. The general type of surface treatment, chip versus sand, as specified, showed that the gradation 1 aggregate produced significantly more streaking, and flushing, and less loss of aggregate. This would indicate that the sand seals were performing their function better than the chip seals except that they may have more construction control problems as indicated by the higher streaking.

The asphalt emulsion type, and the match with aggregate can be important factors during construction. The CRS-2 and the AE 150S showed slight differences, with the CRS-2 showing less loss of aggregate and flushing, but more streaking. These distresses are typically more influenced by variability in application rates and techniques rather than by emulsion type.

The composition of the surface treatments was surprisingly well balanced given the drastic differences between specification and construction values. The void quantities and asphalt amounts did enter into the individual contractor's models of distress. Care must be exercised in interpreting the impact of these composition variables in the models as some anomalous behavior is predicted, such as increased asphalt rate producing more loss of aggregate or less flushing, which is not expected. These models do not provide the complete picture of the interaction of aggregate size with asphalt rate which produces these discrepancies.

The analysis of the individual contractors did provide an indication that different contractors could produce different performing surface treatments. The ranking from worst to best provided a statistical difference, but the intermediate contractors could not be separated from each other.

The effect of climatic zone was very subtle, and complicated by the use of specific materials in several of the zones. Zone 3, the southernmost had the highest rate of streaking to go along with the highest variability on ALD measurements. Zone 3 developed similar flushing to Zone 1, but significantly more medium severity levels, which may reflect the higher ADT in this area and the highest asphalt application rates.

This analysis did provide indications of material interactions for each contractor, but it did not show any dramatic failures related to specific materials or suppliers or contractors.

Predictive models were developed for each contractor, but could not be developed for the database as a whole. These equations should not be used to predict behavior of a surface treatment beyond an age of two years, since there was no data available for higher ages. Before life-cycle predictions can be made, data must be included that will demonstrate the effects of aging and weathering. These factors were explicitly eliminated from this data set.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

INTRODUCTION

The stated goals of this investigation covered several general areas, including:

- Determine the extent of the problem of poor performing surface treatments in South Dakota.
- Identify factors which affect surface treatment performance.
- Develop recommendations for materials and construction methods that will result in improved surface treatment performance.
- Develop criteria for an objective and repeatable procedure for evaluating current condition of surface treatments.
- Develop rational, scientific means of predicting the future performance of surface treatments.
- Develop a comprehensive design procedure for future surface treatment projects.

EXTENT OF PROBLEM

The extent of any problem in South Dakota with the surface treatments cannot be definitively stated based on the results of these 70 projects. Their age was too short to make such an observation with any validity. The projects surveyed did not show an inordinate amount of distress. Less than 10 percent of the projects had developed distress levels high enough to question their performance. This amount, after 2 years, would not be unreasonable for an application that traditionally had a service life of only 5 or so years.

SURVEY

The pavement survey procedure developed by the Ontario Ministry of Transportation was selected for use in this project. It provides a complete survey procedure that in the long term could be used for a complete evaluation of total pavement performance. The specific survey elements that provide data most relevant to evaluating performance of the surface treatment were used on the projects in South Dakota. The survey did not include several of the data elements which relate to pavement structure or ride quality, items which a surface treatment cannot influence.

This survey procedure, with the exception of the rideability determination, was applied to the 70 projects (23 contracts). The surveys were conducted rapidly and the collection of data was simple and straightforward after the first several projects were completed. The surveys themselves can be conducted by trained laboratory technicians or engineering students hired for the summer. The only way to improve design or construction is through the use of longterm performance data. It is recommended that this survey procedure be implemented toward this end.

It is recommended that this survey be repeated in the Summer of 1993. This would provide ages of 3 and 4 years to supplement the 1 and 2 year old data collected in 1991. This would provide a time-sequence of data for the projects which would provide a much better indication of how the distress is developing on each project and would correlate much better with the pavement variables. This survey could be performed by South Dakota personnel and the information could be added to the database provided with this study. The inclusion of this data would greatly increase the validity of the comparisons and trends presented in this study.

FACTORS INFLUENCING PERFORMANCE

The data collected for these 70 projects did not provide for a detailed statistical analysis. The spread in data was concentrated with typically half of the projects showing no distress. This lack of differentiation in the data most likely results from the extremely young age of the surface treatments, one and two years. More time and exposure to traffic and climate might be required to develop significant distress levels that would indicate differences in performance on the different pavements. Since these seals do go some 5 or more years between sealing projects it could require 4 years to develop significantly different distresses that could indicate which pavements actually were performing better than others. Without this differentiation, a statistical separation of the data becomes impossible.

This lack of statistically supported variability in the data was seen in the analysis of the data collected. The regression analysis and the examination of data differences for classes of variables clearly showed that trends were visible in the data. These trends generally followed the expected relationships discussed in the general design philosophy section, but the level of distress developing was generally too low to allow statistical significance to be associated with the trends. The trends suggest areas where problems might be expected to develop, and areas where improved long-term performance may be achieved, but it would take more data of a significantly longer age to substantiate these differences.

Aggregate gradation control should be evaluated to determine if the variability found in these projects is typical. While this degree of variability may not be significant for an aggregate in general, a surface treatment aggregate is not a general aggregate, and designs can change dramatically for gradation variability seen in the field. The proportions in the surface treatments were generally in the correct range, matching aggregate size and asphalt application rate. Mismatched materials did not stand out as significantly different. This indicates that construction activities were sufficiently tuned to the material differences to obtain good construction.

The different contractors produced very different performance characteristics that could be ranked with a significant difference between best and worst. The intermediate rankings could not be differentiated from one another. The differences between each contractor were detailed in the models developed for each distress. No one factor stood out as creating problems for all surface treatments.

CONSTRUCTION RECOMMENDATIONS

The three principle distresses noted were streaking, flushing, and loss of cover aggregate. The common causes of these distresses are discussed below. Streaking is caused by on or more of the following:

- Haphazard rotation of the spray nozzle in the spray bar, so that the spray nozzles discharge on different widths of the road surface.
- Improper height of the spray bar above the road surface.
- Spraying the asphalt binder at too low a temperature so that it cannot fan out properly from the spray nozzles.
- Controlling the quantity of asphalt binder to be applied per square yard by changing the number of gallons per minute discharged from each nozzle, instead of keeping this constant and changing only the forward speed of the truck.
- Partly or completely plugged spray nozzles.

Flushing may be caused by:

- The application of too much binder.
- Insufficient cover aggregate or non uniform application of cover aggregate.
- Excess asphalt on existing surface.

Loss of cover aggregate may result from one or more of the following reasons:

- Late application of aggregate.
- The grade of asphalt is too hard to develop good adhesion between binder and aggregate.
- Cover aggregate is too dusty, dirty, or wet to develop good adhesion to the binder.
- Traffic on the job too soon after completion tearing and throwing off much of the cover stone.
- Rain within a few hours after construction combined with traffic.
- Not enough binder is applied to cement the aggregate into place or a portion of the asphalt binder is lost by absorption into the surface to which it is applied.

These distresses are easily eliminated or controlled with the application of proper construction procedures and design principles. The construction related causes may be addressed through a comprehensive construction specification. The SDDOT surface treatment specification covers the materials, procedures and construction limitations required for constructing an asphalt surface treatment.

The SDDOT construction sequence for surface treatments is generally adequate. The major area which indicates the potential for problems to develop is in the delay between emulsion application and aggregate application as witnessed on the construction project visited by the project personnel. With older chip spreaders a delay may be necessary to allow the emulsion to gain some adhesive properties before the aggregate is applied. Older spreaders tend to drop the aggregate at angles and the aggregate will hit the emulsion, bounce, and roll over. This removes the emulsion from the pavement surface, reducing the binder available to hold the aggregate to the road. New spreaders have a vertical drop and are not prone to this phenomenon. Proper rolling with pneumatic tired rollers should not turn the aggregate either.

This waiting period requires very careful evaluation and timing. When done properly the resulting quality of the surface treatment should not be adversely affected. However, waiting too long will result in loss of aggregate and a flushing surface. This wait does provide one benefit in that the time the traffic must stay off the surface treatment is reduced. Traffic on an emulsion surface treatment that has not set will turn and pull the aggregate out of the emulsion, rather than seating the aggregate further into the asphalt. When the aggregate is placed immediately before the emulsion sets or breaks, the surface treatment will be set and ready for traffic in a shorter time than if the aggregate is placed immediately behind the asphalt binder.

Another area of concern may be the amount of fines in the aggregate. The aggregate gradation specification allows as much as 4 to 5 percent minus #200 sieve material. Many of the projects evaluated had greater than 1 percent passing the #200 sieve (of the 34 projects which had this information, 18 projects had between 1 and 2 percent, 3 project had between 2 and 3 percent, and 3 projects had more than 3 percent passing the # 200 sieve). A maximum of 1 percent passing the #200 sieve is recommended.[4]

Weather and seasonal limitations require that the surface treatment be constructed between June 1 and September 15, the air and surface temperature must be a minimum of 70 °F in the shade, and the conditions be dry. Of the projects surveyed, only one project was constructed significantly out of season. The temperature and humidity requirements could not be checked. In general, late season construction did not guarantee any significant increase in problems.

Traffic too soon after construction may also be a factor, but without further data in this area, no changes can be recommended.

QUALITY CONTROL RECOMMENDATIONS

Quality control appears to be satisfactory in general. If the performance of these surface treatments is to be evaluated and improved in a systematic manner, there must be a systematic procedure for determining application rates in the field. The determination of application rates at several points during a project will provide an indication of how precise the applications are, and provide an indication of variability within the project. This degree of variability may be more significant than the actual amount, but it could not be determined from existing data.

Streaking , as described above, is generally a result of poor construction technique. Proper inspection and calibration prior to beginning a job could decrease the amount of streaking on surface treatment projects significantly.

References 5, 6 and 7 may provide suitable training aids for the field inspections. Reference 6 explains the purposes of surface treatments, how they are constructed and the factors which can affect obtaining consistently good surface treatments. Some of the factors discussed are weather, the existing road surface, the type of asphalt used, the handling and storage of the asphalt, the choice of cover rock, how to control the uniform distribution and application of the asphalt and aggregate, the coordination of the seal coat operation, and the post-construction inspection and possible immediate corrective action. This manual is concise but detailed in the appropriate areas with a liberal use of graphics. References 5 and 7 contain much of the information and in addition provide inspection checklists.

DESIGN PROCEDURE RECOMMENDATIONS

The current design procedure used by the South Dakota Department of Transportation appears to provide good starting asphalt and aggregate spread rates which are then adjusted in the field to suit local conditions. The current procedure does not allow for the use of materials significantly different from those in the specifications, a serious deficiency. The field data indicates that significant differences can develop in the aggregate median size and the condition of the existing pavement. To make appropriate field adjustments, requires considerable knowledge of surface treatment design, construction principles, and field experience. Currently, the guidance available for the field inspection and changes is minimal.

A more comprehensive design procedure such as the ones presented in this report will provide asphalt and aggregate application rates not significantly different from those currently being used. The new design procedure should provide the means for assessing the impact of different circumstances developing on the project such as gradation variability, surface characteristics, traffic variability, and even climate. A more comprehensive design procedure does not necessarily guarantee a better surface treatment, but it provides a consistent means of comparison of requirements for different pavement situations. The field engineer is still required to make adjustments to the design based on local experience and conditions.

Of the three comprehensive design procedures presented, the Asphalt Institute method would be most adaptable to the local conditions. The Pennsylvania method is very simple to use and was developed for environmental conditions somewhat suitable for South Dakota. The Texas method is the most comprehensive procedure with extensive field calibration. However, the climatic conditions under which these calibrations were developed are unlike those of South Dakota. The Asphalt Institute method would allow the development of "multiplying factors" suitable for South Dakota pavements and climatic conditions.

It is highly recommended that a comprehensive design procedure be implemented if improved surface treatments are desired, and if the survey procedures are to be continued to ascertain the exact degree of performance obtained in surface treatments over their useful life. The survey data here did not establish a useful service life upon which economic comparisons can be made.

MATERIAL SELECTIONS

The material selection for these surface treatments did not appear to pose any particular problems. The limited use of limestone aggregates did not support any unique problems that were not seen on projects using siliceous aggregates. One of the three limestone projects did have unacceptably high distresses, but this is a very limited comparison. The mis-matching of emulsion type and aggregate type can create problems if construction does not adequately adjust to it. It appears that these adjustments were made as there is little difference between the combinations.

ECONOMIC IMPLICATIONS

Surface treatments have long been used as cost-effective maintenance strategies. When properly designed and constructed, a single layer surface treatment can be expected to perform 5 to 7 years. However, improper design or construction may lead to early failures.

The cost of designing and constructing a "good" surface treatment is generally no more than the cost of constructing a "bad" surface treatment. What is required is sound knowledge of the principles involved. Many of the problems observed on the projects evaluated could easily be reduced or avoided if the construction specifications were more thoroughly followed and minor modifications are made to the design procedure. The cost of properly designing the surface treatment is minimal. Initially, there may be some cost involved in familiarizing the engineers with the new design procedures. Subsequently, there may be additional work required in monitoring the existing pavements to determine their surface condition, and establishing the proper aggregate variables needed for design prior to constructing the surface treatment. The cost for construction should remain unchanged, as no new materials or equipment are suggested. Slightly more time may be required if inspection and calibration are performed more frequently.

Given that the average age of these projects between surface treatments was seven years, it is not known what increase in life can be provided by the extra quality control measures that would be necessary. At present the economics would not appear to favor a large expenditure to improve quality control.

REFERENCES

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6. Field Manual on Design and Construction of Seal Coats, Texas Transportation Institute, Research Report 214-25, July 1981.

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8. Standard Specification for Roads and Bridges, South Dakota Department of Transportation, 1990.

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10. Wyckoff, C. P., "Asphalt Seal Coats - Factors Affecting and Techniques for Obtaining Consistently Good Seal Coats," Final Report.

11. Seal Coat Handbook, DHT-13, Departmental Information Exchange, (Texas) State Department of Highways and Public Transportation.

APPENDIX A

ANNOTATED BIBLIOGRAPHY

Adams, C. K., "Multiple Seal Coat Design and Construction."

The objective of this study is to identify when a multiple seal coat is a cost-effective alternative to a single seal coat or asphalt concrete construction. Also under this study, a design guideline will be developed for double and triple coats.

Anderson, D., and P. Sebaaly, "Design, Construction, and Performance of Bituminous Seal Coats."

The primary objective of this study is to evaluate the performance of seal coats constructed using various procedures and materials. The major variables to be investigated are existing pavement surface condition, asphalt emulsion application rate, compaction procedures, and control of application rate, compaction procedures, and control of traffic. The experimental design calls for the installment of 24 different test sections at the one-mile Pennsylvania Transportation Institute test track. Test sections will also be installed on selected roadways near the test track to permit comparison of results.

Ball, G., "Developments in Adhesion Agent Testing in New Zealand," New Zealand Roading Symposium, 1987. Vol. 2, National Roads Board, New Zealand, P.O. Box 12-041, Wellington, New Zealand 0-477-07156-2, 1987 pp. 239-247.

This paper reviews the adhesion agent testing that has been carried out in New Zealand over the past four years, and provides sample results to illustrate a number of general trends that have been noted for agent/aggregate adhesions. Given an aggregate, it has proved generally possible for some agent to be found that would satisfy the NRB standard requirements of 80% adhesion, but in some cases the dosages required have been quite high. The evolution of the NRB standard, M/13, as knowledge of agent behavior increased is described. Methods to obtain quantities and types of adhesion agents in chip seal binders have been devised and used to investigate the effect of heat on adhesion agents and to examine material from stripped seals. Results from these seals suggest that absence or deterioration of agent in binders could be a contributing factor in a high proportion of stripping failures. Current and planned laboratory investigations are described; in particular it is hope to elucidate the effect of heat on agents in binders. It is suggested that a carefully

planned series of sealing trials be undertaken to correlate road performance with laboratory test results.

Ballew, J. W., "An Evaluation of the Performance of Contract-Applied Seal Coats," Final Report.

This experimental project examines and evaluates the service lives of contract-applied seal coats versus the lives of seal coats placed by PennDOT's maintenance forces. A total of 80 projects were selected and evaluated in 8 different maintenance districts involving 7 different contractors. All of the work was placed during late summer and the early fall of 1979. Research Project 79-14 documented that seal coats failed due to a number of factors that are detailed in this report. Consequently, Project 79-14 is being closed in favor of the Research Project No. 83-14, "Improved Utilization of Surface Treatments," that is being conducted by the Bureau of Construction and Materials. Project 83-14 is a more thorough examination of seal coats and the possible changes that may be needed.

Beaird, J.L., "Experience of District 11 in the use of Plant Mix Seal Courses," Texas State Department of Highways & Public Transportation, February 1972.

A test program was devised to combat the problem of slick pavements. Prior research and experience in western states had indicated that plant mix seal, a type of open-graded asphaltic concrete surface, provided the pavement structure a durable, uniform, skid-resistant surface that was open-textured and, hence, reduced the hydroplaning potential. The aggregates tested were trap rock, sandstone, and lightweight aggregate. Two separate procedures were used to determine the amount of asphalt for the three materials. Plant operations, including testing and inspection, are described. Before the plant mix seal was placed on the roadway, a cutback asphalt was used, in various application rates, to tack the surface. It was not possible within the test period to evaluate its effect, but there appeared to be no significant difference in placing the mixture with or without tack. The other laydown operations, including the problems encountered, are described in detail. Skid values determined on the test surface immediately after completion and after opening to traffic fell into a range from 0.28 to 0.39. The seal provided a smooth riding surface without any noticeable changes in noise levels for the various aggregate sizes. No ravelling or flushing has been observed to date. The seal provided an adequate void system that permits rain water to travel through the mix rather than sheet across the surface, which tends to alleviate the problem of hydroplaning.

Crants, B., "Emulsified Asphalt Seal Coats Montana's Experience," Montana Depatment of Transportation.

There has never been much of a problem putting a seal coat on an asphalt pavement roadway. A liquid asphalt of reasonable viscosity, an adequate asphalt distributor, and somewhat favorable weather conditions are usually about all competent technicians need to provide a seal coat for an asphaltic concrete road. Montana has never had a seal coat fail.

But, intelligent taxpayers and thoughtful engineers require more than just a seal coat which will extend the life of a pavement for a good many more years. They want more than just to seal surface voids, to prevent moisture intrusion, to block aging from solar exposure; and to provide numerous other benefits.

If the surface of the roadway is so slick it can't be driven on when damp or frosted, if the road is so black that headlights seem to end at the hood ornament, if it has no cover aggregate and is consequently dangerous, no one cares if the pavement life is extended. Montana has never had a seal coat fail--but as recently as 1982, we experienced 75% cover material failures in a season. These failures were chip loss-some lost off the roadway, some lost in a sea of asphalt on the roadway.

We had to do something! We did do something. We didn't come up with all the answers; we probably didn't even ask all the questions. But we improved the success ratio to the point that last year, when chip losses were investigated by a task force, the chip loss was estimated to be near 5 percent on all projects reviewed.

Collins, J.H., and W.J. Mikols, "Block Copolymer Modification of Asphalt Intended for Surface Dressing Applications," Proceedings, Association of Asphalt Paving Technologists, Volume 54, 1985, pp. 1-17.

This article, and the discussion that follows, discusses the modification of asphalt binders by the addition of thermoplastic block copolymers. The polymers included in the study were SBS, SIS, and SEBS. It was found that the addition of these modifiers to asphalt binder systems greatly enhanced the desirable properties of that asphalt, notably increasing penetration, increasing ring and ball softening, improving low temperature ductility, increasing toughness and tenacity, and increasing viscosity at higher service temperatures. It was noted that these changes were dependent on the asphalt being modified. It was also noted that more field trials were needed to assess these effects on in-place pavements.

Davis, D., M. Stroup-Gardiner, J. Epps, and K. Davis, "Correlation of Laboratory Tests to Field Performance for Chip Seals," Transportation Research Board 70th Annual Meeting, Washington, D.C., 1991.

The Nevada Department of Transportation constructed 44 chip seal test sections between Yerington and Wabuska, Nevada. One of the purposes of these test sections was to correlate laboratory and field testing with pavement performance. The laboratory tested consisted of the vialit-time series and the vialit-temperature series. Field testing included only the vialit-time series. Pavement performance was based on pavement evaluations, and percent reflective cracking. The pavement evaluations recorded, overall condition, aggregate retention, aggregate embedment, and bleeding.

After comparing field and laboratory testing with pavement performance four conclusions were made:

1. The field vialit-time series testing did not correspond to laboratory vialit-time series testing because of the variation in curing temperature of the field samples.

2. The laboratory vialit-time series does not predict the performance of paving grade binders, although it is a fairly good indicator of rate of set for emulsions.

3. The laboratory vialit temperature series can detect the effects of aggregate gradation on different binders.

4. Aggregate retention of the sample cured at 0°F is a good indicator of overall chip seal performance. Ratings of 8.0 or greater are likely for overall condition and aggregate retention if the percent aggregate retention for the laboratory sample cured at 0° is greater than 60 percent.

Estakhri, C. K., and M. A. Gonzalez, "Design and Construction of Multiple Seal Coats," Final Report.

The primary objectives of this study were to establish design and construction guidelines for multiple seal coats for the Texas State Department of Highways and Public Transportation. A multiple seal coat is a bituminous surface that results from two or more successive alternating applications of bituminous binder and cover aggregate to an existing paved surface, usually with the smaller aggregate sizes used in each successive layer. From a thorough review of the literature, it was concluded that the key to executing an effective design for multiple seal coats was in the ability to measure the available void space in multiple stone layers that could be filled with binder. A design method developed by the NITRR of South Africa which included a test procedure (Modified Tray Test) for measuring the void content and effective thickness of a stone layer was chosen for further field and laboratory investigation. Based on a statistical analysis of a number of samples, the Modified Tray Test was found to be repeatable. It was also determined that a single sample of stone, as tested by means of the Modified Tray Test, gives a good indication of the overall void content and effective layer of thickness for a particular type and grade of stone. The Modified Tray Test was also used to determine the void content and effective layer thickness of double seals made up of different combinations of four aggregate grades. A relationship was found between the effective layer of thickness of a double seal and the sum of the bottom and top layers separately. The design method was tested by fabricating multiple seal coats in the laboratory and field and, with modifications, was found to produce satisfactory performance.

Estakhri, C. K, and M. A. Gonzalez, "Estimating Voids in a Double Chip Seal," Transportation Research Record 1259, Transportation Research Board, 1990.

In the design of double chip seals, perhaps the most important factor to be computed is the amount of bituminous material required to fill the voids between the aggregate to an optimum depth. A design method developed by the National Institute for Transport and Road Research was evaluated by Texas Transportation Institute (TTI). This method includes a simple test procedure for measuring the void content and effective layer thickness of the stone layers. It also provides for a way of estimating the loss of voids in the seal over its expected life due to embedment in the underlying surface and wear and degradation of the stone. This method also considers the fact that voids within the aggregate layers vary nonlinearly with depth. This design approach is quite different from anything currently used in the United States. TTI evaluated this method by using chip seal aggregates graded to Texas State Department of Highways and Public Transportation specifications. Two double chip seal test roads built in Texas according to the design methods discussed are performing well.

Ford, M. C., "Evaluation of Asphalt Emulsion Surface Treatment Characteristics and Performance," Final Report on Transportation Research Project No 65.

A methodology for evaluating the characteristics and performance of asphalt emulsion seal coats in the laboratory has been developed. A relationship between the aggregate spread modulus and the ratio of aggregate and asphalt application rates to obtain optimum performance was developed. The results of the 20 month long investigation were based on sampling and testing of the in-place seal coat and its emulsion residue and aggregate components. The performance of each seal coat project was determined by use of an accelerated wear device. Better embedment of aggregate was obtained on the seal coat project where steel wheel rollers were used in conjunction with pneumatic tire rollers.

Holmgreen, R.J., "A Seal Coat Design Method," Proceedings, Association of Asphalt Paving Technologists, Volume 54, 1985, pp. 667-672.

A design method for seal coats is presented. The inputs include aggregate embedment depth, aggregate embedment percent, average mat depth, aggregate quantity, dry loose unit weight of the aggregate, a traffic correction factor, and a correction for surface conditions. The output is the asphalt quantity, in gallons/yd^2. The method was developed based on observations of chip seal performance in Texas.

Holmgreen, R. J., and J. A. Epps, and C. H. Hughes, and B. M. Gallaway, "Field Evaluation of the Texas Seal Coat Design Method."

The information contained in this report represents data collected on over 80 seal coats in seven districts in Texas. The sections included variables such as a range of traffic concentration, climate and road surface conditions. All projects used in this study were constructed in 1982 and 1983. A preconstruction field evaluation of site involving a visual evaluation and surface texture test was performed. Specific construction data were gathered from district records which consisted of aggregate spread rates, aggregate and asphalt sources and type. Postconstruction evaluations were conducted at intervals which allowed as many environmental cycles as possible. the data gathered in the course of this study provide the necessary information for further design method refinement and design curve adjustments. Included in this report is the present seal coat design method.

Haas, R.C.G., E. Thompson, F. Meyer, and G.R. Tessier, "The Role of Additives in Asphalt Paving Technology," Proceedings, Association of Asphalt Paving Technologists, Volume 52, 1985, pp. 324-345.

A comprehensive survey was conducted of the various additives and extenders available. The primary uses were to reduce stripping, thermal cracking, rutting, hardening, reflection cracking, to improve consistency, and to reduce costs. The researchers concluded that while there were an impressive number of additives available on the market, it could not be proven that they were cost effective in improving the performance of asphalt pavements. It was recommended that further research be performed.

Hoss, N.P., "Cationic Emulsions for Surface Treatments."

Test roadways of cationic emulsion containing hard asphalt and do not bleed prove satisfactory. Cationic asphaltic emulsions are prepared from select paving grade asphalt cements carefully milled (Homogenized) with a water solution containing special cationic and acid type emulsifiers. The basic difference between emulsified asphalts and cationic emulsion is that the cationic has been processed with the colloid mill which breaks the base asphalt charge into minute charged particles and disperses them into the solution. The emulsion carries a positive electrical charge and, since most mineral surfaces are negatively charged, the polar attraction between the cationic emulsion and the anionic aggregate gives superior adhesion of the asphalt and aggregate system. Field performance shows that cationic emulsions performs equally well with carbonate and siliceous aggregates. Two theories for this compatibility are: (1) due to the high kinetic energy vibration of the cationic emulsifiers, they have a natural affinity for all solid surfaces, and (2) free acids attach the surface of the basis stone and insoluble reaction formed at the bitumen-aggregate interface promotes firm adhesion. Advantages of the use of cationic emulsion surface treatments are : (1) the hard asphalt of 85-100 and 150-200 penetration eliminates bleeding, (2) ambient temperature, though important, is not as critical as for normal surface treatments, (3) though surfacing in the rain is not advised, successful pavements were obtained when surfacing operations were continued uninterrupted during periods of precipitation, (4) a damp roadway with no free water and wet aggregate is desired for best results, (5) the cationic material is extremely fluid and flows into cracks and voids, thereby providing a more waterproof seal, and (6) application temperatures are kept between 110 and 160°F making the operation safer than with the conventional asphalts. Disadvantages to the use of cationic emulsions are: (1) Traffic must be rigidly controlled until the material breaks for best results, (2) no further aggregate embedment will take place after the emulsion breaks, and (3) distributors or containers must be free of all other types of asphaltic materials prior to filling with cationic emulsions. Characteristics and problems in using cationic emulsions are discussed.

Houghton, L. D., "Two-Coat Seals Instead of Two Seal Coats. New Zealand Roading Symposium 1987," Volume 2.

The two-coat seals dealt with in this paper are not the two seal coats normally applied to the majority of granular base course construction in New Zealand. They are a seal of two spray and two chip coats applied in one operation without any appreciable time, traffic, or rolling between coats and which can be used as the surfacing on new construction or as a reseal. The paper describes the design, construction, performance and economics of these two-coat seals with respect to Lower Hutt's limited experience with them to date. This experience shows that in a significant number of situations the two-coat seal may be the surfacisting design methods and/or the modifying of practices and materials to enable the kind of single-coat seal to be applied which gives the best value for money.

Hove, L., and M. Pederson, "How to Optimize the Performance of Surface Dressings," Papers Presented at the IHT Conference, 1988, London.

Sensitivity analysis is used to simplify the determination of some parameters involved in the design of surface dressing. They include: (1) the substrate hardness, which is defined as the penetration of a loaded ball into the substrate and is a direct function of loading time, substrate temperature, ball diameter, and the applied load; (2) the hardness modulus, taken from the hardness measurement at constant temperature; (3) the susceptibility of hardness to loading time at constant temperature; (4) the susceptibility of hardness to temperature; (5) the traffic parameters, which include average daily traffic per lane (ADT), traffic weight groups, number of wheels pumber of traffic passes between application time and the beginning of the first winter and that this relationship is significantly affected by the initial viscosity of the reseal binder. The method of analysis is not entirely new. It analyzes the performance of actual seals (as opposed to laboratory simulations), which means that it takes into account all of the local variations in practice and materials. As these variations from one authority and/or district to another are very real, the authors strongly recommend that roading engineers, materials engineers, and sealing practitioners be encouraged to carry out their own analysis of their own seals and, if at all possible, that this be co-ordinated at a national level. Where possible, the Canterbury test track should be utilized to provide further data for analysis, especially data to do with the effects of heavy commercial traffic. The combination of data from the above recommendations would enable the fine tuning of existing design methods and/or the modifying of practices and materials to enable the kind of single-coat seal to be applied which gives the best value for money.

Hove, L., and M. Pederson, "How to Optimize the Performance of Surface Dressings," Papers Presented at the IHT Conference, 1988, London.

Sensitivity analysis is used to simplify the determination of some parameters involved in the design of surface dressing. They include: (1) the substrate hardness, which is defined as the penetration of a loaded ball into the substrate and is a direct function of loading time, substrate temperature, ball diameter, and the applied load; (2) the hardness modulus, taken from the hardness measurement at constant temperature; (3) the susceptibility of hardness to loading time at constant temperature; (4) the susceptibility of hardness to temperature; (5) the traffic parameters, which include average daily traffic per lane (ADT), traffic weight groups, number of wheels per vehicle, wheel load, contact pressure, diameter of contact area, percentage of ADT, and traffic speed. A simplification of these parameters is presented based on statistical material in traffic reports published by the road directorate in Denmark; (6) the number of equivalent 35 kN wheels per lane per day; (7) the transverse wheel distribution; (8) surface temperature profile; and (9) the derived for the design model. Another equation for the qualitative void related the latter to the void at disposal as related to a smooth substrate, the void related to the substrate, and the void reduction due to embedment. An equation describes the equivalent ball diameter. Trials with the traffic simulator have shown that it is possible to predict the number of wheel passes until bleeding occurs using the above design procedure. Programmable pocket size calculators make it easy and quick to use the design method. An example of the design procedure is given in the appendix. Three parameters are recognized as being of prime importance for the selection of surface dressing binders: wetability, initial strength and brittleness. Exceeding just one of these parameters will ultimately cause the surface dressing to fail. Threshold values are given for these parameters, wetability depending on viscosity and brittleness on the breaking point temperature of the binder. Details are given of a programmable bitumen distributor which allows a variable transverse distribution of the binder necessitated by the objective design method to avoid bleeding in the wheel tracks. The control of the transverse distribution of the binder is connected to a printer. At completion of the job, average width, length, number of square metres, total binder consumption in litres, and average binder application rate are automatically printed out together with the used jet configurations. The required amount of active adhesion agent is added at the time of distribution. The application procedure for a new type of surface dressing called a 2-3 surface dressing is outlined.

Jackson, D.C., N.C. Jackson, and J.P. Mahoney, "Washington State Chip Seal Study," Transportation Research Record No. 1259, Transportation Research Board, National Research Council, Washington, D.C., 1990.

Approximately 50 percent of the Washington State highway system, 3,500 centerline miles, has a bituminous surface treatment (BST). The use of BST is coincident with that portion of the state system with traffic volumes of 2,000 ADT or less. Recent specification changes, such as increasing emulsion yields, decreasing aggregate yields, reducing the allowable time between placement of emulsion and aggregate, and early brooming, along with central office involvement in the BST process, have positively affected the quality of the Washington State Department of Transportation's chip seals. However, some of the chip seals constructed in western Washington in 1988 generated adverse publicity because of dust, traffic delays, and windshield damage. This study recaps the recent specification and construction procedure changes, looks into the details of nine recently completed chip seal projects in western Washington, and also supports the following recommendations, among others: use of polymerized emulsions in western Washington, strong central office support and review of the BST program, use of maintenance people with strong working BST experience as chip seal inspectors, use of finer chips in areas of heavy bicycle traffic to provide a smoother, more uniform surface, and early season completion of BST work.

Kandhal, P.S., and J. B. Motter, "Criteria for Accepting Precoated Aggregates for Seal Coats and Surface Treatments," Final Report.

One of the most common causes of seal coat failures is the presence of dust on the cover aggregate that prevents good adhesion between the applied bituminous binder and the aggregate. Precoating the aggregate with a very thin film of bituminous binder usually solves the dust problem and provides good adhesion. This research was undertaken (a) to evaluate the adhesion of aggregates precoated to varying degrees so that the optimum precoating requirement can be established, and (b) to develop an end-result type test in lieu of the subjective visual test for accepting precoated aggregates. Five AASHTO No. 8 aggregates of different mineralogical compositions and absorptive characteristics were used. These aggregates were precoated with MC-30 cutback asphalt to varying degrees (from salt and pepper effect to 90+ % coating). Pennsylvania Aggregate Retention Test developed in this study was used to evaluate the effect of precoating on aggregate retention loss. Immediate adhesion of the cover aggregate with the bituminous binder was best obtained at 90+ percent precoating. The agreement (reproducibility) between different evaluators who made subjective visual evaluation of the percent precoating was also by far the best at 90+ percent level. Of the three end-result type tests attempted, dry gradation test of the precoated aggregate was determined to be most appropriate with an acceptance criteria of 0.5 percent maximum minus 200 (dust).

It has been recommended to use AC-20 asphalt cement as a precoating material in lieu of MC-30 cutback asphalt, because it can be mixed at higher temperatures in a hot mix asphalt (HMA) plant, does not need any curing, and will cause better aggregate retention.

Kidd, S. Q., "Polymerized Asphalt Emulsion," Final Report.

It has been claimed that polymerized asphalt emulsion has outstanding characteristics of elasticity, adhesion, and cohesion which allows its use in seal coats in high speed, high volume roads, such as interstate highways. Another use would be on a lower classification road with sharp turns which would greatly shorten the life of a regular ship seal. Styrelf is a styrene-butadiene (vulcanized) binder which was added to the base asphalt. Installations varied from an interstate highway with 12,710 average daily traffic (ADT) and 25% trucks to a rural state highway with 1,570 ADT and 15% trucks. Riffe Petroleum Company's product was used in a single installation. It had an ADT of 4,050 with 10% trucks. Owen-Corning Fiberglass Corporation's product was used in a single installation. It had an ADT of 410 with 12% trucks. Polymerized asphalt emulsion that doesn't have high early adhesion is an inferior product, since the need for adhesion is greatest when the surface is new and tender.

Korsgaard, H.C., and C.J. Woehlik, "Investigation of Different Binders for Surface Dressings," Skovvejen, Test Series III.

Different bitumens have been tested as binders for surface dressing on twelve test sections, each 700 m long. The binders comprised 5 straight run bitumens, 2 sbs-bitumen, 1 sr-bitumen, 1 br-bitumen, 1 wax-modified bitumen, and 1 chemcrete modified bitumen. The binders were applied as established in 1983. The changes in penetration at 25°C, ring and ball softening point, and breaking point were measured: softening points increased by 9°C, penetration decreased by 10-58%, and breaking point increased by 0-5°C. All the breaking points were less than 18°C. The change in properties of the modified binders depends on the modifier. An increase in softening point of 11-34°C, a decrease in penetration between 27 and 75%, and an increase breaking point of 0-3°C was obtained. An exception was the chemcrete modified bitumen with an increase in breaking point from -28 to -13°C. In the heavily trafficked lane an increase in rut depth of 1-2 mm, a decrease in friction value from 0.85 to 0.75, and a certain crushing of the largest aggregate fraction was found. The findings were independent of the type of binder. Bleeding appears to be directly related to the amount of binder used, is also independent of the type of binder.

Krauss, Paul, "Polyester Seal Coat," California Department of Transportation, 1987.

This research demonstrated that using polyester as a binder for seal coats is feasible. Resin set time can be controlled and application equipment was developed. As a result of this research, a contract was let to compare a polyester seal coat with an asphalt seal coat. This should be constructed in the spring of 1987 (Contract 10-262404, 10-SJ-99-31.2/32.0).

There are several recommendations that resulted from this research.

A) The chip must be dry and clean to improve bonding to the resin.

B) After the chip is applied to the deck, it should not be disturbed until the polyester is sufficiently cured. Vehicle wheels or rollers overturn and wet the chip and thus leave areas deficient in resin. Movement of the chip while the polyester resin is curing will also irreversibly break the chain linking of the resin molecules that give the polymer its strength. Both cases may cause raveling.

C) It is apparent that the resin must be sprayed to achieve a uniform application and avoid deficient areas.

D) More adequate surface preparation is needed. The bond to the PCC decks on the Pacheco Pass Bridge and the Kings River Bridge was inconsistent. Where debonding occurred, the polyester delaminated in sheets. This suggests that abrasive steel shot blast cleaning or a prime coat such as high molecular weight methacrylate is required to aid the polyester seal coat bond to PCC.

LaForce, R. F., "Crumb Rubber Chip Seal East of Punkin Center," Final Report.

This report documents the performance of rubber asphalt binders as chip seal materials. The test sections consisted of two rubber-asphalt binders, a rubberized cutback (RC-800, the standard chip seal at the time of construction), and a plain AC-10 chip seal. At the end of the evaluation period, the rubber asphalt binders had performed as well as the rubberized RC-800; however, from an economic standpoint the rubberized RC-800 is recommended for use as a chip seal binder on low-volume highway. Since construction of this project, other CDDH studies have shown emulsified polymerized asphalt binders performed as well or better than the RC-800 rubberized material at an additional savings.

Le Sage, J, and P. Archinard, "Routoflex M: An Easy-to-Use, High Performance Binder Particularly Suited for Thin Dressing of Asphaltic Concrete for Road Maintenance," 3rd Eurobitume Symposium 1985, The Hague, Netherlands, September 11-13, 1985.

The use of thin wearing courses must not involve working under over critical conditions. Temperatures close to those normally employed and conventional equipment facilitate the use, and enhance the reliability of special products. the routoflex m binder (alias BP 247) developed for this application jointly by BP and gerland is - thanks to the choice of two suitable polymers - as easy to use as a non-modified bitumen of equivalent penetration value. This routoflex surfacings are laid down at a temperature between 140°C and 170°C, which illustrates their excellent handling characteristics, as more particularly evidenced by the gyratory shear compactor. The plasticity interval (59°C on the ring and ball test, -27°C on the fraass test) is very wide (86°C). Temperature susceptibility is very low (penetration index + 1.67). At low temperatures, flexibility - demonstrated by substantial tensile elongation values - is such that the asphalt concrete at -20°C has a modulus of rigidity equivalent to that obtainable with a 180/220. Cohesion at high duty temperatures is such that the asphaltic concrete performs better on the rutting test at 60°C than 40/50 bitumen, which is already good in performance terms. The fatigue strength of asphaltic concrete obtained is very much superior to that obtainable with 40/50 (0.00022 for relative deformation at million cycles as against 0.00014 adhesion is reflected in an immersion/compression ratio of 0.96 on the furiez test and excellent performance on the stripping test, whatever the nature of the aggregate used. As for aging, oxidation and temperature resistance are very satisfactory as determined by tests of residual cold tensile strength and loss on heating. By virtue of their excellent overall performance they can be employed to obtain very effective thin surfacings for deformadable substrates subject to high deflection, heavy traffic loadings and the effects of weather. Thin routoflex surfacings are particularly suitable for road construction and maintenance in mountainous areas. They can be used in very thin surfacings in the shape of microbetons and high quality chipping-based dressings, mainly for busy roads in built-up areas. Their properties of cohesion, water resistance, aging and fatigue strength already referred to are such that they can constitute excellent pervious surfaces. The characteristics described are generally obtained without increasing the content of binder. Additionally, they are particularly economic in use since thin dressings can be applied to distorted and worn substrates, thus making it possible to postpone more substantial maintenance work, avoid the need for removal and other work required to restore road levels or edges, and also minimize the quantities of materials required per square metre.

Linde, S, "Wearing Courses on Roads and Airfields."

The aim of the project is to study the rheological behavior of polymer-modified bitumen by means of thermo mechanical analysis (tma) and tensile strength. The break-down pattern should, if possible, be clarified by means of gel permeation chromotography (gpc) studies, together with mechanical tests. Models will be made of polymer-modified bitumen and aggregates in order to study the stripping effect in a modified freezing and thawing test in its final phase, and test strips in runways and roads will be laid.

Mahone, D. C., and K. H. McGhee, "Management of Surface Treated Pavements."

The objective is to develop and implement a pavement management system for Virginia's 30,000 miles of low volume paved secondary roads with chip sealed or slurry sealed riding surface. The first step is to conduct a pilot study to develop inventory, condition rating, and prioritization methodologies for a sampling of the state.

McLeod, N.W., "A General Method of Design for Seal Coats and Surface Treatments," Asphalt Paving Technology, 1969, Volume 38, pp. 537-629.

It is the principal objective of this paper to demonstrate that one equation for the quantity of cover aggregate required and another equation for the quantity of asphalt binder to be applied, can be used for the design of either single application or multiple application surface treatments and seal coats.

The required characteristics of both cover aggregates and asphalt binders are reviewed. The superiority of one-size over graded cover aggregates is demonstrated.

Equations are developed for the quantities of cover aggregate and asphalt binder required for single application surface treatments and seal coats. A sample calculation illustrates their use for this purpose.

It is show that these same equations can be employed for the design of multiple seal coats and surface treatments. Sample calculations are included to illustrate their use in this respect.

The principles of construction for single and multiple application surface treatments and seal coats are reviewed.

McLeod, N.W., "Seals and Treatments: How to Get Your Money's Worth," Rural and Urban Roads, Vol. 12 No. 10, October 1974, pp. 38-41.

The need is emphasized for a clear mental picture of what an excellent seal coat should look like under traffic. A common characteristic of commendable treatments is that no asphalt binder can be seen when walking over them. The principle faults of surface treatments and seal coats are listed and discussed. They include streaking, flushing or bleeding, loss of cover aggregate, and the lack of bond between a new seal coat and an old surface. A discussion of factors which yield good results gives consideration to the cover aggregate (particularly one-size material), the average least dimension of cover aggregate, the influence of cover aggregate size on service performance, and the achievement of better adhesion between aggregate and asphalt.

Mellott, D. B. "Polymer Modified Asphalt for Seal Coats," Construction Report.

The Department desires to evaluate asphalt modifiers to enhance aggregate retention for seal coats. We have been looking at various asphalt modifiers in past years have included latex and neoprene type additives. Recently, the asphalt industry has developed various polymer additives that are marketed to solve many of the present problems. These additives are promoted to give "rubbery" characteristics to the asphalt binder materials during the hot pavement surface temperature periods of the summer months when other asphalt binders will become soft and allow loss of the aggregates. These additives are usually costly and increase the project costs significantly. Therefore, it is important to evaluate the cost-effectiveness of their use. After one year of service, the control sections have suffered significant loss of the aggregate and the sections are flushed and asphalt is tracking in the direction of traffic. The polymer modified sections are in better shape than the control sections. All have suffered the usual snowplow damages, such as abrasion of the aggregate by the sliding snowplow shoes and "scuffing" by the bouncing snowplow blade.

Maurer, D.A., "Ralumac Latex-Modified Bituminous Emulsion Mixtures-A Summary of Experience in Pennsylvania," Pennsylvania Department of Transportation.

The objectives of this report are to provide an update on the usage of Ralumac, a cold-laid, latex-modified emulsion paving material, in Pennsylvania. Use of the material as a rut-filler, a surface overlay course, and a bridge deck sealer and wearing surface are discussed. The basic construction procedures for the material are provided, as well as a summary of product performance to date. Significant factors affecting performance are contractor experience and overall quality control. As a contractor's experience increased, placement generally improved and less problems were noted. Performance has generally been adequate. Whenever performance deficiencies are noted, there has been a direct link to inadequacies during construction. Recommendations are made for more positive verification of mix composition and application quantity.

When proper design consideration is provided and construction quality control maintained, Ralumac is a versatile material that can be used as a highway maintenance alternative to extend highway serviceability. Recommendations are made relative to continued use of Ralumac, with limitations, for various applications.

Mills, D. R., and T. J. Keller Jr, "Styrelf Modified Emulsion Chip Seal."

The objectives were to observe the application procedures and the field performance including initial stone retention compared to the Department's conventional chip seal. 3000 gallons of Styrelf Binder were made using AC-20 blended with 3% proprietary polymer Styrelf prior to emulsification. Del #8 aggregate was used. A roadway of dimensions 3620 ft long by 21 ft wide was chip sealed. The emulsion application rate was 0.50 gallon/sq yd and 0.35 gallon/sq yd on the other. The emulsion temperature at both sites was 170°F with an aggregate application rate of 20 lbs/sq yd.

Mills, W.H., "Evaluation of Surface Treatment and Slurry Seal," Proceedings, Association of Asphalt Paving Technologists, Volume 52, 1985, pp. 198-223.

In a continuing effort to upgrade the quality and serviceability of surface treatments and slurry seals work, a supplemental research project was authorized in 1978 to evaluate projects constructed during the last three years.

The objectives were to evaluate the quality of work performed, to define problems evident in finished projects, to compare serviceability of several types of construction, and to develop procedures that would assure desirable improvements.

A unique system for evaluation was used. It was based on study of a total of 500 projects that were selected in each district at random but proportional to the number of projects in the district. Each project was inspected and then rated on the basis of 15 attributes each of which affects the quality and/or serviceability of the completed work. Ratings varied from 10 for a perfect condition to 0 for a failed or unusable condition.

Field work was started in September 1978 and completed in March 1979. A total of 486 projects was studied including 290 triple surface treatments, 101 double surface treatments, 28 single surface treatments, 32 slurry seal projects, and 27 asphaltic concrete resurfacing projects. Ratings indicating satisfactory quality were given to 83-90% of the triple and double surface treatments. Slurry seal projects were rated as satisfactory in regard to the treatment, but deficient in regard to the sealing of cracks in the pavement being resurfaced. Ratings indicating substandard quality were given to seal coats of single surface treatment and then layers of asphaltic concrete. These low ratings were due mostly to cracks which came from the pavement being resurfaced.

Recommendations for preventing defects and alleviating substandard conditions were presented.

Mills, D.R. and T.J. Keller, "Dupont Neoprene Modified Asphalt Chip Seal Demonstrations," Delaware Department of Transportation Divisions of Highways, P.O. Box 778, Dover, Delaware 19901.

The immediate objectives of the study were twofold: to determine through lab testing how the addition of neoprene to a CRS-2 modifies the emulsion properties, and to observe mixing and application procedures and any increase or decrease in initial stone retention. Field performance of the neoprene modified chip seal were compared to conventional CRS-2 and RS-2 surface treatments in regards to skid resistance, stone retention, crack retardance, emulsion bleed-through and low-temperature flexibility.

Musselman, J. A., and E. B. Leitner, and K. H. Murphy, "Evaluation of Various Surface Sealing Techniques for the Preventative Maintenance of Flexible Pavements," Final Report.

The selection of an appropriate Surface Seal Technique for the preventive maintenance of flexible pavements has been a major concern among the various highway agencies for a number of years. In an effort to better equip the engineer in making decisions concerning the selection of the most cost-effective method of pavement maintenance, seven of the different surface sealing techniques currently available in Florida were constructed in the Fall of 1984 for evaluation. The only major problems encountered at the time of construction were the loss of cover material in the sand seal, mineral seal, and surface treatment sections and raveling in the slurry seal section. These problems are believed to have been caused by traffic on the roadway before adequate curing had occurred. The test sections were evaluated immediately after construction and at 6 months, 1 year, 2 years, and 3 years, with the evaluation consisting of rut depth measurements, crack survey, dynamic deflection measurements, rideability, and friction testing. At the conclusion of 3 years, the cost-effectiveness of each section was determined.

Najafi F.T., J. Johns, and H. Humberto," "Survey of States' Chip Seal Coat Practices," paper prepared for presentation at the 70th Annual Meeting (1991) of the Transportation Research Board.

It is more economical to periodically maintain a pavement system throughout its useful life than to wait until it deteriorates. Pavement condition assessments are related to: 1) structural integrity; 2) skid resistance, and 3) rate of deterioration of the pavement. Improved maintenance, thus getting the most out of an existing well-designed roadway system, should be the goal of every public works manager. This paper focuses on the survey of chip seal coat practices in various states of the United States. The survey was performed with a questionnaire, supplemented by telephone interviews. Thirty-five states participated in this study.

The focus of the questionnaire was on the material and design of seal coat practices including construction procedures and equipment. Among the states using chip seal coats, only a few states do not use rapid setting cationic products of any of the different types and viscosities. Many states use at least one type of cationic emulsion. Anionic emulsions were only used by 16% of the states. Based on aggregate requirements, a majority of the states place limits on dust (#200 material), but these limits may be undesirably high at 2 or 3 percent. Controls are also often placed on this elongated pieces and on the flakiness index of aggregate. In general, considerable variability exists in state aggregate requirements.

In the category of design factors, most states consider average daily traffic (ADT), surface condition, and emulsion application temperature in their design procedure. Two other frequently used design factors are aggregate flakiness index and aggregate wastage. In general, the more design factors that are taken into consideration by a state, the greater the probability that field adjustments will not be required.

O'Connor, L. "Performance of Low Quality Asphalt Pavements in Colorado."

This study was initiated to evaluate low quality asphalt pavements constructed in recent years using fine sand aggregates in eastern Colorado. Twenty-one projects were evaluated, some of which were good performers and some of which were poor. An evaluation team visited each project to observe and rate wheelpath rutting, shoving, raveling, and cracking. Rutting, shoving, and associated bleeding were the major problems. Construction records were researched and pavement samples were tested in the Laboratory. The results include (1) asphalts with more uniform distribution of components are performing better than others; (2) lower asphalt penetrations yield higher performance, (3) void content is inversely related to bleeding, (4) AC-10 grade asphalts vary considerably in hardness, (5) bleeding occurs between 2.5 and 3% voids. The recommendations are that fine grained pavements should be designed for not lower than 6% voids and asphalt penetrations should be known before the selection of an asphalt grade from a particular source is made on each project.

Parker Jr., F., and M. Wilson, "Evaluation of Boiling and Stress Pedestal Tests for Assessing Stripping Potential of Alabama Asphalt Concrete Mixtures," Transportation Research Record 1096, 1986 pp. 90-100.

Moisture produces serious distress, reduces performance, and increases the need for maintenance of asphalt concrete pavements. Although moisture is but one of many distress mechanisms contributing to pavement deterioration, it is often a major factor. Moisture damage is attributable to stripping where stripping is the loss of adhesion between aggregate and asphalt cement, or possibly loss of cohesion in the asphalt cement. Boiling tests and stress pedestal tests were performed on asphalt concrete mixes composed of materials common in Alabama. The purposes of these tests were to evaluate the laboratory procedures for (a) assessing the potential of asphalt concrete mixture stripping and effectiveness of antistripping additives and for (b) identifying mix components responsible for stripping. Results from the oil tests indicated that aggregate, asphalt cement, and additive properties affect coating retention. Implications are that each combination must be tested to assess stripping potential and that generalizations are not possible. Reasonable correlations with field performance were obtained with results from entire mixes. Results indicate that boil tests may provide valuable predictions of antistripping agent effectiveness, but that they will not identify aggregate components causing stripping. Results from the stress pedestal tests did not correlate well with field performance. In addition, there were no correlations between mix performance and the performance of individual aggregate components. Implications are that the stress pedestal test has little potential for predicting mix performance or for identifying aggregate components causing stripping for typical Alabama materials.

Pederson, C.M., "Micro Surfacing with Natural Latex Modified Emulsion," Oklahoma Department of Transportation.

This is the final report for the use of emulsified asphalt in a relatively new process called "Ralumac Micro Surfacing." This process was developed in Germany and was first used in the United States in late 1980. In 1982, personnel from the Oklahoma Department of Transportation (ODOT) observed projects in another state and proposed a project in Oklahoma.

The Ralumac process incorporates natural latex rubber with the asphalt emulsion. It is mixed with aggregate and other additives in a traveling pug mill similar to but larger than that of a regular slurry machine.

The construction phase of this demonstration project was completed in June, 1983. The evaluation of data presented shows that the service life of the test area has been enhanced. It is recommended the Ralumac process be approved for routine use as a restoration item for flexible pavements to fill surface ruts and cracks, seal the surface, and restore skid resistance.

Peterson, D.E., "Evaluation of Pavement Maintenance Strategies," NCHRP Synthesis of Highway Practice 77, Transportation Research Board, Washington, D.C., September 1981.

This synthesis provides information of interest to maintenance engineers and others involved in developing and implementing strategies for pavement maintenance. Detailed information is presented on the selection of alternative treatments within the context of a pavement management system. Extensive information is presented on states' practices regarding pavement evaluation, factors that trigger maintenance, types of maintenance strategies and selection of the optimal strategy, and the incorporation of maintenance information in pavement management decision-making.

Prehoehl II, N., and Kemp, G.R., "Binder Modifier Agents for Construction and Maintenance Seals," Transportation Laboratory, California Department of Transportation.

This is the final report for the study Binder Modifier Agents for Construction and Maintenance Seals. Included are complete data from final corings and final observations and photographs of the Copperopolis and Edwards Junction test sections. The data is displayed on tables and graphs comparing the effects of the binder modifier products for each test section. Analysis and usage recommendations are made for each type of product.

The findings show that the products affect skid resistance and the top 1/4 inch of the pavement, but not the lower portion of the pavement or its structural integrity. The findings also indicate that the main benefit of the binder modifier products is to reduce raveling and heal, or cover, fine cracks. It is concluded that the products should not be used until needed and then only where it is safe to use them. The softening and altering agents may be used in travel-way situations where their penetration is complete and where they do not upset the liquid balance of the pavement system, i.e., cause the pavement to lose skid resistance.

Robinson, A., B. Rowley, and F. Young, "Seal Coats in Manitoba," Manitoba Department of Highways and Transportation, Prepared for presentation at 1986 Transportation Research Board, Washington, D.C.

Pavement seal coats of asphalt and aggregate have been used in Manitoba for many years. They are employed both as a dust-free surface on low volume roads and as a wearing surface on pavement. In the latter application, the subject of the paper, seal coats are applied to seal out moisture, provide a lighter colored surface for night time visibility, to improve skid resistance and to reduce pavement oxidation. A side benefit is the improvement in appearance by covering sealed and unsealed cracks and any patching which had been required.

Over 300 miles of seal coats are placed annually by two permanent summer crews. The paper presents application and cost data relative to the Province's program.

Rogue, R., M. Thompson, and D. Anderson, "Bituminous Seal Coats: Design, Performance Measurements, and Performance Prediction," The Pennsylvania Transportation Institute, A Paper Prepared for the 70th Annual Meeting of the Transportation Research Board, January 1991.

A field study was conducted at the Pennsylvania Transportation Institute's Pavement Durability Research Facility at Penn State to determine the effect of specific construction, traffic, and material variables on the performance of bituminous seal coats. As part of this study, an evaluation was also made of the adequacy of existing seal coat design procedures, quality control procedures, and seal coat performance measuring techniques. This paper concentrates on this latter evaluation, while the effects of the different variables are reported elsewhere. The evaluations were based on actual field measurements and led to numerous recommendations for improvements in seal coat design methods, equipment calibration, measurement and evaluation of seal coat performance, prediction of seal coat life, and the appropriate use of seal coats as a maintenance technique. These recommendations are reported herein.

Finally, a definitive pattern of seal coat macrotexture degradation was identified under this very closely monitored field experiment. This finding was used to develop a seal coat life prediction model. Aggregate wear rates and embedment rates were measured on two surfaces under closely monitored traffic loading conditions. The wear and embedment rates were used to illustrate the potential of the seal coat life prediction model to evaluate the effects of different variables on expected seal coat life. Based on the deficiencies observed in the existing design procedures, updated design charts that use more objective methods of evaluating the existing pavement surface are proposed. Potential methods for rating the surface are proposed.

Rogue, R., D. Anderson, and M. Thompson, "Effect of Material, Design, and Construction Variables on Seal Coat Performance," The Pennsylvania Transportation Institute, A Paper Prepared for the 70th Annual Meeting of the Transportation Research Board, January 1991.

This paper describes a field study that was conducted at the Pavement Durability Research Facility of the Pennsylvania Transportation Institute (PTI) at Penn State and PA Route 64 to determine the effect of specific construction, traffic, and materials variables on the performance of bituminous seal coats. Condition of the existing surface (worn or leveled), emulsion application rate, rolling patterns, time between construction operations and opening to traffic, and polymer modification were among the study variables. Accelerated traffic was applied to the sections for 1 year, and the performance, skid resistance, visual evaluations, and mean texture depth were documented.

Design and construction variables were found to diminish the other study variables. Conclusions are presented that relate to the different phases of a seal coat operation including surface preparation, materials selection and specification, seal coat design, construction procedures, and quality control.

Rust, F.C. and F. Hugo, "Towards Performance Related Design Criteria and Specifications for Modified Binders," Association of Asphalt Paving Technologists.

The increasing use of bitumen-rubbers and other modified binders to inhibit reflection cracking highlighted the need to determine performance-related design criteria and establish specifications for those materials. To do this, it was necessary to investigate the phenomena of load-associated crack movement and crack reflection. The development of the Crack-Activity Meter (CAM) and its use with the Heavy Vehicle Simulator (HVS) has led to an improved understanding of crack movement behavior. Trial sections, on route N3, which were built to determine the field performance of various modified binders under normal traffic as well as initial results from this experiment, are discussed in this paper. To date, fatigue testing under simulated crack movement in the laboratory was conducted on three bitumen rubbers, one conventional bitumen and four modified binders used in the N3 trials. Initial results from this work, including fatigue curves of the materials, are reported. The correlation between laboratory fatigue performance and the rheological properties of the above materials are also discussed.

"Seal Coats."

Seal coating is the largest single item of maintenance expenditure for county and city streets. The many variables associated with both selection of materials and application methods make identification of the elements which contribute to either the success or failure of a seal coat extremely difficult. This project will review the many studies which have been conducted on this subject in order to ascertain those methods and materials which guarantee the greatest chance of success. The final product of this project will be a brief manual outlining proper materials selection and application methods.

Scholl, L. G., and R. C. Negrete, and E. W. Brooks, "Evaluation of Performance and Cost-Effectiveness of This Pavement Surface Treatments," Interim Report #2.

This is the second report to result from the subject study. It represents the first major effort to evaluate the available data on"thin pavement surface treatments" in Oregon and to define "cost effectiveness: for this purpose. The 87 projects studied here were constructed in 1984, 1985, and 1986. This report includes pavement condition data collected annually through 1989. Three different "cost-effectiveness indices" are defined and used to compare similar types of treatments. The Longevity Cost Index

(LCI) is based on the median service life, price, and traffic loading of each treatment type. After more of the treatments fail, this index is expected to be the most meaningful of the three. It is applied here in a preliminary effort to compare the cost-effectiveness of two types of chip seals. The two other indices, based on changes in pavement condition, are also explored for comparing the treatments. As a supplemental effort, this report addresses the question, "which treatment is the most appropriate in a given situation?" To accomplish this, an outline of selection criteria for various treatments is presented. This is based on experience in Oregon and the available literature.

"Seal Coat Evaluation Procedure," Highway Research News, Highway Research Board 1966 No. 24, pp. 40-52.

A quick and inexpensive method of measuring the condition of seal coats is reported. The purpose in making a condition survey of seal coats is to determine to what degree the seal coat is performing the task for which it was intended. Bituminous surface treatments should perform the following functions: (1) prevent entrance of moisture and air into the underlying road surface, (2) develop a surface texture more resistant to skidding that the existing surface, (3) enliven an old dry or weathered surface with fresh bituminous binder, (4) reinforce or build up a weak or inadequate pavement, (5) improve the luminosity of the pavement or the night-driving characteristics of the road, (6) provide demarcation between road segments, especially between driving surface and paving shoulders, (7) improve surface irregularity and overall appearance of the pavement surface, and (8) provide an abrasion-resistant surface. Seal coats are also frequently placed primarily for improving the appearance of the pavement surface, especially on surfaces that have been extensively patched. In order to evaluate the success of a seal coat in performing the major functions for which it was intended, five factors must be rated independently: (1) chip retention, (2) skid resistance, (3) uniformity of application, (4) tracking, and (5) bleeding. Numerical ratings for evaluating each of these factors are described and the forms used in rating are presented.

Seiler, J. "Seal Coat Handbook."

This report is developed and reported in a handbook format in order to present seal coat information in an easy to follow and easy to understand sequence. Contained in this handbook are the various aspects of seal coats from asphalt to aggregate and surface preparation to final cleaning. A popular seal coat design method is also included for easy reference. Also contained in this handbook are experiences of individuals in different areas of the state. Rather than giving District by District information, Districts are combined into areas. Dividing the Districts into areas is justifiable because a survey of seal coat experience showed similar problems and results in Districts within certain parts of the state due to similar climatic and environmental conditions. Lastly, selected asphalt additives are researched and discussed. Detailed explanations of advantages of polymers and latexes are given along with tables describing some manufactured additive products.

Selim, A. A., "Enhancing the Bond of Emulsion-Based Seal Coats with Antistripping Agents," Transportation Research Record No. 1217, Transportation Research Board, 1989.

Seal coats are highly regarded as a pavement maintenance tool because, among other functions, they enhance the friction value of existing road surfaces. Asphalt emulsions are commonly used in seal coat construction for their adaptability to environmental and handling conditions, and the better the bond between emulsion and aggregate, the better the friction value of the seal coat. This study seeks to find out whether antistripping agents enhance the bond between aggregate and emulsion, consequently improving the friction value of the seal coat; to determine the best way of including the antistripping agent in the seal coat; and to establish a mathematical model to predict the friction value of a particular seal coat at any time after construction. To those ends, several seal-coat test sections were prepared, subjected to traffic for several months, and then evaluated. The outcome of the research reveals that (a) including the antistripping agent in a seal coat improves the bond between aggregate and asphalt and reduces the tendency of aggregate particles to rotate under horizontal drag forces, both of which led to higher friction values; (b) mixing the antistripping agent with the emulsion instead of applying it to the aggregate surface improved the total bond and led to higher frictional values; and (c) quadratic models were better than exponential models at predicting friction values of seal coats at any time after construction.

Selim, A. A., "Qualitative Assessment of the Sioux Quartzite in Asphalt Hot Mixes," Transportation Research Record 1096, Transportation Research Board, 1986.

Quartzite is known to be a more expensive material than natural aggregate (natural gravel and sand) to use in asphalt hot mixes. Therefore, many engineers are reluctant to use it in order to keep construction costs down, particularly during periods of difficult economic times. This point of view did no justice to quartzite, particularly when the engineering properties of quartzite are recognized by many professionals as being superior to natural aggregate. A study was conducted to determine the feasibility of using quartzite in hot mixes in lieu of natural aggregate in areas near the quartzite outcrops. Laboratory tests indicated that mixes made with quartzite yielded better air voids, flow, density, and voids in mineral aggregates (VMA). Field performances proved that quartzite surfaces possess higher Dynaflect deflection values as well as higher skid resistance numbers. Economic analysis revealed that during a reasonable lifespan of pavement, the total expenses incurred (initial investment, maintenance, etc.) are less for quartzite surfaces than for natural aggregate surfaces. At the break-even point between quartzite and natural aggregate, the difference in costs can be used to transport quartzite greater distances. Computer programs were developed to determine the distance quartzite can justifiably be used without adding any more expenses to the pavement.

Selim, A. A., and M. A. Ezz-Aldin, "Correlation Between Field and Laboratory Performance of Liquid Asphalt-Based Seal Coats," Transportation Research Record No. 1259, Transportation Research Board, National Research Council, Washington, D.C., 1990.

The success of any seal coat depends not only on the quality of the binder and the aggregate (chips), but also on the compatibility of the two materials. Compatible binder-aggregate combinations will result in a long-lasting seal coat, and incompatible combinations will result in chip loss, bleeding, and other problems. The use of additives in seal coats, whether applied to the binder or to the aggregate, has proved very useful in prolonging the life of a seal coat and improving its field performance. Polymer modified cutback (RC-3000R) and plain cutback (RC-3000) were used, along with three different types of aggregate chips [blotter gravel (BG), pea rock (PR), and quartzite (Q)], to determine the best binder-aggregate combination. Also, seal coats made with liquid asphalt were examined closely in terms of laboratory performance (using the modified Vialit test) and field performance (using an evaluation technique developed in South Dakota). The RC-3000R quartzite combination performed the best in the field and the MC-3000/BG combination was the worst. The field performance of test sections that were subjected to traffic for over 2 years resulted in a ranking of all test sections from 1 to 6, with 1 being the best in performance. Two parameters extracted from the Vialit test were found to have an excellent correlation with field performance—initial retention and the additional chip loss due to impact.

Semmelink, C. J., "A Rational Design Approach for Single and Double Surfacing Seals Based on the Modified Tray Test," Transportation Research Record 1106, Transportation Research Board, 1986.

Important factors influence the performance of surfacing seal, or surface treatments, such as the loss of voids that results from the wear of the aggregate and the effect of traffic on the embedment of the aggregate in the underlying layer on which it is constructed. Research results are given that indicate the likely reasons why single seals are generally more susceptible to fatting-up than double seals. It is shown how the modified tray test can be used to avoid this problem. A rational approach to the design of single and double seals that incorporates the actual measured void content instead of an accepted average quantity is outlined. The accurate determination of the stone spread rate with the modified tray test is also discussed.

Scloo, J. L. M., "Seal Coating Practice in Saskatchewan," Transportation Research Record 1096, Transportation Research Board, 1986.

Surface treatment utilizing seal coats is a relatively inexpensive method of maintaining a highway pavement surface. Saskatchewan policy requires that seal coats be applied to all pavement surfaces at intervals to delay the need for structural rehabilitation. Seals are used to prevent moisture penetration, arrest fatigue block deterioration, restore friction resistance, and stop raveling. The primary sealing materials used are graded aggregates and high float emulsified asphalts. Some chip sealing with rapid-setting cationic or rubber-modified asphalts have also been used. Performance and defect levels of seals are mainly related to construction quality and are a function of distributor condition, type of asphalt and aggregate, application rates, surface preparation, and construction of joints and the climatic conditions in which they are applied. Seal coats have served Saskatchewan well by deferring the need for more costly rehabilitation by increasing the life of the pavement surfaces maintained and easing demands on cash flow.

"Seven Fundamentals for Durable Spraybar Work—Jobs you can be Proud of," Roads and Streets Vol. 118, No. 8, August 1975.

The following seven simple principles should be considered when putting down long-lasting asphalt seals and treatments; (1) a surface treatment will fail without a good enough foundation; (2) everyone on the job needs to have a clear mental picture of what a really top-quality surface treatment or seal coat looks like under traffic; (3) the more common faults (streaking, flushing or bleeding, loss of aggregate, and lack of bond) should be looked for and avoided; (4) carefully check the cover aggregate gradation and also watch particle flatness by specifying a maximum flakiness index; (5) determine the average least dimension since good performance is more likely with larger cover aggregate; and (7) get good adhesion. These seven steps add little if anything to the job cost and assure the quality of asphalt surface treatments and seal coats.

Shook, J. F., and W. L. Shook, and T.Y. Yapp, "The Effects of Emulsion Variability on Seal Coats" Pennsylvania Department of Transportation, 1990.

This project was conducted because of concern that variabilities in the viscosity of asphalt emulsions as delivered to the job site may be contributing to the problems with seal coat performance. The study included a literature survey; an analysis of differences between PennDOT and supplier test results for emulsion viscosity and properties of the asphalt residue; and field studies conducted on eight different seal coat projects in three Pennsylvania counties. The analysis of supplier and PennDOT test results indicated that there are major variations in viscosity test values from different suppliers and within a given plant from individual suppliers; suppliers and within a given plant from individual suppliers; also between viscosity test values reported by some suppliers and test values reported by PennDOT. Field performance data obtained on five seal coat jobs constructed in Pennsylvania in 1987 indicated that better performance may be obtained with emulsions which have higher viscosities, higher percentages of residual asphalt and higher residual asphalt penetration values, within current specification limits. However, the study did not produce evidence that current PennDOT specification limits on emulsion viscosity, asphalt cement content or residual asphalt penetration should be changed. The use of statistical quality control charts were recommended to improve uniformity of production.

Shuler, S., "Chip Seals for High Traffic Pavements," Transportation Research Record No. 1259, Transportation Research Board, National Research Council, Washington, D.C., 1990.

Chip seals have been successfully used on highways with traffic volumes in excess of 5,000 vehicles per day. The performance life of those chip seals averages 6 to 7 years, with some applications lasting much longer, Unfortunately, a significant number of chip seals have not performed adequately. Some agencies refuse to use this potentially cost effective approach to pavement rehabilitation and maintenance as a consequence. By developing a more fundamental understanding of the causes of chip seal failures on high traffic volume facilities, improved design methods, construction materials and methods, equipment, and specifications can be developed. These improved procedures will form the basis of implementation packages that will encourage state highway administrations and other public agencies to utilize chip seals on high-volume pavements. Reasons for chip seal failure on high traffic volume facilities and methods that have been used to overcome these difficulties are described. In addition, methods are described for predicting potential adhesive qualities of chip seal binders by using a modification of the Vialit procedure. Also, techniques are described for producing pressure distributor nozzles that can be effectively calibrated, resulting in known binder distribution transverse to the centerline. These nozzles, which have been used on one experimental project, were produced to provide higher binder volume outside the wheelpaths.

Shuler, S. and D. I. Hanson, "Improving Durability of Open-Graded Friction Courses," Transportation Research Record 1259, Transportation Research Board, 1990.

Open-graded friction course mixtures were evaluated in the laboratory to determine the potential for stripping. A boiling test was used to measure the potential for stripping mixtures containing three asphalts used in New Mexico with and without both liquid antistripping additives and hydrated lime. Mixtures were also evaluated with the same three binders after modification with a polymer. All testing was conducted on mixtures after the optimum binder content was determined by using the open-graded friction course mix design procedure described by FHWA. Results of this study indicate that optimum asphalt content of open-graded friction course mixtures varies depending on the asphalt, antistripping agent type, and quantity and whether the binder is polymer modified. Stripping potential as measured by the Texas Boiling Test was significantly reduced after addition of antistripping agents to the asphalt or aggregate and after polymer modification of the binders.

Shuler, T. S., R. D. Pavlovich, and J. Epps, "A Field Performance of Rubber-Modified Asphalt Paving Materials," Transportation Research Record 1034, 1985, pp. 96-102.

Six types of paving systems containing ground tire rubber are evaluated. Asphalt-rubber seal coats and interlayers are the construction applications in which most ground rubber has been used, and, therefore, most of the results of this study relate to these two paving processes. Asphalt-rubber interlayers studied in this research do not appear to always improve performance of overlays compared with control sections. However, the negative performance of some installations does not appear to be related to fundamental material properties but to inappropriate use of some interlayers. It is believed that improved performance of such systems can be demonstrated if use is limited to specified modes of pavement distress. Asphalt-rubber seal coat performance also indicates some unfavorable performance compared with control sections. However, this adverse performance can be related directly to a high incidence of flushing distress. A recommendation is given for design of asphalt-rubber seal coats similar to conventional seal coats. A lack of rational design procedures for determining material quantities is cited as the primary cause of some detrimental asphalt-rubber seal coat performance in the past. Four other rubber-modified paving processes were investigated; however, because of the relatively few projects involved, specific conclusions regarding these types of applications are difficult to assess. Further study is recommended as more projects of this type are constructed.

Simering, R. K., and M. Callahan, "Field Demonstration of Foamed Asphalt. Muscatine County," Final Report.

The foamed asphalt concept has been around since the 1950's. Rising oil prices have created a renewed interest in this process. The purpose of this project was to construct and asphalt base using the foamed asphalt process and to evaluate its performance. A 4.2 mile length of Muscatine County road A-91 was selected for the research project. Asphalt contents of 4.5% and 5.5%, moisture contents of 70% and 90% of optimum, and fog, single chip, and double chip seal coats were used in various combinations to lay 9 test sections of 4-inch foamed asphalt base. After five years of service and evaluation, several conclusions can be made concerning the performance of the foamed asphalt bases: (1) the foamed asphalt process can work as shown by the excellent performance of Sections 2 and work as shown by the excellent performance of Sections 2 and 3; (2) foamed asphalt base requires a well compacted subgrade and a road profile suitable for good drainage of water—test section failures were mostly due to a poor subgrade and subsurface moisture; and (3) when the base is placed in two or more lifts, extreme care must be exercised to insure adequate bonding is achieved between lifts. Any future research with foamed asphalt should include various asphalt depths in order to determine a thickness/strength relationship for foamed asphalt.

Sime, J. M., "Use of Asphalt Emulsions in Connecticut," Final Report.

Five different pavement seal coats were applied to secondary roads during August and September 1979. The pavement-study sections were selected from ConnDOT's District I and II liquid-surface-treatment-program schedules. The performance of each was monitored for three years. The two secondary roads selected for the study had aged, distressed pavements. One lane of each two-lane road received a Class 12 bituminous concrete thin-surface-leveling course prior to seal coating. Researchers documented the rate at which pre-existing cracks reflected through each seal coat. The reflection cracking rate appeared to be dependent upon seal coat thickness. All of the experimental seal coats provided adequate skid resistance during the three-year monitoring period. Primary recommendations are: (1) Apply thicker seal coats to lengthen service life, i.e. 3/8, 5/8, and 1/2-inch chip seal coats will outperform thinner sand and grits seal coats; (2) Utilize several seal coat designs throughout the State to capitalize on locally-available and economical materials; and (3) Prepare the pavement surface to high standards prior to a seal coat application, including the compaction of any bituminous-concrete leveling course with either rubber-tire or steel-wheel rollers.

Sinha, K. C., "Evaluation of Cost Effectiveness of Pavement Surface Maintenance Activities."

The objectives of the study are to analyze the impact of various pavement surface maintenance activities on pavement surface life and to develop a set of criteria that can be used to determine under what conditions a particular surface maintenance activity is most cost effective. The maintenance activities will consider routine work such as patching, joint and crack sealing as well as periodic work such as sand sealing and chip sealing. Several measures of effectiveness will be considered including PSI, PCI, RN, PSI-ESAL loss and several direct distress measurements.

Swanson H., and D. Woodham, "Use of Road Oils by Maintenence," Final Report, July 1989, Colorado Depatment of Highways.

The objective of this study was to determine which materials are most effective for each maintenance activity and, thereby, reduce the total number of road oils purchased and handled. Observations and evaluations of more than 240 test sections over a three-year period in all maintenance sections of the state have provided results which satisfy the objective. AC oils performed best for hot mix. Emulsions or MC oils can be used for cold mix Emulsions have proven to be the best oils for all types of seal coats. Asphalt crack fillers containing large amounts of polymerized rubber and meeting ASTM D 3405 or D 1190 are best; however, filling cracks with any oil is beneficial. RC-800 Rubberized is a good compromise between cost and quality.

Vallerga, B. A. and J. R. Bagley, "Design of Asphalt-Rubber Single Surface Treatments with Multilayered Aggregate Structure," Asphalt Pavement Construction: New Materials and Techniques, ASTM STP 724, J.A. Scherocman, Ed., American Society for Testing and Materials, 1980, pp. 22-38.

A newly developed asphalt-rubber material with unique adhesive and rheological properties has made it possible to form highly elastic single surface treatments with a multilayered aggregate structure. Conventional asphalt distributor trucks are used to apply a heavy spread of the hot asphalt-rubber material on a prepared surface followed by the immediate embedment of aggregate chips into this cast-in-place membrane by conventional chip spreading and rolling equipment and procedures. A sufficient quantity of aggregate chips must be applied both to build up the multilayered aggregate structure and to provide a skid-resistant pavement surface. The composition and properties of the asphalt-rubber material are described together with procedures for constructing the surface treatment. Audit results are presented from an experimental field installation of a multilayered single surface treatment consisting of four test sections, where the rates of application of the asphalt-rubber membrane material ranged from 1.86 to 8.87 hot litre/m^2 (0.41 to 1.96 hot gal/yd^2) with corresponding aggregate retention rates of 13 to 37 kg/m^2 (24 to 68lb/yd^2). Based on these audit results and experience gained from the observed performance of other field installations, a nomograph for designing such multilayered aggregate single-surface treatments has been formulated and is presented. The nomograph can be used to determine the rates of application of asphalt-rubber material and aggregate chips to obtain a desired thickness of surface treatment or, alternatively, to determine the spread rate of aggregate chips and thickness of the surface treatment for a specific rate of asphalt-rubber membrane application.

Wilhelmson, H. and P-O Jonsson, "Surface Treatments for Economical Maintenance of Roads --- Pre Conference Proceedings 3rd IRF Middle East Regional Meeting. Towards Better Road Performance," Riyadh, Saudi Arabia, 13-18 February 1988. 6 Volumes.

When the structural integrity of a pavement is sound, surface seals are in many cases economical alternative to traditional overlays for raveled, stripped, and cracked roads. These may be slurry seals, chip seals, or a combination of chip and slurry seals. The report describes Swedish experience with slurry seal for low traffic volume roads, streets and airports and ship seal for medium traffic volume roads.

For roads with high traffic volume a combination of chip seal and slurry seal, called cape seal, has been tested with good results. Cape seal is a surface dressing with chips overlaid by a slurry seal. The report deals further on with design of chip seals, with good performance in hot and cold weather and under heavy traffic. There are still some problems to be solved. For example the size and amount of rock for different applications, the best emulsions for local aggregates, the applications, the best emulsions for local aggregates, the cost efficiency of polymerized bitumen etc.

Wyckoff, C. P., "Asphalt Seal Coats - Factors Affecting and Techniques for Obtaining Consistently Good Seal Coats," Final Report.

This is a manual written for those who direct or physically construct asphalt seal coats. The text is based on field experiences. The manual contains: the reasons for seal coating; each type of seal coat discussed as to the purposes of the seal and how it is constructed; and particular emphasis on chip seals and the factors which can affect obtaining consistently good seal coats. Some of these factors are the weather, the road surface on which the seal is laid, the type of asphalt used, the handling and storage of the asphalt, the choice of cover rock, how to control the uniform distribution and application of the asphalt and rock, the coordination of the seal coat operation, and the post-seal inspection and possible immediate correction. This manual is concise but detailed in the appropriate areas with liberal use of graphics.

APPENDIX B

SURFACE TREATMENT DESIGN PROCEDURES

The Asphalt Institute Method

C. SURFACE TREATMENT DESIGN

6.13 SINGLE SURFACE TREATMENTS

When a decision has been made that a surface treatment is to be used, the next step is to find the proper rates of application for asphalt emulsion and aggregate. The objective is to produce a pavement surface one stone thick with enough asphalt to hold the aggregate in place, but not so much that it will bleed. Several methods can be used for this purpose. The one described here was modified by N. W. McLeod* from a method developed by the Country Roads Board of Victoria, Australia. It involves the following principles:

1. When one-size cover aggregate is dropped by a spreader on an asphalt film, the particles lie in unarranged positions. The voids between the particles are approximately 50 percent.
2. Rolling partly reorients the aggregate particles and reduces the voids to about 30 percent.
3. Finally, after considerable traffic, the particles become oriented into their densest positions, with all lying on their flattest sides, and the voids are further reduced to approximately 20 percent.
4. Since the particles lie on their flattest sides, the average thickness of a surface treatment is determined from the overall average smallest dimension of the aggregate particles. This is called the "average least dimension" (ALD) of the cover aggregate.

   The average least dimension of any approximately one-size cover aggregate can be determined by measuring a number of individual aggregate particles with a caliper or by using slotted screens (see Appendix D).
5. For good performance, the quantity of asphalt binder used should fill about 70 percent of the 20 percent void space [see 3 above] if the traffic volume is moderate (500 to 1000 vehicles per day). However, the asphalt binder should fill not more than 60 percent of the 20 percent void space if the traffic volume is high (more than 2,000 vehicles per day).

Note that these principles are based on one-size cover aggregate. Most often, one-size aggregate is not available economically and graded aggregate, which has fewer voids, has to be used. The voids in this material in a loose weight condition will be somewhat less than the 50 percent for one-size aggregate. This means therefore, that the ultimate void space in a surface treatment using graded cover aggregate will be less than 20 percent. A correction must be made in the design method for this condition or a bleeding pavement may result.

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*McLeod, Norman W., "Seal Coat and Surface Treatment Design and Construction Using Asphalt Emulsions," a paper presented at the First Annual Meeting, Asphalt Emulsion Manufacturers Association, Washington, January 27–29, 1974.

These considerations, together with practical experience, have led to the development of the equation below for the quantity of cover aggregate in a surface treatment.

U.S. Customary	*S.I. Metric**
$C = M[46.8(1 - 0.4V)HGE]$	$C = M[(1 - 0.4V)HGE]$

where

C = cover aggregate applications, lb/yd^2 (kg/m^2)

V = voids in the cover aggregate in loose weight condition, $V = 1 - \frac{W}{62.4G}$ or metric ($V = 1 - \frac{W}{1000G}$) percent, expressed as a decimal

W = loose unit weight of cover aggregate lb/ft (kg/m^3), AASHTO Method T 19 (ASTM Method C 29), (Appendix E)

G = bulk specific gravity of cover aggregate, AASHTO Method T 85 (ASTM Method C 127)

H = average least dimension (ALD) of cover aggregate, in. (mm), (Appendix D)

E = wastage factor to allow for cover stone loss, due to whip-off and unevenness of spread, Table VI-3

M = a multiplying factor that must be evaluated by experience with local conditions of climate, traffic, cover aggregate, etc., and may have a value greater or less than 1.0 which is its normal value.

The quantity of emulsified asphalt to be applied is found by the following equation:

U.S. Customary	*S.I. Metric*
$B = K\left[\frac{2.244\,HTV + S + A}{R}\right]$	$B = K\left[\frac{0.40\,HTV + S + A}{R}\right]$

where

B = emulsified asphalt application, gal/yd^2 ($litre/m^2$)

H = average least dimension of cover aggregate, in. (mm), (Appendix D)

T = traffic factor (Table VI-4)

V = voids in cover aggregate, loose weight condition (see equation for cover aggregate application above), percent expressed as a decimal

S = correction, gal/yd^2 ($litre/m^2$), for texture of surface on which surface treatment is to be placed.

Texture	Correction, S *gal/yd²*	*litre/m²*
Black, flushed asphalt	-0.01 to -0.06	(-0.04 to -0.27)
Smooth, non-porous	0.00	(0.00)
Absorbent — slightly porous, oxidized	0.03	(0.14)
— slightly pocked, porous, oxidized	0.06	(0.27)
— badly pocked, porous, oxidized	0.09	(0.40)

*International System of Units (S.I.) being adopted throughout the world.

TABLE VI-3 AGGREGATE WASTAGE FACTORS

Percentage Waste* Allowed for	Wastage Factor, E
1	1.01
2	1.02
3	1.03
4	1.04
5	1.05
6	1.06
7	1.07
8	1.08
9	1.09
10	1.10
11	1.11
12	1.12
13	1.13
14	1.14
15	1.15

**Due to whip-off and handling.*

TABLE VI-4 TRAFFIC FACTORS FOR SURFACE TREATMENTS

Aggregate	*Traffic Factor = Percentage (expressed as a decimal) of 20 percent void space in cover aggregate to be filled with asphalt*				
	Traffic — Vehicles per Day				
	Under 100	100 to 500	500 to 1,000	1,000 to 2,000	Over 2,000
Recognized Good Type of Aggregate	0.85	0.75	0.70	0.65	0.60

NOTES:

(1) *The factors above do not make allowance for absorption by the road surface or by absorptive cover aggregate.*

(2) *Values shown in the table are from "Seal Coat and Surface Treatment Design and Construction Using Asphalt Emulsions," by Norman W. McLeod, January 1974.*

A = correction, gal/yd^2 ($litre/m^2$) for absorption of asphalt into cover stone (disregard except for obviously porous stone)

R = residual asphalt in emulsion, percent expressed as a decimal. Typical values are:

Emulsified Asphalt	*R*
RS-1	0.58
RS-2	0.63
CRS-1	0.65
CRS-2	0.69

K = A multiplying factor that must be evaluated by experience with local conditions of climate, traffic, cover aggregate, etc., and may have a value either less than or greater than 1.0, which may be its normal value. However, experience has shown that for emulsion use in colder northern areas, "K" can have a value of about 1.2.

Example:

Standard size No. 7 crushed granite is to be used on a slightly porous pavement for a surface treatment cover aggregate with CRS-2 emulsified asphalt. Find the quantities of aggregate and emulsion to be applied. Traffic is estimated to be 800 vehicles per day.

—Median size of aggregate = 0.40 in. (10 mm), Figure VI-7

—Flakiness Index = 20, Appendix D

—Average least dimension, H = 0.29 in. (7.4 mm), Appendix D

—Loose unit weight of aggregate, W = 96 lb/ft^3 (1538 kg/m^3), Appendix E

—Bulk specific gravity, G = 2.65, AASHTO Method T 85

—Voids in cover aggregate, $V = 1 - \dfrac{96}{62.4 \times 2.60} = 1 - 0.58 = 0.42$

or metric $\left(V = 1 - \dfrac{1538}{1000 \times 2.65} = 1 - 0.58 = 0.42\right)$

—Wastage factor, E = 1.04, Table VI-3

—Traffic factor, T = 0.70, Table VI-4 (for 800 vpd)

—Texture correction, S = 0.03 gal/yd^2 (0.13 $litre/m^2$)

—Aggregate absorption correction, A = 0.00

—Residual asphalt, R = 0.69 percent (CRS-2)

—Multiplying factor "M" = 1.0

—Multiplying factor "K" = 1.0

Then — *Emulsified asphalt application*

$$B = K \left[\frac{2.244\ HTV + S + A}{R}\right] \quad \text{or metric} \quad B = K\left[\frac{0.40\ HTV + S + A}{R}\right]$$

$$B = 1.0 \left[\frac{2.244 \times 0.29 \times 0.70 \times 0.42 + 0.03}{0.69}\right]$$

or metric
$$B = 1.0 \left[\frac{0.40 \times 7.4 \times 0.70 \times 0.42 + 0.13}{0.69}\right]$$

$$B = 0.32 \text{ gal/yd}^2 \ (1.45 \text{ litre/m}^2)$$

Cover Aggregate Application

$$C = M\,[46.8\,(1 - 0.4\ V)\ HGE]$$

or metric $C = M\,[(1 - 0.4\ V)\ HGE]$

$$C = 1.0\,[46.8\,(1 - 0.4 \times 0.42)\ .29 \times 2.65 \times 1.04]$$

or metric $C = 1.0\,[(1 - 0.4 \times 0.42) \times 7.4 \times 2.65 \times 1.04]$

$$C = 31.1 \text{ lb/yd}^2 \ (16.9 \text{ kg/m}^2)$$

6.14 MULTIPLE SURFACE TREATMENTS

There are several arbitrary design methods for multiple surface treatments. In the method described here, each course is designed as though it is a single surface treatment. For each succeeding course the nominal top size of cover stone should be not more than one-half the size of that for the previously placed course. No allowance is made for wastage. Also, after the first course, no correction is made for underlying surface texture.

After the amount of emulsified asphalt for each course is determined, the total for all courses is obtained. For double surface treatments, McLeod recommends 40 percent of the total asphalt emulsion for the first application and 60 percent for the second. For triple treatment, the total quantity should be split 30-40-30.

The asphalt and aggregate quantities determined with these equations will suit most field conditions. As indicated by the "M" and "K" multiplying factors, there may be times when an upward or a downward adjustment must be made because of climate, traffic, cover aggregate, or other conditions.

In multiple surface treatments, the first course of cover aggregate generally determines the thickness. Subsequent courses partially fill the upper voids in the previously placed courses.

Here is an example of double surface treatment design to be placed in June:

First Course

—Standard size No. 6 crushed limestone. See Figure VI-8 for grading

—Median size of aggregate = 0.59 in. (15 mm), Figure VI-8

—Flakiness Index = 0.27, Appendix D

—Average least dimension, H = 0.40 in. (10.1 mm), Appendix D

—Loose unit weight of aggregate, W = 94 lb/ft^3 (1506 kg/m^3), Appendix E

—Bulk specific gravity, G = 2.60, AASHTO Method T 85

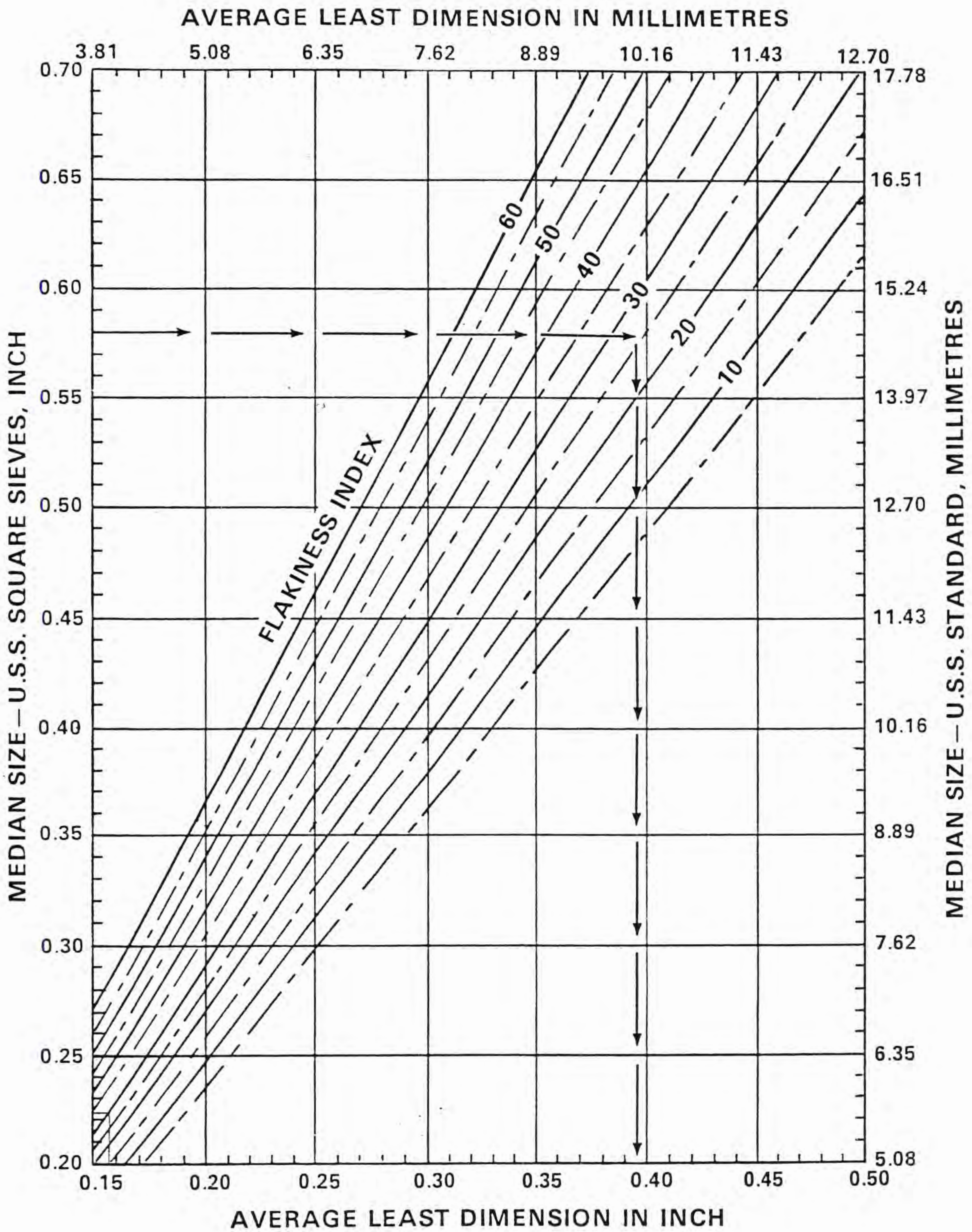


Figure D-3 Chart for determining Average Least Dimension of aggregate.

Texas State Department of Highways and Public Transportation Method

Calculations

The quantity of aggregate expressed in terms of square yards of road surface that can be covered with a cubic yard of aggregate and the quantity of asphalt in gallons per square yard can be found as described below:

Aggregate Quantity

$$S = \frac{27W}{Q}$$

$$A = 5.61E\left(1 - \frac{W}{62.4G}\right)(T) + V$$

where:

S = Quantity of aggregate required, sq. yds. per cu. yd.

W = Dry loose unit weight, lbs. per cu. ft.

Laboratory Tests

Dry Loose Unit Weight. The dry loose unit weight determination shall be made in accordance with Tex-404-A, except that the aggregate shall be tested in an oven-dry condition.

Bulk Specific Gravity. The bulk specific gravity shall be made in accordance with Tex-403-A for all natural aggregate and by the test method Tex 433-A for synthetic aggregates.

Board Test. Place a sufficient quantity of aggregate on a board of known area such that full coverage one stone in depth is obtained. A one-half square yard area ia a convenient laboratory size. The weight of the aggregates applied in this area is obtained and converted to units of pounds per square yard. Good lighting is recommended and care should be taken to place the aggregate only one stone deep.

Calculations

The quantity of aggregate expressed in terms of square yards of road surface that can be covered with a cubic yard of aggregate and the quantity of asphalt in gallons per square yard can be found as described below:

Aggregate Quantity

$$S = \frac{27W}{Q}$$

$$A = 5.61E\left(1 - \frac{W}{62.4G}\right)(T) + V$$

where:

S = Quantity of aggregate required, sq. yds. per cu. yd.

W = Dry loose unit weight, lbs. per cu. ft.

Q = Aggregate quantity determined from board test, lbs. per sq. yd.

A = Asphalt quantity, gallons/sq. yd. @ 60°F

E = Embedment depth obtained from Figure 3 as follows:

$$E = ed$$

where:

e = Percent embedment (Figure 3)

d = Average mat depth, inches

$= \frac{1.33Q}{W}$ $\frac{\#/\square'}{\#/C^{\prime}}$

G = Dry bulk specific gravity of aggregate

T = Traffic correction factor obtained from Table 7

V = Correction of surface condition obtained from Table 8

5.61 = (7.48) (9/12), or conversion factor

Note: Asphalt quantities calculated by these methods are for asphalt cement. Appropriate corrections must be made where a cutback or an emulsion is used.

Sample Calculations

Given:

(W) Dry loose unit weight of aggregate = 52.4 lbs./cu. ft.

(G) Dry bulk specific gravity of aggregate = 1.57

(Q) Quantity of aggregate (board test) = 9.7 lbs./sq. yd.

Traffic = 700 vehicles per day per lane

Roadway Surface Condition = slightly pocked, porous, oxidized

Quantity of Aggregate

$$S = \frac{27W}{Q} = \frac{27(52.4)}{97} = 146 \text{ sq. yds. (square yards of roadway surface per 1 cubic yard of aggregate)}$$

Quantity of Asphalt

$$A = 5.61E\ (1 - \frac{W}{62.4G})\ (T) + V$$

$$d = \frac{1.33Q}{W} = \frac{1.33(9.7)}{52.4} = .246 \text{ inches}$$

e = 40 percent from Figure 3 for synthetic aggregates

$E = ed = .40(.246) = 0.0985$ inches

T = 1.05 from Table 7

V = +0.03 from Table 8

$$A = 5.61\ (0.0985)\ (1 - \frac{52.4}{62.4(1.57)})\ (1.05) + 0.03$$

A = 0.30 gallons of asphalt per square yard of roadway surface

If an emulsion or cutback is to be used, the quantity to be utilized must be corrected for the amount of volatiles present in the asphalt material. The approximate amount of volatiles present in those cutbacks recommended for use in seal coats are shown on Table 9. For example, the seal coat design method suggests that 0.30 gallons per square yard of residual asphalt cement is required. Theoretically the amount of RC-250 to be placed on the pavement is

$$\frac{0.30}{.75} = 0.40$$

However, field experience indicates that bleeding is likely if the theoretical amount is utilized. Thus, it is recommended that the calculated theoretical value be reduced and the method described below be utilized to calculate the amount of cutback to be utilized.

$$A_{recommended} = A + K\ (A_{theoretical} - A)$$

where:

$A_{recommended}$ = recommended quantity of cutback or emulsified asphalt

A = residual quantity of asphalt obtained from the design method given above

$A_{theoretical}$ = theoretical quantity of cutback or emulsified asphalt obtained by dividing A by the quantity of residual asphalt in the cutback (Table 9) or emulsion and as described above.

K = correction factor based on field experience

It should be noted that correction factors (K) have not been verified for cutbacks by carefully controlled field experiments and therefore should be used as guidelines only: Suggested K factors for cutbacks are as follows:

K = 0.70 for spring construction

K = 0.60 for summer construction

K = 0.80 for fall construction

K = 0.90 for winter construction

If the RC-250 is to be placed in the fall, the quantity to be used is

$$A_{recommended} = 0.30 + 0.80\ (\frac{0.30}{0.75} - 0.30)$$

$A_{recommended}$ = 0.38 gallons of RC-250 per square yard of roadway surface

Field trial sections placed in Texas and reported in reference 18 suggest that reduced quantities of emulsion (as compared to the theoretical value calculated) can be utilized successfully. Thus, it is recommended that the calculated theoretical value be reduced and the method outlined above be utilized.

It should be noted that corrective factors (K) have not been verified by extensive controlled field experiments and therefore should be used as guidelines only. Suggested K factors for emulsions are as follows:

$K = 0.60$ for spring construction

$K = 0.40$ for summer construction

$K = 0.70$ for fall construction

$K = 0.90$ for winter construction

Assuming that the design method suggests that 0.30 gallons per square yard is required, the amount of an EA-CRS-2h emulsion that contains 70 percent residual asphalt that should be used in the summer is

$$A_{recommended} = 0.30 + 0.40\left(\frac{0.30}{0.70} - 0.30\right)$$

$A_{recommended} = 0.35$ gallons of EA-CRS-2h emulsion

per square yard of roadway surface.

It should be noted that the quantity of asphalt to be sprayed from the asphalt distributor must be corrected for temperature in order that the proper quantity will be retained on the roadway as measured at 60°F. If the design quantity of asphalt cement was 0.30 and the spray temperature was 340°F, the temperature correction factor would be 0.9057 (Table 10). Thus, $\frac{0.30}{0.9057}$ or 0.33 gallons of asphalt cement per square yard would be sprayed at 340°F in order to have 0.30 gallons per square yard on a 60°F surface. Temperature correction factors for asphalt cement are shown on Table 10, for cutbacks on Table 11 and for emulsions on Table 12.

Table 7. Asphalt Application Rate -- Correction Due To Traffic					
	Traffic - Vehicles Per Day Per Lane				
	Over 1,000	500 to 1,000	250 to 500	100 to 250	Under 100
Traffic Factor (T)	1.00	1.05	1.10	1.15	1.20

Table 8. Asphalt Application Rate Correction Due to Existing Pavement Surface Condition	
Description of Existing Surface	Asphalt Quantity Correction gal/sq. yd.
Flush asphalt surface	-0.06
Smooth, nonporous surface	-0.03
Slightly porous, slightly oxidized surface	0.00
Slightly pocked, porous, oxidized surface	+0.03
Badly pocked, porous, oxidized surface	+0.06

Table 9. Approximate Quantity of Cutter Stock in Cutbacks Commonly Used for Seal Coat Operations

Type and Grade Of Cutback	Approximate Quantity of Cutter Stock percent by weight
RC-2	27
RC-250	25
RC-3	20
RC-4	17
RC-5	13
MC-800	20
MC-3000	15

Table 10. Temperature-Volume Corrections for Asphalt Contents.*

t	M	t	M	t	M	t	M	t	M
0	1.0211	50	1.0035	100	0.9861	150	0.9689	200	0.9520
1	1.0208	51	1.0031	101	0.9857	151	0.9686	201	0.9516
2	1.0204	52	1.0028	102	0.9854	152	0.9682	202	0.9513
3	1.0201	53	1.0024	103	0.9851	153	0.9679	203	0.9509
4	1.0197	54	1.0021	104	0.9847	154	0.9675	204	0.9506
5	1.0194	55	1.0017	105	0.9844	155	0.9672	205	0.9503
6	1.0190	56	1.0014	106	0.9840	156	0.9669	206	0.9499
7	1.0186	57	1.0010	107	0.9837	157	0.9665	207	0.9496
8	1.0183	58	1.0007	108	0.9833	158	0.9662	208	0.9493
9	1.0179	59	1.0003	109	0.9830	159	0.9658	209	0.9489
10	1.0176	60	1.0000	110	0.9826	160	0.9655	210	0.9486
11	1.0172	61	0.9997	111	0.9823	161	0.9652	211	0.9483
12	1.0169	62	0.9993	112	0.9819	162	0.9648	212	0.9479
13	1.0165	63	0.9990	113	0.9816	163	0.9645	213	0.9476
14	1.0162	64	0.9986	114	0.9813	164	0.9641	214	0.9472
15	1.0158	65	0.9983	115	0.9809	165	0.9638	215	0.9469
16	1.0155	66	0.9979	116	0.9806	166	0.9635	216	0.9466
17	1.0151	67	0.9976	117	0.9802	167	0.9631	217	0.9462
18	1.0148	68	0.9972	118	0.9799	168	0.9628	218	0.9459
19	1.0144	69	0.9969	119	0.9795	169	0.9624	219	0.9456
20	1.0141	70	0.9965	120	0.9792	170	0.9621	220	0.9452
21	1.0137	71	0.9962	121	0.9788	171	0.9618	221	0.9449
22	1.0133	72	0.9958	122	0.9785	172	0.9614	222	0.9446
23	1.0130	73	0.9955	123	0.9782	173	0.9611	223	0.9442
24	1.0126	74	0.9951	124	0.9778	174	0.9607	224	0.9439
25	1.0123	75	0.9948	125	0.9775	175	0.9604	225	0.9436
26	1.0119	76	0.9944	126	0.9771	176	0.9601	226	0.9432
27	1.0116	77	0.9941	127	0.9768	177	0.9597	227	0.9429
28	1.0112	78	0.9937	128	0.9764	178	0.9594	228	0.9426
29	1.0109	79	0.9934	129	0.9761	179	0.9590	229	0.9422
30	1.0105	80	0.9930	130	0.9758	180	0.9587	230	0.9419
31	1.0102	81	0.9927	131	0.9754	181	0.9584	231	0.9416
32	1.0098	82	0.9923	132	0.9751	182	0.9580	232	0.9412
33	1.0095	83	0.9920	133	0.9747	183	0.9577	233	0.9409
34	1.0091	84	0.9916	134	0.9744	184	0.9574	234	0.9405
35	1.0088	85	0.9913	135	0.9740	185	0.9570	235	0.9402
36	1.0084	86	0.9909	136	0.9737	186	0.9567	236	0.9399
37	1.0081	87	0.9906	137	0.9734	187	0.9563	237	0.9395
38	1.0077	88	0.9902	138	0.9730	188	0.9560	238	0.9392
39	1.0074	89	0.9899	139	0.9727	189	0.9557	239	0.9389
40	1.0070	90	0.9896	140	0.9723	190	0.9553	240	0.9385
41	1.0067	91	0.9892	141	0.9720	191	0.9550	241	0.9382
42	1.0063	92	0.9889	142	0.9716	192	0.9547	242	0.9379
43	1.0060	93	0.9885	143	0.9713	193	0.9543	243	0.9375
44	1.0056	94	0.9882	144	0.9710	194	0.9540	244	0.9372
45	1.0053	95	0.9878	145	0.9706	195	0.9536	245	0.9369
46	1.0049	96	0.9875	146	0.9703	196	0.9533	246	0.9365
47	1.0046	97	0.9871	147	0.9699	197	0.9530	247	0.9362
48	1.0042	98	0.9868	148	0.9696	198	0.9526	248	0.9359
49	1.0038	99	0.9864	149	0.9693	199	0.9523	249	0.9356

t	M	t	M	t	M	t	M	t	M
250	0.9352	300	0.9187	350	0.9024	400	0.8864	450	0.8705
251	0.9349	301	0.9184	351	0.9021	401	0.8861	451	0.8702
252	0.9346	302	0.9181	352	0.9018	402	0.8857	452	0.8699
253	0.9342	303	0.9177	353	0.9015	403	0.8854	453	0.8696
254	0.9339	304	0.9174	354	0.9011	404	0.8851	454	0.8693
255	0.9336	305	0.9171	355	0.9008	405	0.8848	455	0.8690
256	0.9332	306	0.9167	356	0.9005	406	0.8845	456	0.8687
257	0.9329	307	0.9164	357	0.9002	407	0.8841	457	0.8683
258	0.9326	308	0.9161	358	0.8998	408	0.8838	458	0.8680
259	0.9322	309	0.9158	359	0.8995	409	0.8835	459	0.8677
260	0.9319	310	0.9154	360	0.8992	410	0.8832	460	0.8674
261	0.9316	311	0.9151	361	0.8989	411	0.8829	461	0.8671
262	0.9312	312	0.9148	362	0.8986	412	0.8826	462	0.8668
263	0.9309	313	0.9145	363	0.8982	413	0.8822	463	0.8665
264	0.9306	314	0.9141	364	0.8979	414	0.8819	464	0.8661
265	0.9302	315	0.9138	365	0.8976	415	0.8816	465	0.8658
266	0.9299	316	0.9135	366	0.8973	416	0.8813	466	0.8655
267	0.9296	317	0.9132	367	0.8969	417	0.8810	467	0.8652
268	0.9293	318	0.9128	368	0.8966	418	0.8806	468	0.8649
269	0.9289	319	0.9125	369	0.8963	419	0.8803	469	0.8646
270	0.9286	320	0.9122	370	0.8960	420	0.8800	470	0.8643
271	0.9283	321	0.9118	371	0.8957	421	0.8797	471	0.8640
272	0.9279	322	0.9115	372	0.8953	422	0.8794	472	0.8636
273	0.9276	323	0.9112	373	0.8950	423	0.8791	473	0.8633
274	0.9273	324	0.9109	374	0.8947	424	0.8787	474	0.8630
275	0.9269	325	0.9105	375	0.8944	425	0.8784	475	0.8627
276	0.9266	326	0.9102	376	0.8941	426	0.8781	476	0.8624
277	0.9263	327	0.9099	377	0.8937	427	0.8778	477	0.8621
278	0.9259	328	0.9096	378	0.8934	428	0.8775	478	0.8618
279	0.9256	329	0.9092	379	0.8931	429	0.8772	479	0.8615
280	0.9253	330	0.9089	380	0.8928	430	0.8768	480	0.8611
281	0.9250	331	0.9086	381	0.8924	431	0.8765	481	0.8608
282	0.9246	332	0.9083	382	0.8921	432	0.8762	482	0.8605
283	0.9243	333	0.9079	383	0.8918	433	0.8759	483	0.8602
284	0.9240	334	0.9076	384	0.8915	434	0.8756	484	0.8599
285	0.9236	335	0.9073	385	0.8912	435	0.8753	485	0.8596
286	0.9233	336	0.9070	386	0.8908	436	0.8749	486	0.8593
287	0.9230	337	0.9066	387	0.8905	437	0.8746	487	0.8590
288	0.9227	338	0.9063	388	0.8902	438	0.8743	488	0.8587
289	0.9223	339	0.9060	389	0.8899	439	0.8740	489	0.8583
290	0.9220	340	0.9057	390	0.8896	440	0.8737	490	0.8580
291	0.9217	341	0.9053	391	0.8892	441	0.8734	491	0.8577
292	0.9213	342	0.9050	392	0.8889	442	0.8731	492	0.8574
293	0.9210	343	0.9047	393	0.8886	443	0.8727	493	0.8571
294	0.9207	344	0.9044	394	0.8883	444	0.8724	494	0.8568
295	0.9204	345	0.9040	395	0.8880	445	0.8721	495	0.8565
296	0.9200	346	0.9037	396	0.8876	446	0.8718	496	0.8562
297	0.9197	347	0.9034	397	0.8873	447	0.8715	497	0.8559
298	0.9194	348	0.9031	398	0.8870	448	0.8712	498	0.8555
299	0.9190	349	0.9028	399	0.8867	449	0.8709	499	0.8552

*Specific gravity of materials at 60°F above 0.966.

t = Observed temperature in degrees Fahrenheit.

M = Multiplier for correcting oil volumes to the basis of 60°F.

Table 11. Temperature-Volume Correction for Cutback Asphalts.*

t	M	t	M	t	M	t	M	t	M	t	M	t	M	t	M	t	M	t	M
0	1.0241	50	1.0040	100	0.9842	150	0.9647	200	0.9456	250	0.9268	300	0.9083	350	0.8902	400	0.8724	450	0.8550
1	1.0237	51	1.0036	101	0.9838	151	0.9643	201	0.9452	251	0.9264	301	0.9080	351	0.8899	401	0.8721	451	0.8547
2	1.0233	52	1.0032	102	0.9834	152	0.9639	202	0.9448	252	0.9260	302	0.9076	352	0.8895	402	0.8717	452	0.8543
3	1.0229	53	1.0028	103	0.9830	153	0.9635	203	0.9444	253	0.9257	303	0.9072	353	0.8891	403	0.8714	453	0.8540
4	1.0225	54	1.0024	104	0.9826	154	0.9632	204	0.9441	254	0.9253	304	0.9069	354	0.8888	404	0.8710	454	0.8536
5	1.0221	55	1.0020	105	0.9822	155	0.9628	205	0.9437	255	0.9249	305	0.9065	355	0.8884	405	0.8707	455	0.8533
6	1.0217	56	1.0016	106	0.9818	156	0.9624	206	0.9433	256	0.9245	306	0.9061	356	0.8881	406	0.8703	456	0.8529
7	1.0213	57	1.0012	107	0.9814	157	0.9620	207	0.9429	257	0.9242	307	0.9058	357	0.8877	407	0.8700	457	0.8526
8	1.0209	58	1.0008	108	0.9810	158	0.9616	208	0.9425	258	0.9238	308	0.9054	358	0.8873	408	0.8696	458	0.8522
9	1.0205	59	1.0004	109	0.9806	159	0.9612	209	0.9422	259	0.9234	309	0.9050	359	0.8870	409	0.8693	459	0.8519
10	1.0201	60	1.0000	110	0.9803	160	0.9609	210	0.9418	260	0.9231	310	0.9047	360	0.8866	410	0.8689	460	0.8516
11	1.0197	61	0.9996	111	0.9799	161	0.9605	211	0.9414	261	0.9227	311	0.9043	361	0.8863	411	0.8686	461	0.8512
12	1.0193	62	0.9992	112	0.9795	162	0.9601	212	0.9410	262	0.9223	312	0.9039	362	0.8859	412	0.8682	462	0.8509
13	1.0189	63	0.9988	113	0.9791	163	0.9597	213	0.9407	263	0.9219	313	0.9036	363	0.8856	413	0.8679	463	0.8505
14	1.0185	64	0.9984	114	0.9787	164	0.9593	214	0.9403	264	0.9216	314	0.9032	364	0.8852	414	0.8675	464	0.8502
15	1.0181	65	0.9980	115	0.9783	165	0.9589	215	0.9399	265	0.9212	315	0.9029	365	0.8848	415	0.8672	465	0.8498
16	1.0177	66	0.9976	116	0.9779	166	0.9585	216	0.9395	266	0.9208	316	0.9025	366	0.8845	416	0.8668	466	0.8495
17	1.0173	67	0.9972	117	0.9775	167	0.9582	217	0.9391	267	0.9205	317	0.9021	367	0.8841	417	0.8665	467	0.8492
18	1.0168	68	0.9968	118	0.9771	168	0.9578	218	0.9388	268	0.9201	318	0.9018	368	0.8838	418	0.8661	468	0.8488
19	1.0164	69	0.9964	119	0.9767	169	0.9574	219	0.9384	269	0.9197	319	0.9014	369	0.8834	419	0.8658	469	0.8485
20	1.0160	70	0.9960	120	0.9763	170	0.9570	220	0.9380	270	0.9194	320	0.9010	370	0.8831	420	0.8654	470	0.8481
21	1.0156	71	0.9956	121	0.9760	171	0.9566	221	0.9376	271	0.9190	321	0.9007	371	0.8827	421	0.8651	471	0.8478
22	1.0152	72	0.9952	122	0.9756	172	0.9562	222	0.9373	272	0.9186	322	0.9003	372	0.8823	422	0.8647	472	0.8474
23	1.0148	73	0.9948	123	0.9752	173	0.9559	223	0.9369	273	0.9182	323	0.9000	373	0.8820	423	0.8644	473	0.8471
24	1.0144	74	0.9944	124	0.9748	174	0.9555	224	0.9365	274	0.9179	324	0.8996	374	0.8816	424	0.8640	474	0.8468
25	1.0140	75	0.9940	125	0.9744	175	0.9551	225	0.9361	275	0.9175	325	0.8992	375	0.8813	425	0.8637	475	0.8464
26	1.0136	76	0.9936	126	0.9740	176	0.9547	226	0.9358	276	0.9171	326	0.8989	376	0.8809	426	0.8633	476	0.8461
27	1.0132	77	0.9932	127	0.9736	177	0.9543	227	0.9354	277	0.9168	327	0.8985	377	0.8806	427	0.8630	477	0.8457
28	1.0128	78	0.9929	128	0.9732	178	0.9539	228	0.9350	278	0.9164	328	0.8981	378	0.8802	428	0.8626	478	0.8454
29	1.0124	79	0.9925	129	0.9728	179	0.9536	229	0.9346	279	0.9160	329	0.8978	379	0.8799	429	0.8623	479	0.8451
30	1.0120	80	0.9921	130	0.9725	180	0.9532	230	0.9343	280	0.9157	330	0.8974	380	0.8795	430	0.8619	480	0.8447
31	1.0116	81	0.9917	131	0.9721	181	0.9528	231	0.9339	281	0.9153	331	0.8971	381	0.8792	431	0.8616	481	0.8444
32	1.0112	82	0.9913	132	0.9717	182	0.9524	232	0.9335	282	0.9149	332	0.8967	382	0.8788	432	0.8612	482	0.8440
33	1.0108	83	0.9909	133	0.9713	183	0.9520	233	0.9331	283	0.9146	333	0.8963	383	0.8784	433	0.8609	483	0.8437
34	1.0104	84	0.9905	134	0.9709	184	0.9517	234	0.9328	284	0.9142	334	0.8960	384	0.8781	434	0.8605	484	0.8433
35	1.0100	85	0.9901	135	0.9705	185	0.9513	235	0.9324	285	0.9138	335	0.8956	385	0.8777	435	0.8602	485	0.8430
36	1.0096	86	0.9897	136	0.9701	186	0.9509	236	0.9320	286	0.9135	336	0.8952	386	0.8774	436	0.8599	486	0.8427
37	1.0092	87	0.9893	137	0.9697	187	0.9505	237	0.9316	287	0.9131	337	0.8949	387	0.8770	437	0.8595	487	0.8423
38	1.0088	88	0.9889	138	0.9693	188	0.9501	238	0.9313	288	0.9127	338	0.8945	388	0.8767	438	0.8592	488	0.8420
39	1.0084	89	0.9885	139	0.9690	189	0.9498	239	0.9309	289	0.9124	339	0.8942	389	0.8763	439	0.8588	489	0.8416
40	1.0080	90	0.9881	140	0.9686	190	0.9494	240	0.9305	290	0.9120	340	0.8938	390	0.8760	440	0.8585	490	0.8413
41	1.0076	91	0.9877	141	0.9682	191	0.9490	241	0.9301	291	0.9116	341	0.8934	391	0.8756	441	0.8581	491	0.8410
42	1.0072	92	0.9873	142	0.9678	192	0.9486	242	0.9298	292	0.9113	342	0.8931	392	0.8753	442	0.8578	492	0.8406
43	1.0068	93	0.9869	143	0.9674	193	0.9482	243	0.9294	293	0.9109	343	0.8927	393	0.8749	443	0.8574	493	0.8403
44	1.0064	94	0.9865	144	0.9670	194	0.9478	244	0.9290	294	0.9105	344	0.8924	394	0.8746	444	0.8571	494	0.8399
45	1.0060	95	0.9861	145	0.9666	195	0.9475	245	0.9286	295	0.9102	345	0.8920	395	0.8742	445	0.8567	495	0.8396
46	1.0056	96	0.9857	146	0.9662	196	0.9471	246	0.9283	296	0.9098	346	0.8916	396	0.8738	446	0.8564	496	0.8393
47	1.0052	97	0.9854	147	0.9659	197	0.9467	247	0.9279	297	0.9094	347	0.8913	397	0.8735	447	0.8560	497	0.8389
48	1.0048	98	0.9850	148	0.9655	198	0.9463	248	0.9275	298	0.9091	348	0.8909	398	0.8731	448	0.8557	498	0.8386
49	1.0044	99	0.9846	149	0.9651	199	0.9460	249	0.9272	299	0.9087	349	0.8906	399	0.8728	449	0.8554	499	0.8383

*Specific gravity of materials at 60°F of 0.850 to 0.966.
After Reference 21.

t = Observed temperature in degrees Fahrenheit.

M = Multiplier for correcting oil volumes to the basis of 60°F.

Table 12. Temperature-Volume Corrections for Emulsified Asphalts.

t	M	t	M	t	M
60	1.00000	90	.99250	121	.98475
61	.99975	91	.99225	122	.98450
62	.99950	92	.99200	123	.98425
63	.99925	93	.99175	124	.98400
64	.99900	94	.99150	125	.98375
65	.99875	95	.99125	126	.98350
66	.99850	96	.99100	127	.98325
67	.99825	97	.99075	128	.98300
68	.99800	98	.99050	129	.98275
69	.99775	99	.99025	130	.98250
70	.99750	100	.99000	131	.98225
71	.99725	101	.98975	132	.98200
72	.99700	102	.98950	133	.98175
73	.99675	103	.98925	134	.98150
74	.99650	104	.98900	135	.98125
75	.99625	105	.98875	136	.98100
76	.99600	106	.98850	137	.98075
77	.99575	107	.98825	138	.98050
78	.99550	108	.98800	139	.98025
79	.99525	109	.98775	140	.98000
80	.99500	110	.98750	141	.97975
81	.99475	111	.98725	142	.97950
82	.99450	112	.98700	143	.97925
83	.99425	113	.98675	144	.97900
84	.99400	114	.98650	145	.97875
85	.99375	115	.98625	146	.97850
86	.99350	116	.98600	147	.97825
87	.99325	117	.98575	148	.97800
88	.99300	118	.98550	149	.97775
89	.99275	119	.98525	150	.97750
		120	.98500		

t = Observed temperature in degrees Fahrenheit.

M = Multiplier for correcting volumes to the basis of 60°F.

PENNSYLVANIA DESIGN METHOD FOR SEAL COATS AND SURFACE TREATMENTS

A. MATERIAL NEEDED

A 50-lb. representative sample of stone to be used.

B. INFORMATION NEEDED

1. Average Daily Traffic (ADT)

2. Condition of the existing surface to be treated out of the following five categories.

(a) Flushed asphalt surface - Significant portion of the pavement has free bitumen on the surface.

(b) Smooth nonporous surface - Tightly textured surface; fine and/or coarse aggregate are tightly enmeshed in a bitumen matrix.

(c) Slightly porous, oxidized surface - Beginning stage of oxidation; small pieces of fine and/or coarse aggregate are beginning to ravel out of the surface.

(d) Slightly pocked, porous and oxidized surface - Characterized by significant loss of fine and/or coarse aggregate from the pavement surface.

(e) Badly-pocked, porous and oxidized surface - Severe loss of surface aggregate; remaining aggregate can be loosened easily; the bitumen holding the aggregate is dry with complete loss of sticky characteristic. This category should also be used for treating open graded mixture surfaces, such as, FB-1 and FB-2.

3. Type of bitumen to be used (asphalt cement/cutback/emulsion).

4. Type of aggregate (limestone/gravel/slag).

C. EQUIPMENT NEEDED

1. One-third Cubic Ft. Unit Weight Steel Bucket (Inside Dimensions 8.0" Dia. x 11.5" H) meeting PTM 609.

2. Large Scoop 4-1/2" wide x 9" long.

3. Heavy Duty Portable Platform Style Scale, capacity 205 lbs. with 0.01 lb. sub-graduations.

4. Mechanical or portable hand-operated sieve shaker, capacity 6 full height or 13 half-height 8" dia. sieves with pan and cover.

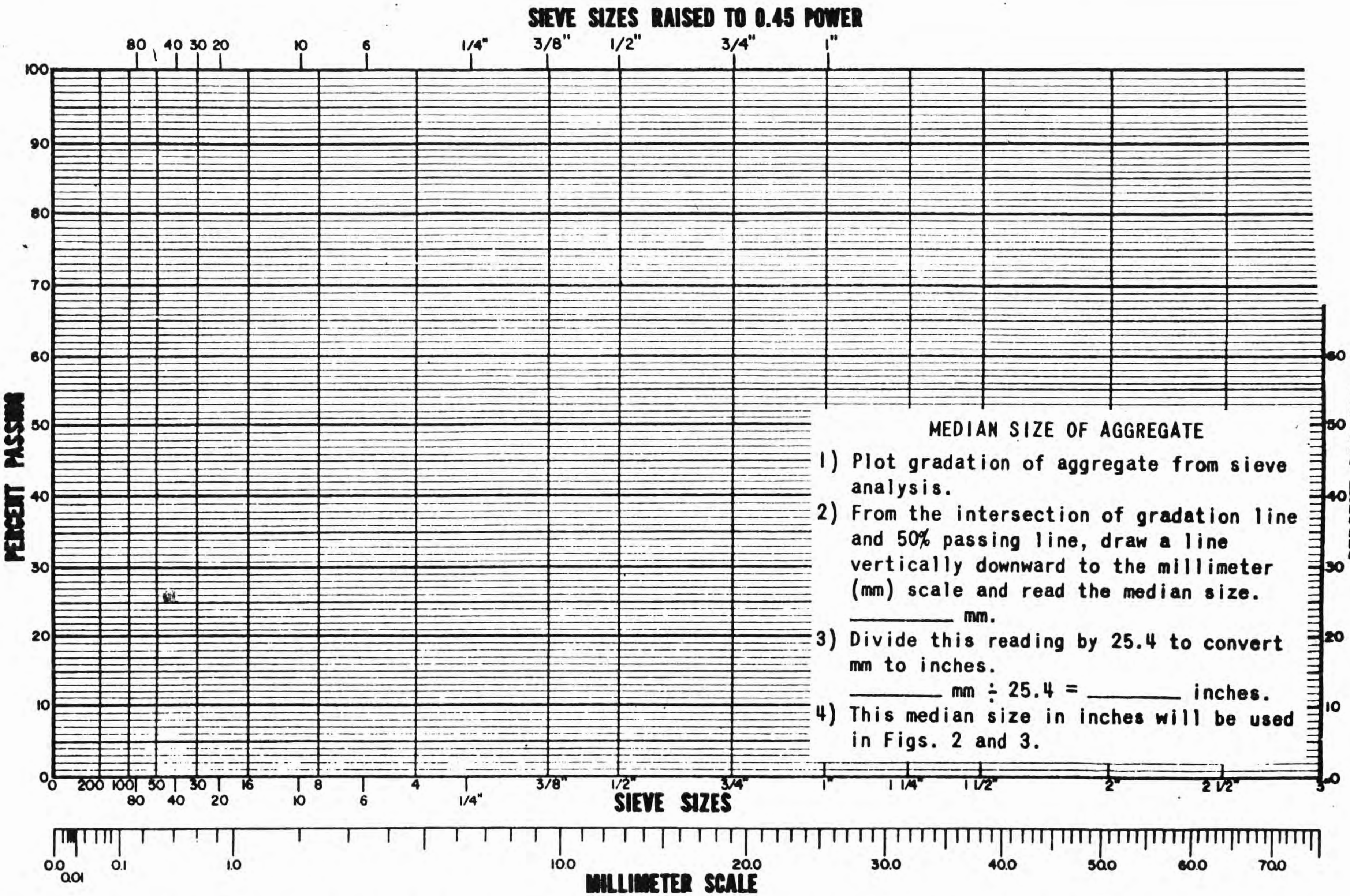
5. A set of sieves 1", 3/4", 1/2", 3/8", #4 and #8 with pan, cover and cleaning brush (meeting AASHTO M92).

TR-303 (10-81)

FIG. I GRADATION CHART

DISTRICT__________ COUNTY__________ L.R.__________ SECTION__________

AGGREGATE TYPE__________ SUPPLIER__________



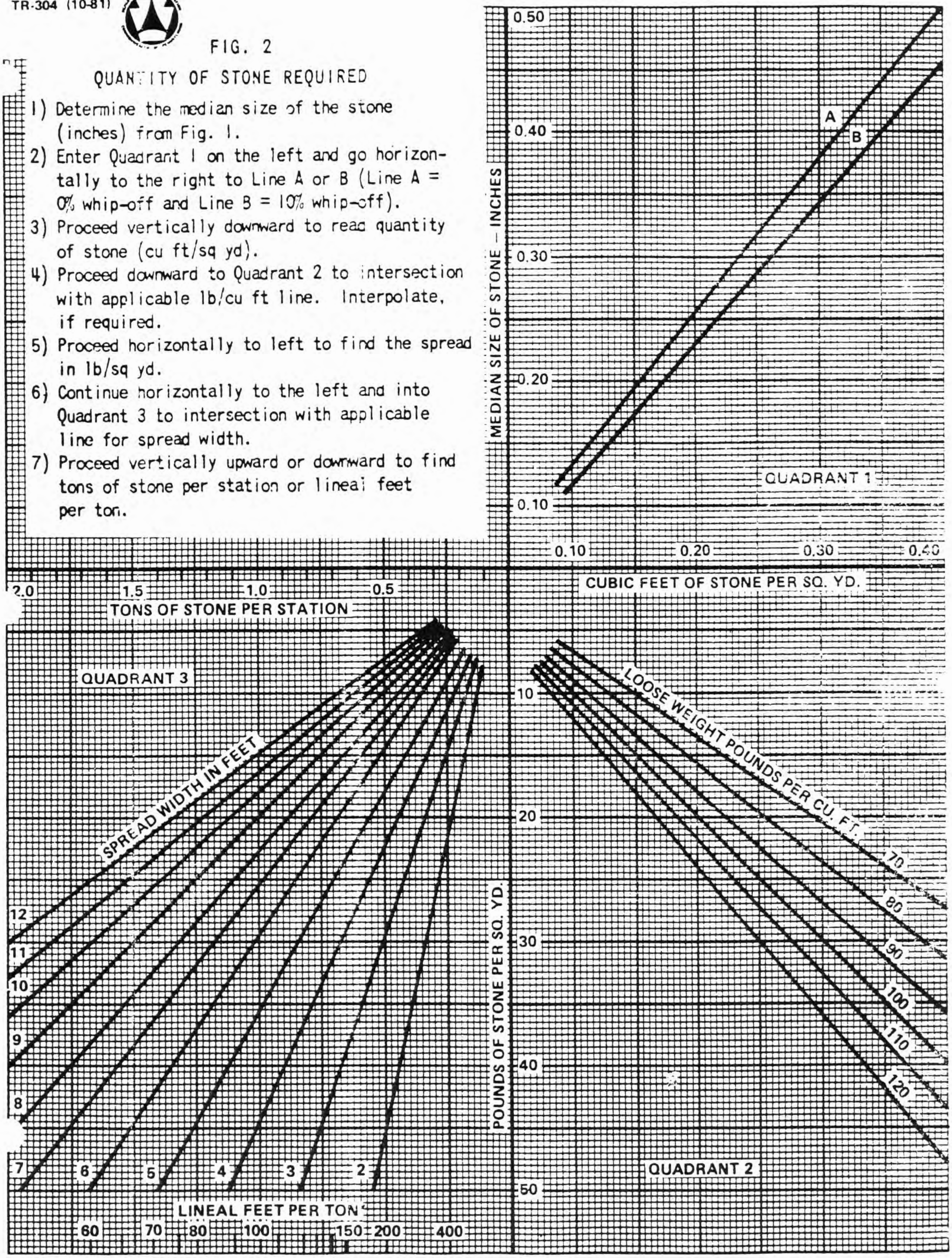
MEDIAN SIZE OF AGGREGATE

1) Plot gradation of aggregate from sieve analysis.
2) From the intersection of gradation line and 50% passing line, draw a line vertically downward to the millimeter (mm) scale and read the median size.
________ mm.
3) Divide this reading by 25.4 to convert mm to inches.
________ mm ÷ 25.4 = ________ inches.
4) This median size in inches will be used in Figs. 2 and 3.

FIG. 2

QUANTITY OF STONE REQUIRED

1) Determine the median size of the stone (inches) from Fig. 1.
2) Enter Quadrant 1 on the left and go horizontally to the right to Line A or B (Line A = 0% whip-off and Line B = 10% whip-off).
3) Proceed vertically downward to read quantity of stone (cu ft/sq yd).
4) Proceed downward to Quadrant 2 to intersection with applicable lb/cu ft line. Interpolate, if required.
5) Proceed horizontally to left to find the spread in lb/sq yd.
6) Continue horizontally to the left and into Quadrant 3 to intersection with applicable line for spread width.
7) Proceed vertically upward or downward to find tons of stone per station or lineal feet per ton.

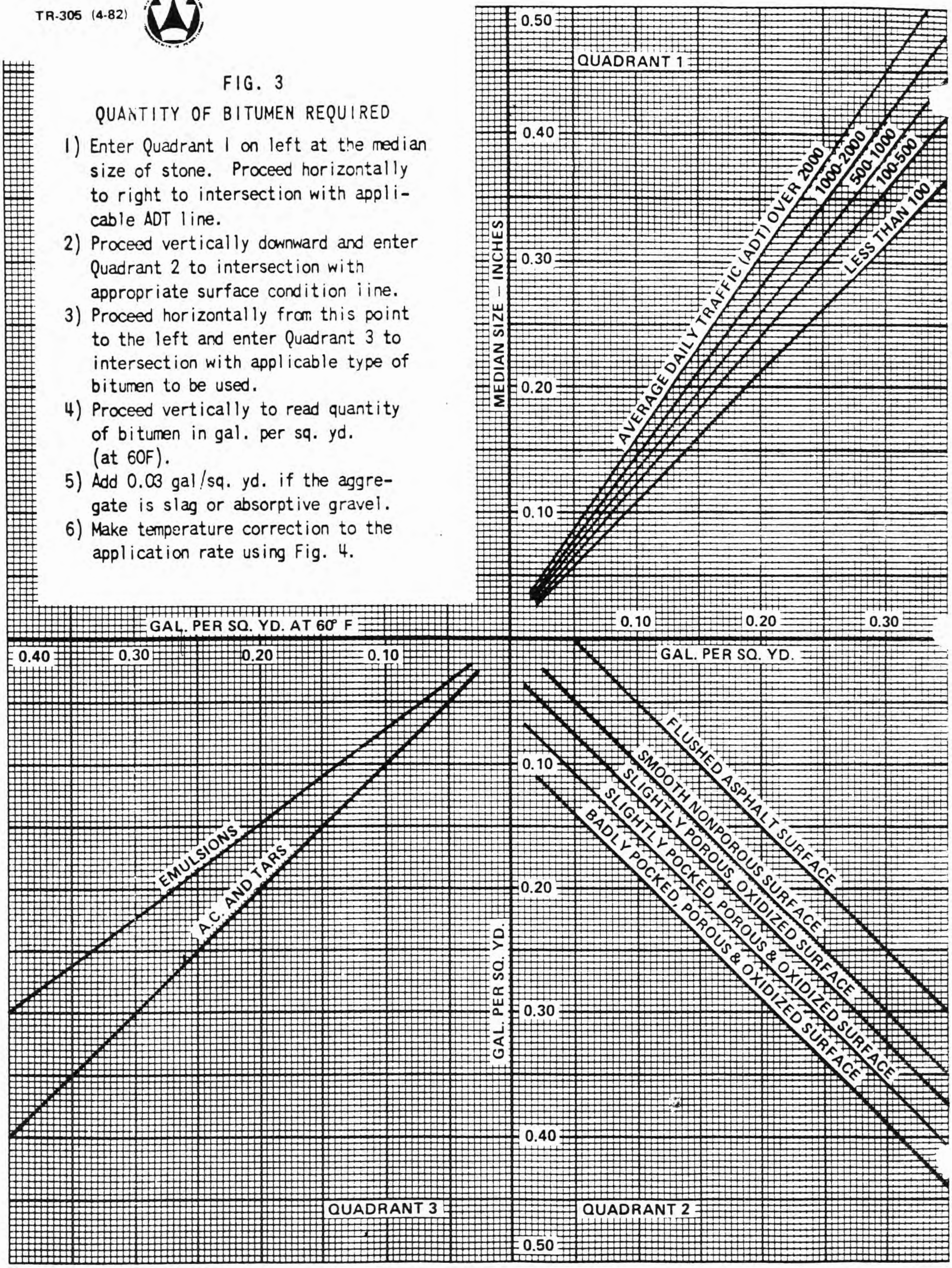


TR-305 (4-82)

FIG. 3

QUANTITY OF BITUMEN REQUIRED

1) Enter Quadrant I on left at the median size of stone. Proceed horizontally to right to intersection with applicable ADT line.
2) Proceed vertically downward and enter Quadrant 2 to intersection with appropriate surface condition line.
3) Proceed horizontally from this point to the left and enter Quadrant 3 to intersection with applicable type of bitumen to be used.
4) Proceed vertically to read quantity of bitumen in gal. per sq. yd. (at 60F).
5) Add 0.03 gal/sq. yd. if the aggregate is slag or absorptive gravel.
6) Make temperature correction to the application rate using Fig. 4.



TR-307 (11-75)

FIG. 4. TEMPERATURE GALLONAGE CONVERSION CHART FOR BITUMINOUS SURFACE TREATMENT APPLICATIONS

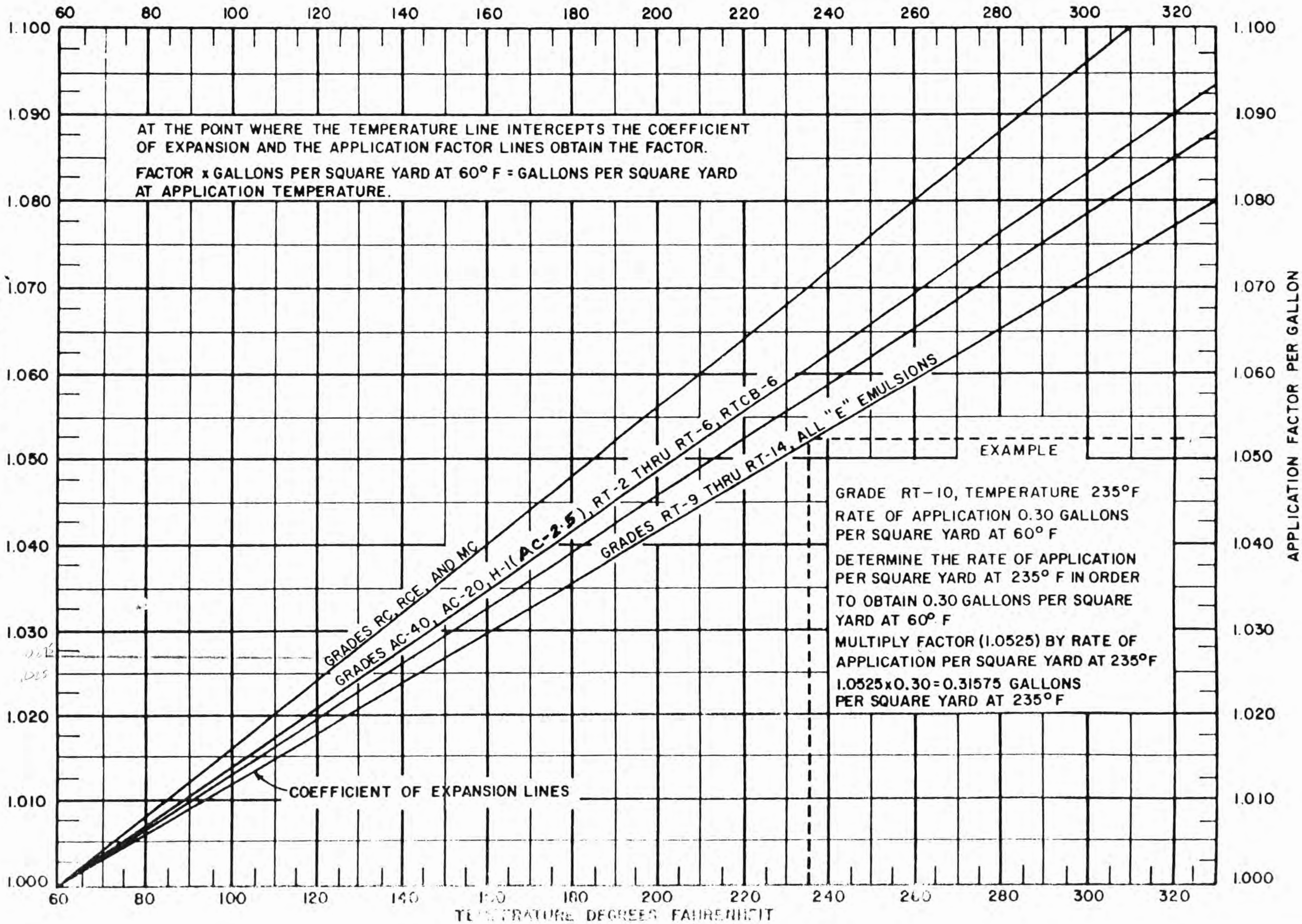
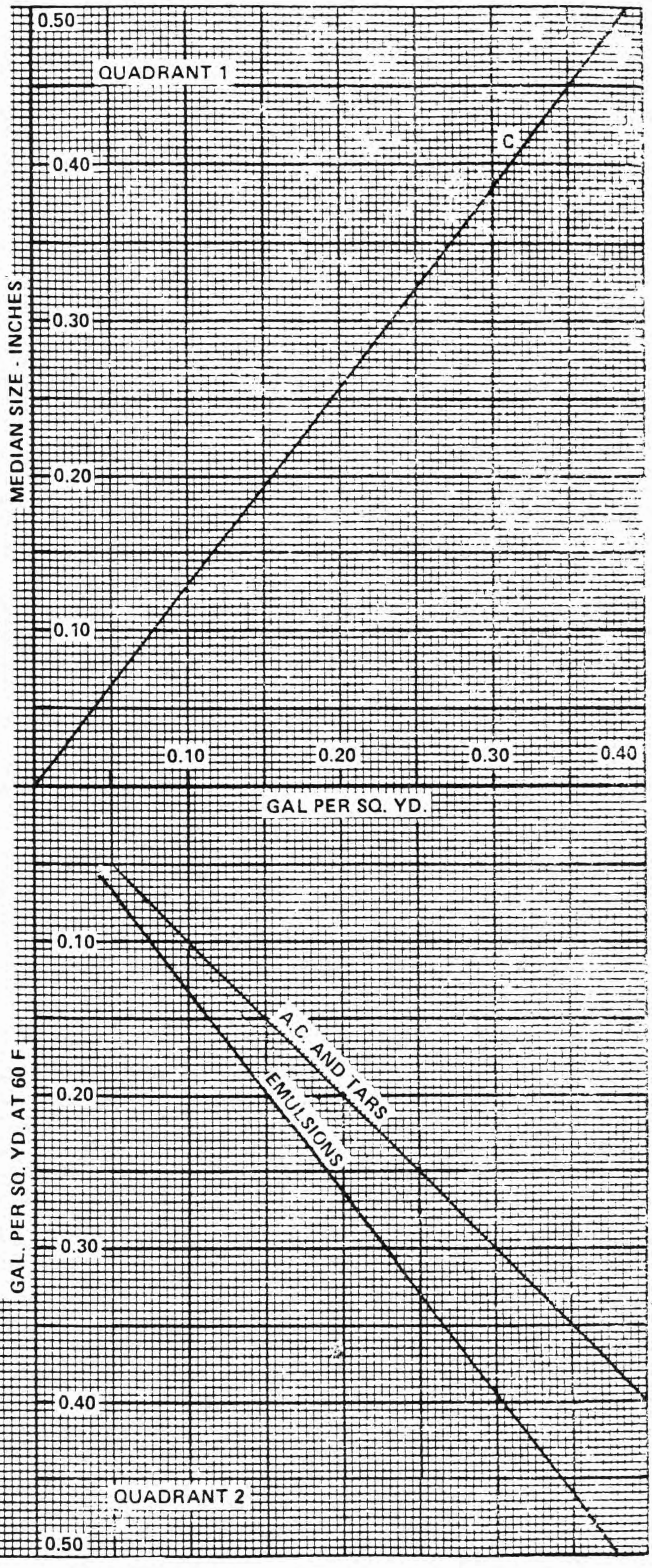


FIG. 5

QUANTITY OF BITUMEN REQUIRED (DOUBLE APPLICATION)

1) Enter Quadrant I on left at the median size of stone to be used in first application (e.g., Pa. #2). Proceed horizontally to right to intersection with Line C.
2) Proceed vertically downward and enter Quadrant 2 to intersection with applicable type of bitumen to be used.
3) Proceed horizontally to read quantity of bitumen in gal per sq yd (say Q_1 gal per sq yd).
4) Enter Quadrant I on left at the median size of stone to be used in second application (e.g., Pa. #1B). Proceed horizontally to right to intersection with Line C.
5) Repeat Steps 2 and 3 above. and read quantity of bitumen in gal per sq yd (say Q_2 gal per sq yd).
6) Total bitumen (Q) required for double application $= Q_1 + Q_2$
7) Bitumen required for first application (gal/sq yd) $= 0.4\ Q$
8) Bitumen required for second application = 0.6 Q
9) Make temperature corrections to the application rates using Fig. 4.

Note: The quantities in steps (7) and (8) may be reversed if so desired by the Engineer.



EXAMPLES ON DESIGN OF

SEAL COATS AND SURFACE TREATMENTS

EXAMPLE NO. 1

DESIGN OF SINGLE APPLICATION (SEAL COAT)

A. AGGREGATE

Pa. #1B (AASHTO #8) Limestone Aggregate. A 50-lb. representative sample was obtained from the stockpile.

B. INFORMATION GATHERED

1. Average Daily Traffic (ADT) = 450
2. Condition of the existing surface to be treated: Slightly pocked, porous and oxidized surface
3. Type of bitumen to be used: E-2 or E-3 Emulsified Asphalt
4. Type of Aggregate: Pa. #1 B Limestone
5. Assume 10% whip-off loss

C. TESTING OF AGGREGATE

1. Loose Weight Determination (PTM 609, Section 7): The stone weighed 100 pounds per cu. ft.
2. Sieve Analysis and Gradation: Initial weight of the stone graded was 12 lbs. The worksheet follows:

Passing	Weight of Material on sieve, lbs.	Accumulative Weight Passing, lbs.	Total Percent
1/2"	0	12	100
3/8"	1.8	10.2	85
#4	8.4	1.8	15
#8	1.4	0.4	3
Pan	0.4	-	-

D. DESIGN OF SINGLE APPLICATION

Plot the various percentages passing sieves 1/2", 3/8", #4 and #8 on the Gradation Chart (see Figure 1 - Example No. 1). Connect the points by straight lines to obtain the gradation line. From the intersection of gradation line and 50% passing line, draw a line vertically downward to the millimeter scale and read the median size as 6.8 mm. Divide 6.8 by 25.4 to convert mm to inches. So the median size is 0.27 inch.

Quantity of Stone (pounds per sq. yd.):

See Fig. 2 of Example 1. Enter Quadrant 1 on the left at 0.27 inch median size. Go horizontally to the right to Line B (10% whip-off). Proceed vertically downward to Quadrant 2 and intersect with 100 pounds per cu. ft. line. Proceed horizontally to left to find the spread in lb/sq. yd. = 23.5. So the quantity of stone for the single application is 23.5 lbs. per sq. yd. Quadrant 3 can be used, if necessary, for computing the tonnage of stone required per station. If the roadway or spread width is 12 ft., 1.55 tons of stone would be required per station.

NOTE: Use Line A (0% whip-off) if the seal coat is applied on shoulder or precoated stone is used or the past experience indicates minimal whip-off loss.

Quantity of Bitumen (gal. per sq. yd.):

See Fig. 3 of Example 1. Enter Quardrant 1 on left at 0.27 inch median size. Go horizontally to the right to intersect with 100-500 ADT line (since ADT = 450). Proceed vertically downward and enter Quadrant 2 to intersect with appropriate surface condition line. In this example, the surface is slightly pocked, porous and oxidized. Proceed horizontally from this point to the left and enter Quadrant 3 to intersect with applicable type of bitumen (emulsion in this case). Proceed vertically to read quantity of bitumen in gal. per sq. yd. (at 60°F) = 0.375. Assume that the temperature of E-2 or E-3 emulsion in the distributor is 165°F. Use Fig. 4 to determine the application rate at 165°F. Enter the graph at 165°F temperature, proceed vertically to intersect with emulsion line and then proceed horizontally to the left to read the application factor = 1.031. Obtain the application rate at 165°F as follows:

$$1.031 \times 0.375 = 0.387 \text{ gal/sq. yd.}$$

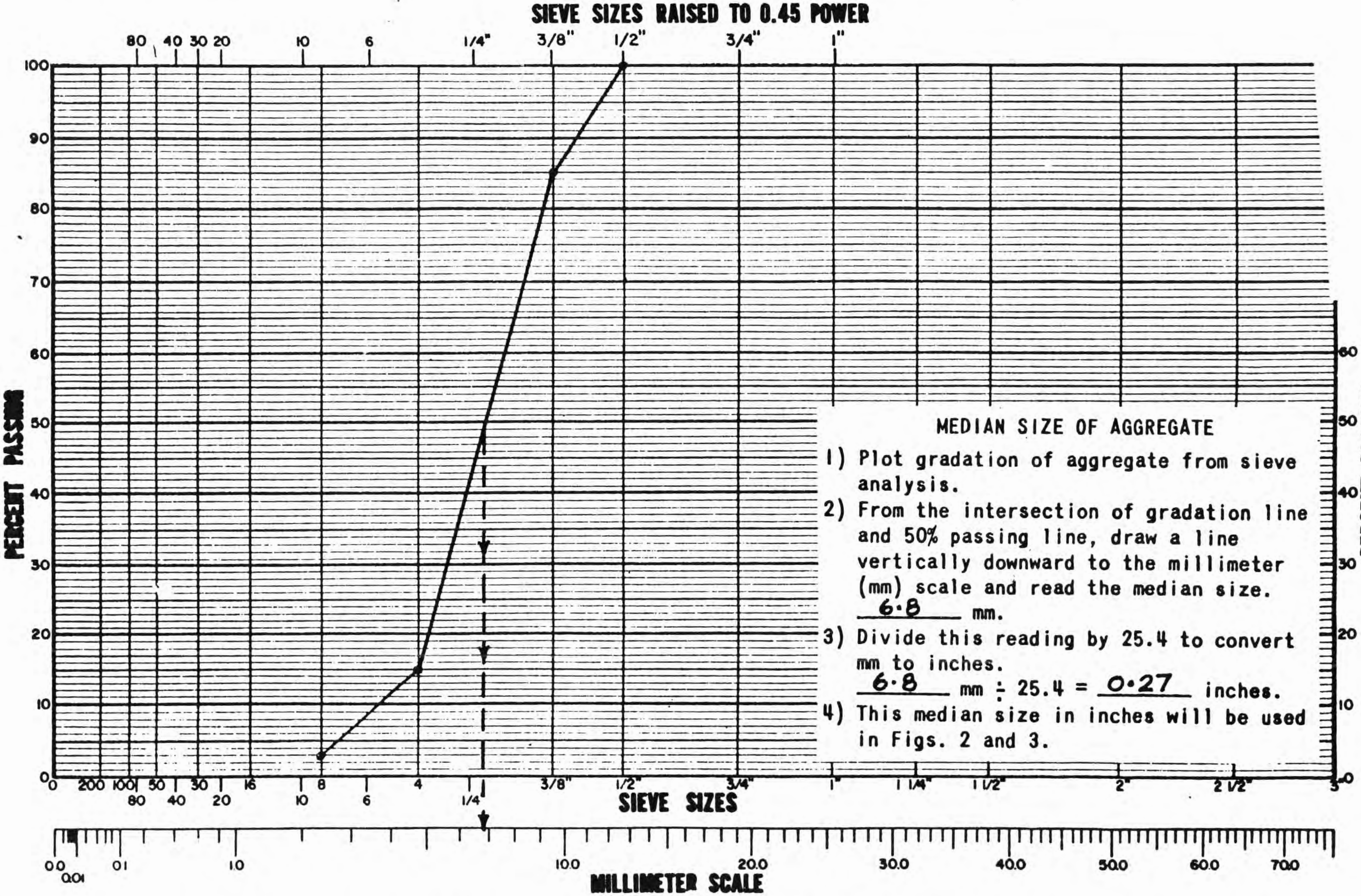
So the bitumen application rate (at 165°F) on the job shall be 0.39 gal/sq. yd.

TR-303 (10-81)

FIG. I GRADATION CHART — EXAMPLE NO. 1

DISTRICT ______ COUNTY ______ L.R. ______ SECTION ______

AGGREGATE TYPE 1B LIME STONE SUPPLIER ______



MEDIAN SIZE OF AGGREGATE

1) Plot gradation of aggregate from sieve analysis.
2) From the intersection of gradation line and 50% passing line, draw a line vertically downward to the millimeter (mm) scale and read the median size. 6.8 mm.
3) Divide this reading by 25.4 to convert mm to inches. 6.8 mm ÷ 25.4 = 0.27 inches.
4) This median size in inches will be used in Figs. 2 and 3.

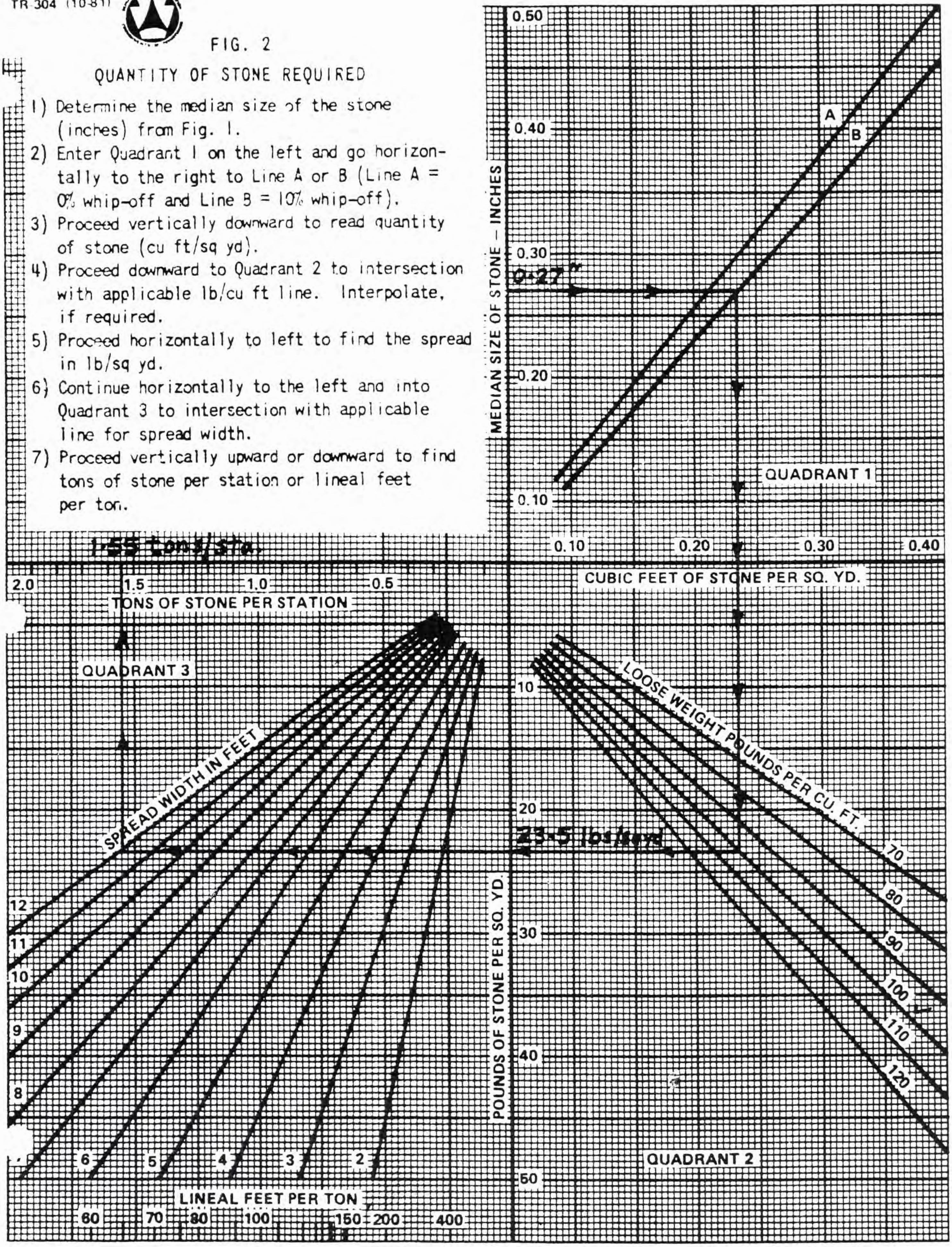
TR 304 (10-81)

EXAMPLE NO. 1

FIG. 2

QUANTITY OF STONE REQUIRED

1) Determine the median size of the stone (inches) from Fig. 1.
2) Enter Quadrant 1 on the left and go horizontally to the right to Line A or B (Line A = 0% whip-off and Line B = 10% whip-off).
3) Proceed vertically downward to read quantity of stone (cu ft/sq yd).
4) Proceed downward to Quadrant 2 to intersection with applicable lb/cu ft line. Interpolate, if required.
5) Proceed horizontally to left to find the spread in lb/sq yd.
6) Continue horizontally to the left and into Quadrant 3 to intersection with applicable line for spread width.
7) Proceed vertically upward or downward to find tons of stone per station or lineal feet per ton.



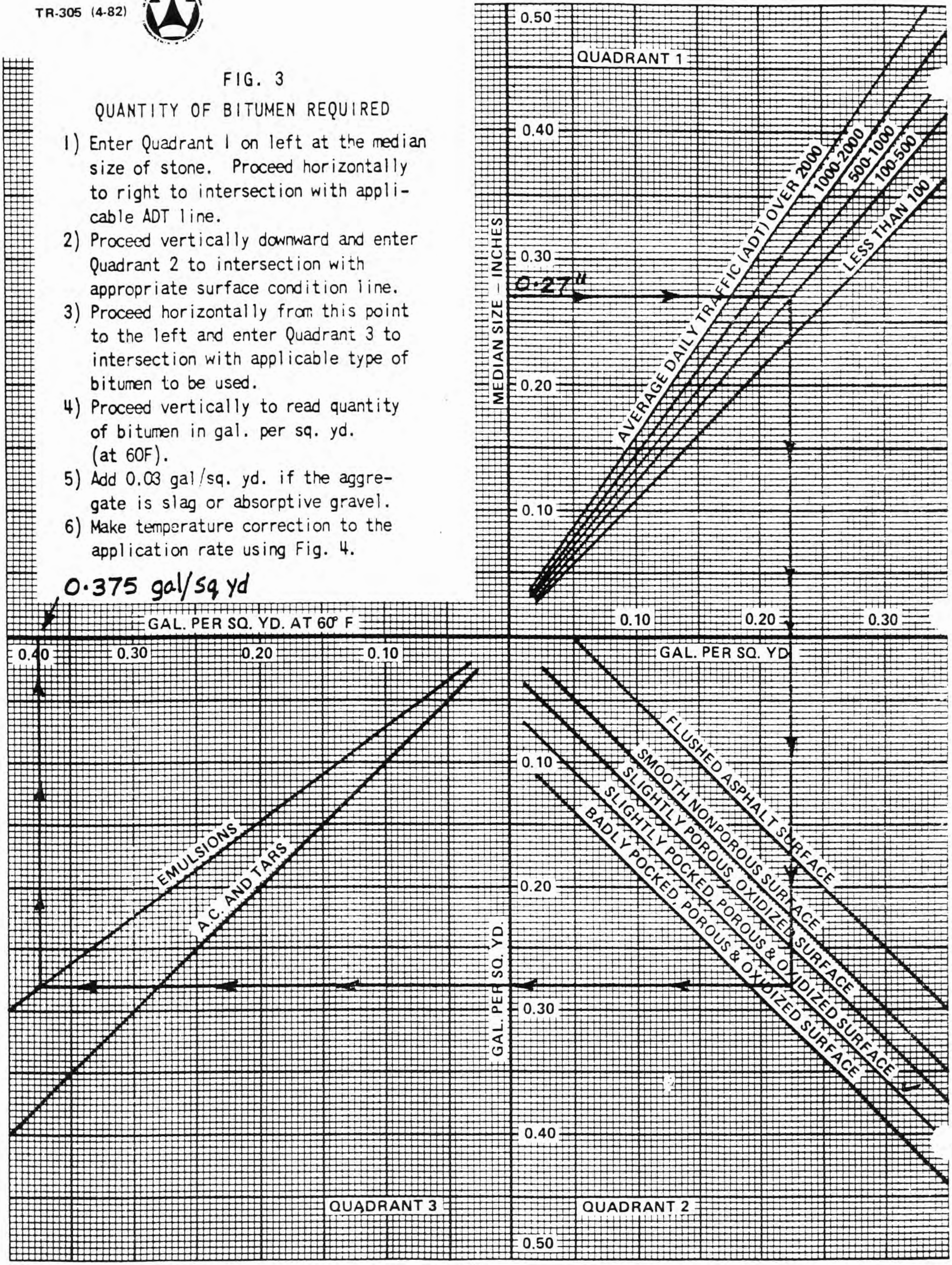
EXAMPLE NO. 1

FIG. 3

QUANTITY OF BITUMEN REQUIRED

1) Enter Quadrant I on left at the median size of stone. Proceed horizontally to right to intersection with applicable ADT line.
2) Proceed vertically downward and enter Quadrant 2 to intersection with appropriate surface condition line.
3) Proceed horizontally from this point to the left and enter Quadrant 3 to intersection with applicable type of bitumen to be used.
4) Proceed vertically to read quantity of bitumen in gal. per sq. yd. (at 60F).
5) Add 0.03 gal/sq. yd. if the aggregate is slag or absorptive gravel.
6) Make temperature correction to the application rate using Fig. 4.

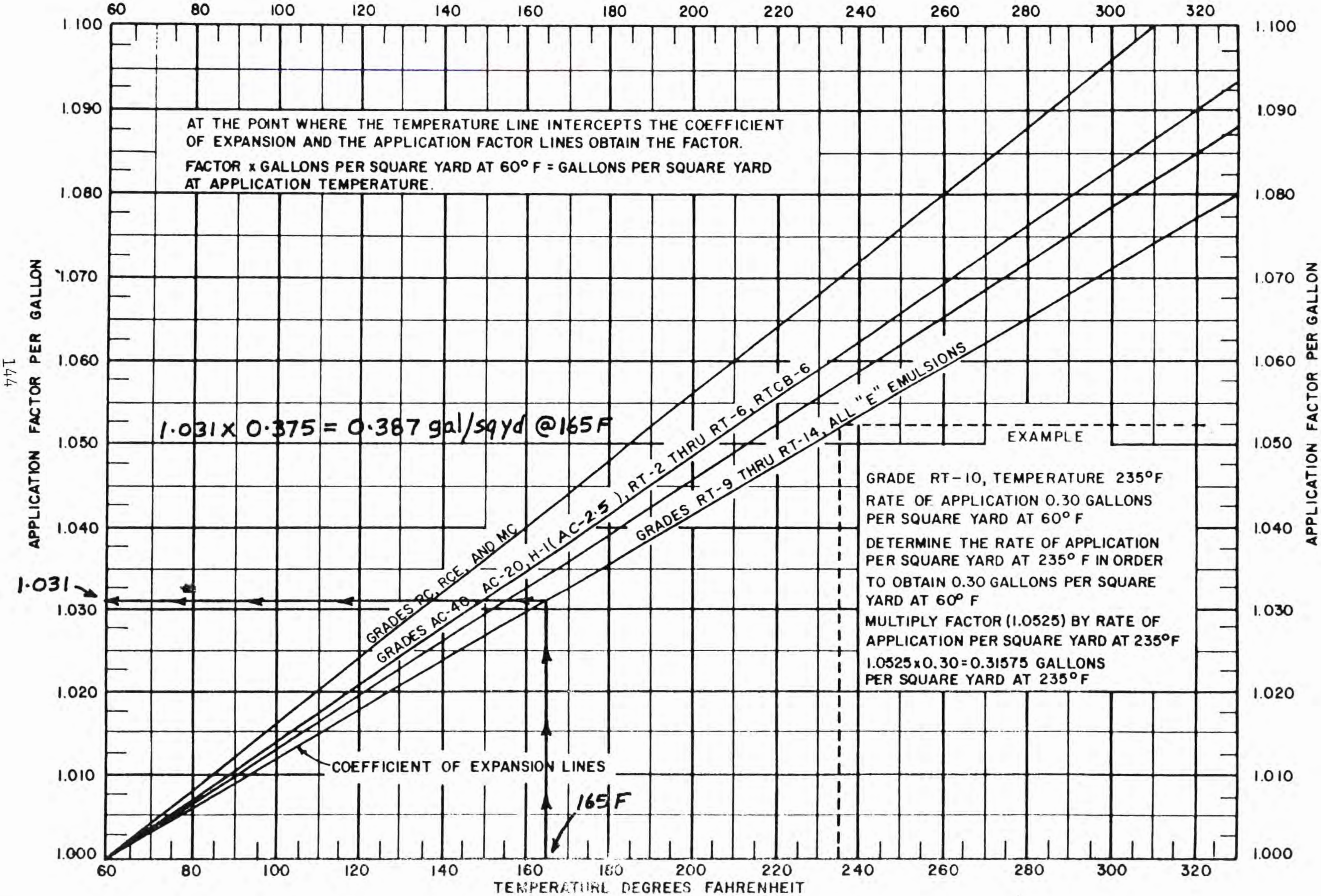
0·375 gal/sq yd



TR-307 (11-75)

EXAMPLE NO. 1

FIG. 4. TEMPERATURE GALLONAGE CONVERSION CHART FOR BITUMINOUS SURFACE TREATMENT APPLICATIONS



144

EXAMPLE NO. 2

DESIGN OF DOUBLE APPLICATION (SURFACE TREATMENT)

A. AGGREGATES

Pa. #1B (AASHTO #8) and #2 (AASHTO #67) Limestone Aggregates

B. INFORMATION GATHERED

1. Condition of the existing surface to be treated: Badly pocked, porous and oxidized surface.

2. Type of bitumen to be used: E-2 or E-3 Emulsified Asphalt

3. Type of Aggregate: Limestone

4. Assume 0% whip-off loss for the second application rate

C. TESTING OF AGGREGATE

1. Loose Weight Determination (PTM 609, Section 7): Assume that both aggregates weighed 100 pounds per cu. ft.

2. Sieve Analysis and Gradation: See Example No. 1 for worksheet. Assume that #1B stone has the same gradation as given in Example No. 1 and has a median size of 0.27 inch.

The following gradation was obtained for #2 stone:

Sieve Size	Percent Passing
1"	100
3/4"	96
3/8"	45
#4	6
#8	2

The above gradation has been plotted on Fig. 1 (Example No. 2) and the median size has been determined to be 0.40 inch.

D. DESIGN OF DOUBLE APPLICATION

Quantity of Stone (pounds per sq. yd.):

See Fig. 2 of Example 2. Enter Quadrant 1 on the left side at 0.40 and 0.27 inch median sizes for Pa. #2 and #1B aggregates, respectively. Go horizontally to the right to Line A (0% whip-off). Proceed vertically downward to Quardrant 2 and intersect with 100 pounds per cu. ft. line. Proceed horizontally to the left to find the spread in lbs/sq. yd. The following application rates are obtained:

Pa. #2	31.5 lbs./sq. yd.
#1B	21.0 lbs./sq. yd.

Quantity of Bitumen (gal. per sq. yd.):

See Fig. 5 of Example 2. Enter Quardrant 1 on the left side at 0.40 and 0.27 inch median sizes for Pa. #2 and #1B aggregates, respectively. Go horizontally to the right to Line C. Proceed vertically downward to Quadrant 2 and intersect with applicable type of bitumen (emulsion in this case). Proceed horizontally to the left to read quantities of bitumen as follows:

Q_1 = 0.405 gal. per sq. yd. (at 60°F)

Q_2 = 0.275 gal. per sq. yd. (at 60°F)

Total bitumen (Q) required for double application

$= Q_1 + Q_2$

= 0.405 + 0.275 = 0.68 gal. per sq. yd.

NOTE: If a slag or absorptive gravel aggregate is used, the total bitumen (Q) should be increased by 0.06 gal. per sq. yd. This example involves limestone aggregates.

Bitumen required for first application on a smooth, nonporous surface

= 0.4 Q = 0.4 x 0.68 = 0.27 gal./sq. yd.

Since the existing surface is badly pocked, porous and oxidized, add 0.09 gal/sq. yd. The corrected bitumen required for first application

= 0.27 + 0.09 = 0.36 gal/sq. yd.

Bitumen required for second application

= 0.6 Q = 0.6 x 0.68 = 0.41 gal./sq. yd.

These application rates in gal./sq. yd. are at 60°F, so make temperature corrections using Fig. 4 (see Example 1 for procedure) corresponding to the actual temperature of the emulsion in the distributor.

If the emulsion temperature is 165°F, the application rates at 165°F will be:

First Application Rate = 1.031 x 0.36 = 0.37 gal/sq. yd.

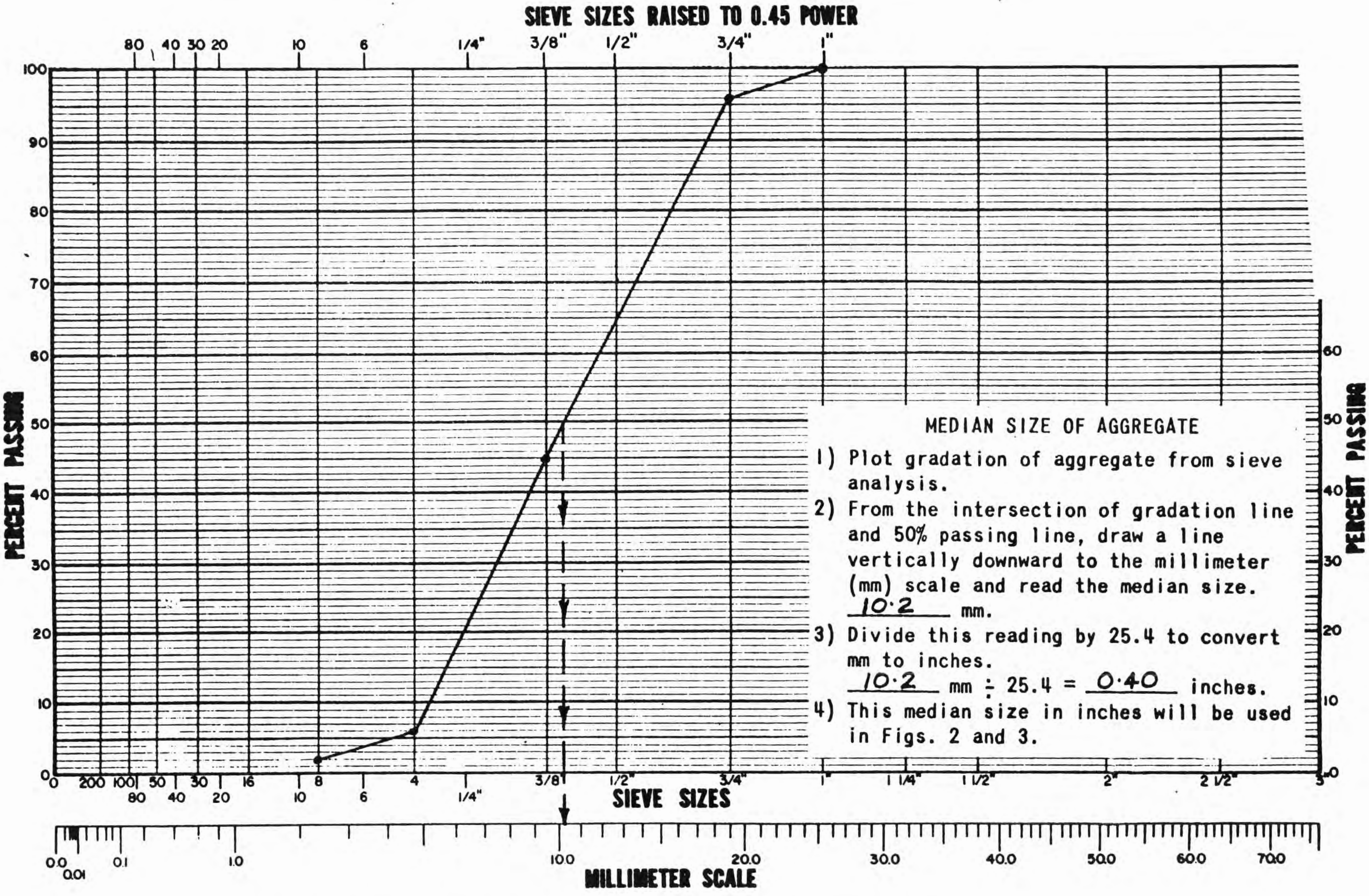
Second Application Rate = 1.031 x 0.41 = 0.42 gal/sq. yd.

TR-303 (10-81)

FIG. I GRADATION CHART (EXAMPLE NO. 2)

DISTRICT______ COUNTY______ L.R.______ SECTION______

AGGREGATE TYPE PA. # 2 LIME STONE SUPPLIER______



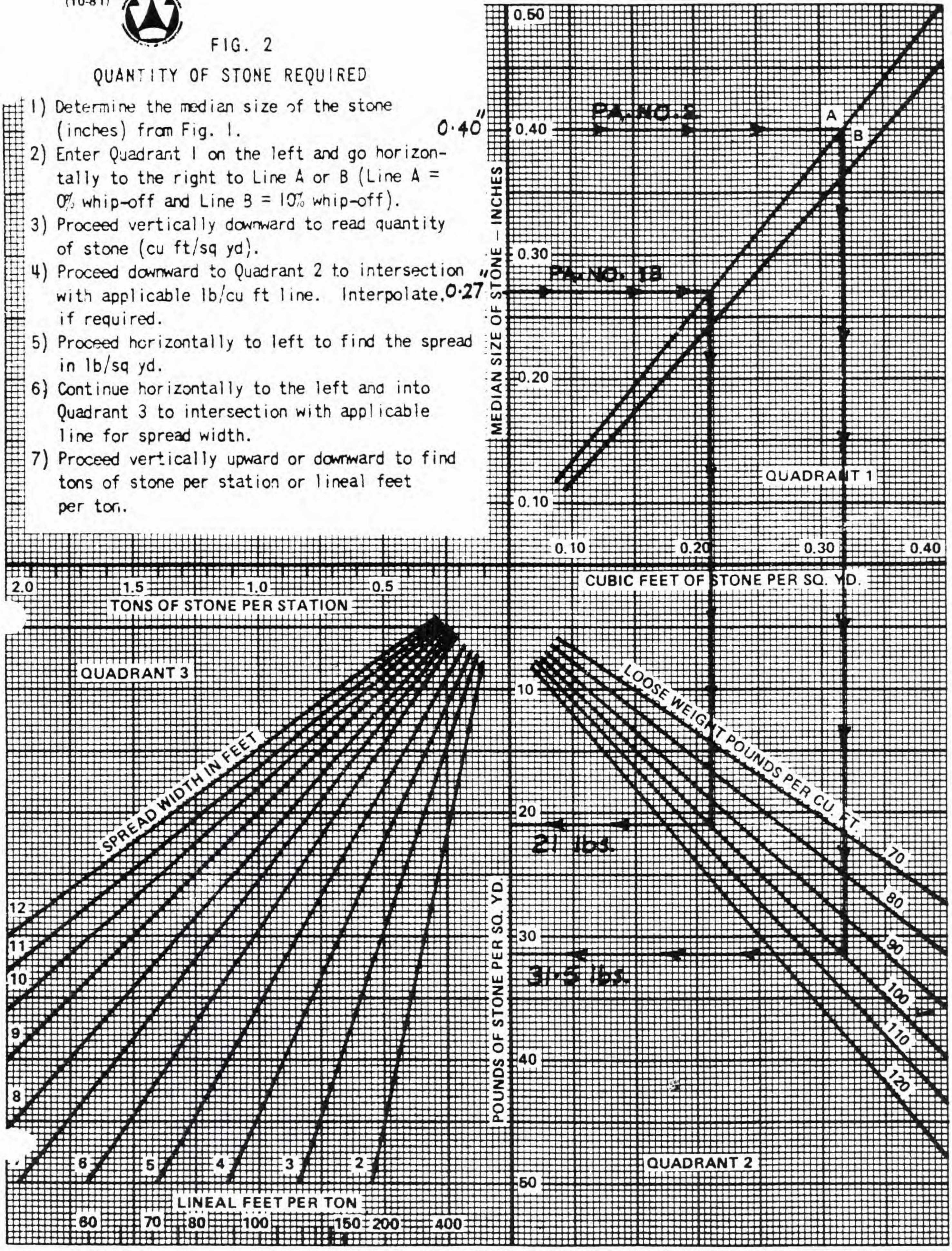
EXAMPLE NO. 2

(10-81)

FIG. 2

QUANTITY OF STONE REQUIRED

1) Determine the median size of the stone (inches) from Fig. 1.
2) Enter Quadrant 1 on the left and go horizontally to the right to Line A or B (Line A = 0% whip-off and Line B = 10% whip-off).
3) Proceed vertically downward to read quantity of stone (cu ft/sq yd).
4) Proceed downward to Quadrant 2 to intersection with applicable lb/cu ft line. Interpolate, if required.
5) Proceed horizontally to left to find the spread in lb/sq yd.
6) Continue horizontally to the left and into Quadrant 3 to intersection with applicable line for spread width.
7) Proceed vertically upward or downward to find tons of stone per station or lineal feet per ton.



TR-306 (10-81)

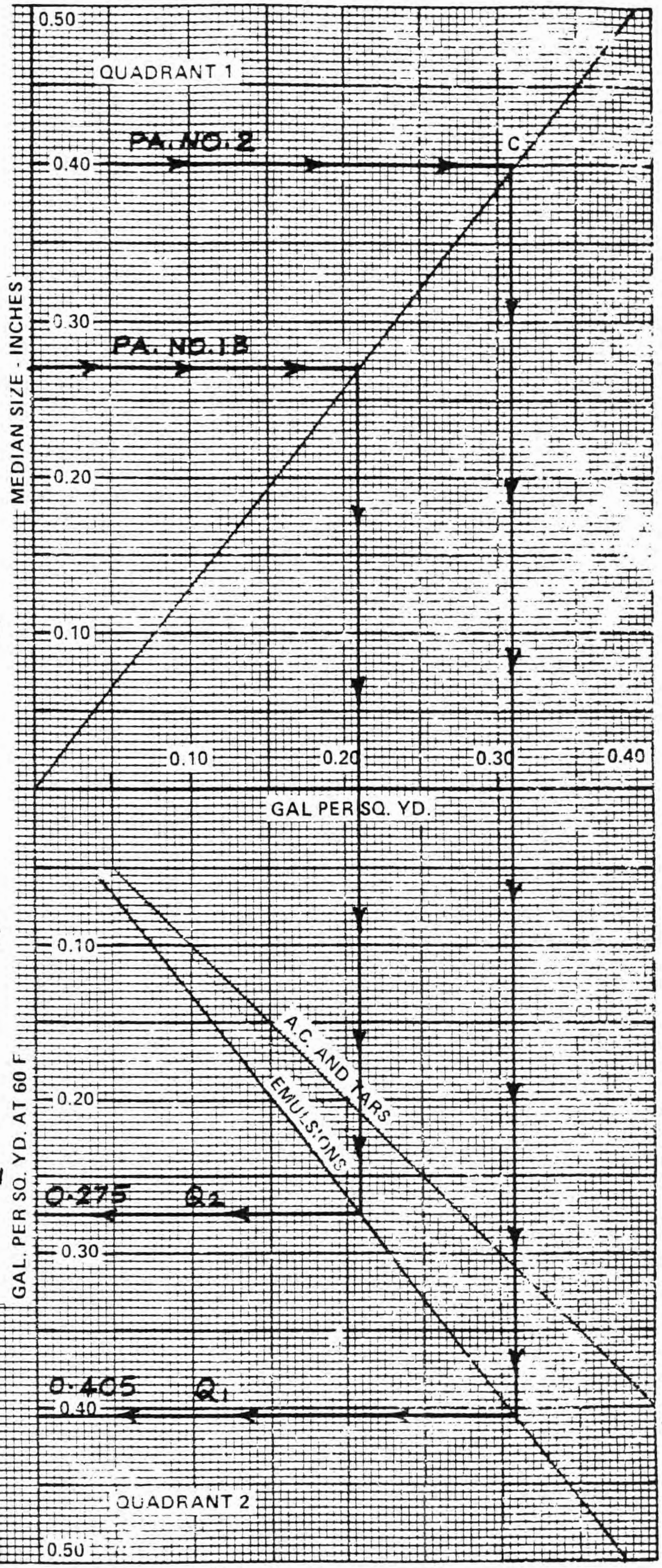
FIG. 5

QUANTITY OF BITUMEN REQUIRED (DOUBLE APPLICATION)

1) Enter Quadrant I on left at the median size of stone to be used in first application (e.g., Pa. #2). Proceed horizontally to right to intersection with Line C.
2) Proceed vertically downward and enter Quadrant 2 to intersection with applicable type of bitumen to be used.
3) Proceed horizontally to read quantity of bitumen in gal per sq yd (say Q_1 gal per sq yd). **= 0·405**
4) Enter Quadrant I on left at the median size of stone to be used in second application (e.g., Pa. #1B). Proceed horizontally to right to intersection with Line C.
5) Repeat Steps 2 and 3 above, and read quantity of bitumen in gal per sq yd (say Q_2 gal per sq yd). **= 0·275**
6) Total bitumen (Q) required for double application $= Q_1 + Q_2$ **= 0·405 + 0·275 = 0·68**
7) Bitumen required for first application (gal/sq yd) = 0.4 Q **= 0·4 × 0·68 = 0·27** **Add 0·09 for surface. Total = 0·36**
8) Bitumen required for second application = 0.6 Q **= 0·6 × 0·68 = 0·41**
9) Make temperature corrections to the application rates using Fig. 4.

Note: The quantities in steps (7) and (8) may be reversed if so desired by the Engineer.

EXAMPLE NO. 2



APPENDIX C

SOUTH DAKOTA ASPHALT SURFACE TREATMENT SPECIFICATION

360.1 DESCRIPTION

This work consists of an application of asphalt covered with a spread of cover aggregate.

360.2 MATERIALS

A. **Asphalt:** Asphalt shall conform to Section 890.

B. **Cover Aggregate:** Cover aggregate shall conform to Section 881.

360.3 CONSTRUCTION REQUIREMENTS

A. **Weather and Seasonal Requirements:** Surface treatment operations will be permitted only during daylight hours, when conditions are dry and when wind does not adversely affect the spraying operation.

Minimum temperatures and seasonal limitations are as follows:

COVER AGGREGATE	AIR & SURFACE TEMP. (IN THE SHADE)	SEASONAL LIMITATIONS (DATES ARE INCLUSIVE)
Type 1	70 degrees F.	June 1 - Sept. 15
Type 2	70 degrees F.	June 1 - Sept. 15
Type 3A	60 degrees F.	June 1 - Aug. 31
Type 3A	70 degrees F.	Sept 1 - Sept. 15
Type 3B	50 degrees F.	May 1 - Dec. 1

B. **Equipment:** The following equipment shall be furnished:

1. A rotary power broom.
2. Equipment for heating and applying the asphalt conforming to the requirements of Section 330.
3. A self-propelled aggregate spreader, with positive controls capable of depositing the required quantity of aggregate uniformly over the full width of the asphalt application. When spreading Type 2 cover aggregate, the spreader shall apply the larger

SECTION 360
ASPHALT SURFACE TREATMENT

360.1 DESCRIPTION

This work consists of an application of asphalt covered with a spread of cover aggregate.

360.2 MATERIALS

A. **Asphalt:** Asphalt shall conform to Section 890.

B. **Cover Aggregate:** Cover aggregate shall conform to Section 881.

360.3 CONSTRUCTION REQUIREMENTS

A. **Weather and Seasonal Requirements:** Surface treatment operations will be permitted only during daylight hours, when conditions are dry and when wind does not adversely affect the spraying operation.

Minimum temperatures and seasonal limitations are as follows:

COVER AGGREGATE	AIR & SURFACE TEMP. (IN THE SHADE)	SEASONAL LIMITATIONS (DATES ARE INCLUSIVE)
Type 1	70 degrees F.	June 1 - Sept. 15
Type 2	70 degrees F.	June 1 - Sept. 15
Type 3A	60 degrees F.	June 1 - Aug. 31
Type 3A	70 degrees F.	Sept 1 - Sept. 15
Type 3B	50 degrees F.	May 1 - Dec. 1

B. **Equipment:** The following equipment shall be furnished:

1. A rotary power broom.

2. Equipment for heating and applying the asphalt conforming to the requirements of Section 330.

3. A self-propelled aggregate spreader, with positive controls capable of depositing the required quantity of aggregate uniformly over the full width of the asphalt application. When spreading Type 2 cover aggregate, the spreader shall apply the larger

SECTION 360
ASPHALT SURFACE TREATMENT

360.1 DESCRIPTION

This work consists of an application of asphalt covered with a spread of cover aggregate.

360.2 MATERIALS

A. **Asphalt:** Asphalt shall conform to Section 890.

B. **Cover Aggregate:** Cover aggregate shall conform to Section 881.

360.3 CONSTRUCTION REQUIREMENTS

A. **Weather and Seasonal Requirements:** Surface treatment operations will be permitted only during daylight hours, when conditions are dry and when wind does not adversely affect the spraying operation.

Minimum temperatures and seasonal limitations are as follows:

COVER AGGREGATE	AIR & SURFACE TEMP. (IN THE SHADE)	SEASONAL LIMITATIONS (DATES ARE INCLUSIVE)
Type 1	70 degrees F.	June 1 - Sept. 15
Type 2	70 degrees F.	June 1 - Sept. 15
Type 3A	60 degrees F.	June 1 - Aug. 31
Type 3A	70 degrees F.	Sept 1 - Sept. 15
Type 3B	50 degrees F.	May 1 - Dec. 1

B. **Equipment:** The following equipment shall be furnished:

1. A rotary power broom.

2. Equipment for heating and applying the asphalt conforming to the requirements of Section 330.

3. A self-propelled aggregate spreader, with positive controls capable of depositing the required quantity of aggregate uniformly over the full width of the asphalt application. When spreading Type 2 cover aggregate, the spreader shall apply the larger

SECTION 360
ASPHALT SURFACE TREATMENT

360.1 DESCRIPTION

This work consists of an application of asphalt covered with a spread of cover aggregate.

360.2 MATERIALS

A. **Asphalt:** Asphalt shall conform to Section 890.

B. **Cover Aggregate:** Cover aggregate shall conform to Section 881.

360.3 CONSTRUCTION REQUIREMENTS

A. **Weather and Seasonal Requirements:** Surface treatment operations will be permitted only during daylight hours, when conditions are dry and when wind does not adversely affect the spraying operation.

Minimum temperatures and seasonal limitations are as follows:

COVER AGGREGATE	AIR & SURFACE TEMP. (IN THE SHADE)	SEASONAL LIMITATIONS (DATES ARE INCLUSIVE)
Type 1	70 degrees F.	June 1 - Sept. 15
Type 2	70 degrees F.	June 1 - Sept. 15
Type 3A	60 degrees F.	June 1 - Aug. 31
Type 3A	70 degrees F.	Sept 1 - Sept. 15
Type 3B	50 degrees F.	May 1 - Dec. 1

B. **Equipment:** The following equipment shall be furnished:

1. A rotary power broom.
2. Equipment for heating and applying the asphalt conforming to the requirements of Section 330.
3. A self-propelled aggregate spreader, with positive controls capable of depositing the required quantity of aggregate uniformly over the full width of the asphalt application. When spreading Type 2 cover aggregate, the spreader shall apply the larger

aggregate to the surface ahead of the smaller aggregate. An approved tail gate spreader may be substituted for the above described spreader when applying Type 3B cover aggregate.

4. Four smooth pneumatic tired rollers for each spreader in use. The rollers shall completely cover an overall surface width of at least 60 inches and furnish a minimum uniform rolling pressure of 250 pounds per inch of rolling width.

C. **Surface Preparation:** The surface shall be thoroughly swept with a rotary power broom and cleaned of all foreign material. Appurtenances immediately adjacent to the surface to be treated shall be protected from the splatter of asphalt. Freshly primed bases shall be cured prior to the application of surface treatments.

D. **Application of Asphalt:** The asphalt shall be maintained within a temperature range of 120 degrees F to 180 degrees F. during application. Asphalt shall be applied by a pressure distributor in a uniform and continuous manner. Unauthorized increases in the asphalt application rate will not be eligible for payment.

The angle of the spray nozzles and the height of the spray bar shall be set to obtain uniform distribution. A strip of building paper, at least three feet in width and with a length equal to that of the spray bar plus one foot, shall be used at the beginning of each spread. The distributor shall travel at the established speed when the spray bar is opened. Skipped areas and deficiencies shall be immediately corrected. Areas inaccessible to the distributor shall be satisfactorily covered by hand spray methods.

Spraying operations shall not proceed when it is evident the asphalt spread will not be covered with aggregate and rolled all in accordance with the prescribed schedule.

E. **Application of Cover Aggregate:** Cover aggregate shall be spread immediately following application of the asphalt. Under wind conditions of five miles per hour or less, the spread of cover aggregate shall follow within eight minutes of the application of the asphalt. When the wind velocities are greater, the maximum time between applications of asphalt and cover aggregate shall be reduced as directed.

Time limits for spreading of cover aggregate on "High Float" Emulsified Asphalt shall be adjusted as directed to fit project conditions.

A complete aggregate coverage, shall be continually maintained. A strip of asphalt application approximately four inches wide, along that side of the spread forming a longitudinal joint with the adjacent spread shall be left uncovered. The adjacent asphalt and cover aggregate application shall overlap this strip. In lieu of this procedure a butt joint may be constructed using special end nozzles.

Longitudinal joints, other than at centerline, will not be permitted within the center 24 feet.

When loading trucks the cover aggregate shall be screened to minimize segregation, eliminate oversize and effectively break up or discard material bonded into chunks. When required, aggregate shall be uniformly moistened before or during loading.

Unauthorized increases in application rates will not be eligible for payment.

Prior to rolling, the contractor may be directed to adjust inequalities in the spread of Type 3 cover aggregate with a drag broom.

F. **Rolling:** Rolling shall begin immediately behind the spreader and shall consist of four complete coverages using pneumatic tired rollers. The rolling shall be completed within 40 minutes after the cover aggregate is applied. Rollers shall be operated in unison at a close interval, and if the width of spread allows, in a staggered formation. Rollers shall not be operated at a speed in excess of five miles per hour. Asphalt and cover aggregate applications shall not extend more than 1/2 mile beyond the rolling operation. With the use of minimum specified equipment the project shall be completed in 1/2 mile increments, except for the sweeping of excess cover aggregate. The weight and tire pressures of the rollers shall be varied as directed to obtain optimum embedment of the cover material without undue crushing of the aggregate. Special attention shall be given to the transverse and longitudinal joints during rolling. Unsatisfactory joints shall be corrected without additional compensation. Turning of rollers on the freshly treated surface is prohibited. Rolling at night or when light conditions would create a traffic hazard will not be allowed.

G. **Traffic Control:** Construction operations shall be coordinated to minimize traffic delays. One-way traffic shall be maintained during application of the surface treatment on driving lanes. Upon completion of rolling, traffic will be permitted to travel on the treated surface. Traffic shall be controlled by pilot cars and flaggers during application of the surface treatment on driving lanes with the speed of pilot cars not to exceed 20 miles per hour on the freshly applied surface treatment for a period of at least four hours after application.

The width, arrangement and sequence of the parallel application strips shall not unduly inconvenience traffic.

H. **Maintenance and Repair:** Areas of the surface treatment which peel or are otherwise unsatisfactory shall be repaired with additional asphalt, cover aggregate and rolling. Compensation for repairs due to causes beyond the control of the Contractor will be paid at the contract unit price for asphalt surface treatment.

The finished surface treatment shall be uniform and smooth riding. Transverse or horizontal ridges, raveled spots, wheel marks, depressions, abrupt color changes and other inequalities shall be corrected. Payment will not be made for this correction work.

Asphalt splattered on roadway appurtenances shall be satisfactorily cleaned off by the Contractor.

Loose material left on the surface shall be lightly broomed off during the cool period of early morning after a waiting period of 34 hours from the time of application.

Broomed off material in curb and gutter sections will be picked up by Department Maintenance forces.

360.4 METHOD OF MEASUREMENT

A. **Asphalt for Surface Treatment:** Asphalt for surface treatment will be measured to the nearest 0.1 ton.

B. **Cover Aggregate:** Cover aggregate will be measured to the nearest 0.1 ton.

360.5 BASIS OF PAYMENT

A. **Asphalt for Surface Treatment:** Asphalt for surface treatment will be paid for at the contract price per ton.

B. **Cover Aggregate:** Cover aggregate specified will be paid for at the contract price per ton.

APPENDIX D

DATA

Table 16. Other project information.

PROJ NO	HGWY NO	ADT	ASPHALT TYPE	DESIGN ASPHALT APPLICATION RATE GAL/SY	ACTUAL ASPHALT APPLICATION RATE GAL/SY	AGGREGATE GRADATION	AGGREGATE APPLICATION RATE LB/SY	LAST LAST YEAR SEALED	CLIMATI ZONE
1	44	871	CRS-2	0.27	0.26	2A	24	81	3
1	50	3,176	CRS-2	0.27	0.26	2A	24	85	2
1	50Z	265	CRS-2	0.27	0.26	2A	24	85	3
1	1804	86	AE 200S	0.38	0.26	2A	40	76	3
2	18	2,134	CRS-2	0.27	0.28	2A	24	87	3
2	19	263	CRS-2	0.27	0.28	2A	24	87	3
2	44	897	CRS-2	0.27	0.28	2A	24	86	3
2	115	1,978	CRS-2	0.27	0.28	2A	24	86	2
3	25	757	AE 150S	0.27	0.24	1B	25	85	1
3	45	853	AE 150S	0.27	0.24	1B	25	86	1
3	239	90	AE 150S	0.27	0.24	1B	25	87	1
3	253	156	AE 150S	0.27	0.24	1B	25	86	1
4	19A	765	CRS-2	0.27	0.26	2A	24	85	3
4	46	811	CRS-2	0.27	0.26	2A	24	85	3
4	103	960	CRS-2	0.27	0.26	2A	24	85	3
5	10	580	AE 150S	0.24	0.25	2B	22	78	1
5	12	483	AE 150S	0.24	0.25	2B	22	84	1
5	12Z	750	AE 150S	0.24	0.25	2B	22	82	1
5	47	365	AE 150S	0.24	0.25	2B	22	87	1
5	63	485	AE 150S	0.24	0.25	2B	22	80	1
5	212	878	AE 150S	0.24	0.25	2B	22	84	1
5	1804	625	AE 150S	0.24	0.25	2B	22	77	1
6	28	345	AE 150S	0.24	0.24	1B	22	74	2
6	37	1,200	AE 150S	0.24	0.24	1B	22	76	2
6	212	980	AE 150S	0.24	0.24	1B	22	86	2
6	212Z	1,886	AE 150S	0.24	0.24	1B	22	85	2
6	281	1,210	AE 150S	0.24	0.24	1B	22	84	2
7	14	1,210	AE 150S	0.24	0.25	2B	22	88	2
7	14Z	1,068	AE 150S	0.24	0.25	2B	22	84	2
7	73	730	AE 150S	0.24	0.25	2B	22	85	2
8	53	50	AE 150S	0.24	0.24	2B	22	75	3
8	248	318	AE 150S	0.24	0.24	2B	22	54	3
8	248Z	1,115	AE 150S	0.24	0.24	2B	22	84	3
9	47	452	AE 150S	0.24	0.24	2B	22	86	2
10	22	365	AE 150S	0.26	0.24	1B	24	86	2
10	25	321	AE 150S	0.26	0.24	1B	24	84	1
10	28	766	AE 150S	0.26	0.24	1B	24	80	2

Table 16. Other project information.

PROJ NO	HGWY NO	ADT	ASPHALT TYPE	DESIGN ASPHALT APPLICATION RATE GAL/SY	ACTUAL ASPHALT APPLICATION RATE GAL/SY	AGGREGATE GRADATION	AGGREGATE APPLICATION RATE LB/SY	LAST LAST YEAR SEALED	CLIMATI ZONE
10	106	731	AE 150S	0.26	0.24	1B	24	84	1
11	79	2,953	AE 150S	0.28	0.28	2A	26	87	3
12	12	1,346	AE 150S	0.24	0.26	2B	22	83	1
12	12Z	1,344	AE 150S	0.24	0.26	2B	22	84	1
12	63	499	AE 150S	0.24	0.26	2B	22	49	1
12	63Z	370	AE 150S	0.24	0.26	2B	22	85	2
12	1806	70	AE 150S	0.24	0.26	2B	22	87	1
13	1804	150	AE 150S	0.28	0.25	2A	26	75	1
14	11	2,090	CRS-2	0.27	0.26	2A	24	85	3
15	38	6,422	CRS-2	0.27	0.26	2A	24	87	3
16	18	600	CRS-2	0.27	0.26	2A	24	79	3
16	37	1,200	CRS-2	0.27	0.26	2A	24	84	3
16	50	1,244	CRS-2	0.27	0.26	2A	24	84	3
16	81	2,368	CRS-2	0.27	0.26	2A	24	80	3
17	12	1,550	AE 150S	0.26	0.24	1B	24	85	1
17	12Z	2,100	AE 150S	0.26	0.24	1B	24	85	1
17	37	496	AE 150S	0.26	0.24	1B	24	85	1
17	37Z	922	AE 150S	0.26	0.24	1B	24	85	1
18	79	748	AE 150S	0.28	0.28	2A	26	83	2
19	12	2,306	AE 150S	0.28	0.28	2A	26	89	1
20	14	700	AE 150S	0.24	0.24	2B	22	84	2
20	34	485	AE 150S	0.24	0.24	2B	22	88	2
21	44	330	AE 150S	0.24	0.24	2B	22	87	3
22	14	2,862	CRS-2	0.26	0.23	2A	24	73	2
22	22	577	AE 150S	0.26	0.23	1B	24	83	2
22	28	667	AE 150S	0.26	0.23	1B	24	72	2
22	101	475	AE 150S	0.26	0.23	1B	24	83	2
22	212	3,294	AE 150S	0.26	0.23	1B	24	79	2
22	218	515	AE 150S	0.26	0.23	1B	24	75	2
23	28	375	AE 150S	0.24	0.28	1B	22	85	2
23	34	410	AE 150S	0.24	0.28	1B	22	86	2
23	45	310	AE 150S	0.24	0.28	1B	22	79	2
23	212	1,426	AE 150S	0.24	0.28	1B	22	84	2

Table 16. Other project information (continued).

PROJ NO	HGWY NO	DITCH LINE	ASPHALT PRODUCER	AGGREGATE PRODUCER	AGG TYPE	CONTRACTOR	MONTH CONSTR	YEAR CONSTR
1	44	4	JEBRO SIOUX CITY, IA	FISHER, MITCHELL	S	ASPHALT SURFACING CO., S.F.	8	90
1	50	5	JEBRO SIOUX CITY, IA	FISHER, MITCHELL	S	ASPHALT SURFACING CO., S.F.	8	90
1	50Z	5	JEBRO SIOUX CITY, IA	FISHER, MITCHELL	S	ASPHALT SURFACING CO., S.F.	8	90
1	1804	6	JEBRO SIOUX CITY, IA	FISHER, MITCHELL	S	ASPHALT SURFACING CO., S.F.		90
2	18	4	JEBRO SIOUX CITY, IA	CONCRETE MATERIALS, S.F.	S	ASPHALT SURFACING CO., S.F.	6	90
2	19	5	JEBRO SIOUX CITY, IA	CONCRETE MATERIALS, S.F.	S	ASPHALT SURFACING CO., S.F.	6	90
2	44	5	JEBRO SIOUX CITY, IA	CONCRETE MATERIALS, S.F	S	ASPHALT SURFACING CO., S.F.	7	90
2	115	7	JEBRO SIOUX CITY, IA	CONCRETE MATERIALS, S.F.	S	ASPHALT SURFACING CO., S.F.	6	90
3	25	11	KOCH MARSHALL, MN	CONSTRUCTION MATERIALS-SUM	S	MCLAUGHLIN & SCHULZ	7	90
3	45	8	KOCH MARSHALL, MN	CONSTRCUCTION MATERIALS-SU	S	MCLAUGHLIN & SCHULZ		90
3	239	8	KOCH MARSHALL, MN	JENSEN-HERREID	S	MCLAUGHLIN & SCHULZ	8	90
3	253	6	KOCH MARSHALL, MN	JENSEN-HERREID	S	MCLAUGHLIN & SCHULZ	8	90
4	19A	10	JEBRO SIOUX CITY, IA	CONCRETE MATERIALS, S.F.	S	ASPHALT SURFACING CO., S.F.	7	90
4	46	5	JEBRO SIOUX CITY, IA	FISHER, MITCHELL	S	ASPHALT SURFACING CO., S.F.	7	90
4	103	5	JEBRO SIOUX CITY, IA	L. G. EVERIST, D.R.	S	ASPHALT SURFACING CO., S.F.	7	90
5	10	7	CENEX LAUREL, MT	JENSEN-HERREID	S	MCLAUGHLIN & SCHULZ	8	90
5	12	6	CENEX LAUREL, MT	JENSEN-HERREID	S	MCLAUGHLIN & SCHULZ	6	90
5	12Z	6	CENEX LAUREL, MT	JENSEN-HERREID	S	MCLAUGHLIN & SCHULZ	8	90
5	47	6	CENEX LAUREL, MT	JENSEN-HERREID	S	MCLAUGHLIN & SCHULZ	8	90
5	63	10	CENEX LAUREL, MT	JENSEN-HERREID	S	MCLAUGHLIN & SCHULZ	8	90
5	212	7	CENEX LAUREL, MT	JENSEN-HERREID	S	MCLAUGHLIN & SCHULZ	6	90
5	1804	8	CENEX LAUREL, MT	JENSEN-HERREID	S	MCLAUGHLIN & SCHULZ	8	90
6	28	5	HILLS MATERIAL, R.C.	CON AGGREGATE, WATERTOWN	S	HILLS MATERIAL	7	90
6	37	6	HILLS MATERIAL, R.C.	CON AGGREGATE, WATERTOWN	S	HILLS MATERIAL	7	90
6	212	8	HILLS MATERIAL, R.C.	CON AGGREGATE, WATERTOWN	S	HILLS MATERIAL	7	90
6	212Z	7	HILLS MATERIAL, R.C.	CON AGGREGATE, WATERTOWN	S	HILLS MATERIAL	7	90
6	281	8	HILLS MATERIAL, R.C.	CON AGGREGATE, WATERTOWN	S	HILLS MATERIAL	7	90
7	14	6	HILLS MATERIAL, R.C.	BIRDSALL, BLUNT	S	HILLS MATERIAL	8	90
7	14Z	6	HILLS MATERIAL, R.C.	BIRDSALL, BLUNT	S	HILLS MATERIAL	8	90
7	73	10	HILLS MATERIAL, R.C.	BIRDSALL, BLUNT	S	HILLS MATERIAL	8	90
8	53	7	HILLS MATERIAL, R.C.	BIRDSALL, BLUNT	S	HILLS MATERIAL	6	90
8	248	7	HILLS MATERIAL, R.C.	BIRDSALL, BLUNT	S	HILLS MATERIAL		90
8	248Z	8	HILLS MATERIAL, R.C.	BIRDSALL, BLUNT	S	HILLS MATERIAL	6	90
9	47	5	HILLS MATERIAL, R.C.	BIRDSALL, BLUNT	S	HILLS MATERIAL	6	90
10	22	7	KOCH MARSHALL, MN	L. G. EVERIST, BROOKINGS	S	MCLAUGHLIN & SCHULZ	6	90
10	25	5	KOCH MARSHALL, MN	CONST MATERIALS, SUMMIT	S	MCLAUGHLIN & SCHULZ	6	90
10	28	9	KOCH MARSHALL, MN	L. G. EVERIST, BROOKINGS	S	MCLAUGHLIN & SCHULZ	7	90
10	106	6	KOCH MARSHALL, MN	CONST MATERIALS, SUMMIT	S	MCLAUGHLIN & SCHULZ		90

Table 16. Other project information (continued).

PROJ NO	HGWY NO	DITCH LINE	ASPHALT PRODUCER	AGGREGATE PRODUCER	AGG TYPE	CONTRACTOR	MONTH CONSTR	YEAR CONSTR
11	79	6	HILLS MATERIAL, R.C.	HILLS MATERIAL, R.C.	L	HILLS MATERIAL	6	89
12	12	4	KOCH PILLSBURY, ND	JENSEN-HERREID	S	DAVIS CO., SIOUX CITY, NE	8	89
12	12Z	6	KOCH PILLSBURY, ND	JENSEN-HERREID	S	DAVIS CO., SIOUX CITY, NE		89
12	63	0	KOCH PILLSBURU, ND	JENSEN-HERREID	S	DAVIS CO., SIOUX CITY, NE	8	89
12	63Z	6	KOCH PILLSBURY, ND	JENSEN-HERREID	S	DAVIS CO., SIOUX CITY, NE	8	89
12	1806	6	KOCH PILLSBURY, ND	JENSEN-HERREID	S	DAVIS CO., SIOUX CITY, NE	8	89
13	1804	9	KOCH MARSHALL, MN	DRIES PIT, HOVEN, SD	S	MCLAUGHLIN & SCHULZ	9	89
14	11	5	JEBRO SIOUX CITY, IA	CONCRETE MATERIALS, S.F.	S	ASPHALT SURFACING CO., S.F.	8	89
15	38	3	JEBRO SIOUX CITY, IA	CONCRETE MATERIALS, S.F.	S	ASPHALT SURFACING CO., S.F.	8	89
16	18	5	JEBRO SIOUX CITY, IA	FISHER, MITCHELL	S	ASPHALT SURFACING CO., S.F.		89
16	37	6	JEBRO SIOUX CITY, IA	FISHER, MITCHELL	S	ASPHALT SURFACING CO., S.F.	7	89
16	50	5	JEBRO SIOUX CITY, IA	FISHER, MITCHELL	S	ASPHALT SURFACING CO., S.F.	7	89
16	81	13	JEBRO SIOUX CITY, IA	FISHER, MITCHELL	S	ASPHALT SURFACING CO., S.F.	6	89
17	12	6	CENEX LAUREL, MT	LAKEVIEW PIT, ABERDEEN	S	MCLAUGHLIN & SCHULZ	9	89
17	12Z	6	CENEX LAUREL, MT	LAKEVIEW PIT, ABERDEEN	S	BITUMINOUS PAVING, MN	8	89
17	37	8	CENEX LAUREL, MT	THORPE PIT, BRITTON	S	BITUMINOUS PAVING, MN	7	89
17	37Z	6	CENEX LAUREL, MT	CONST MATERIALS, SUMMIT	S	BITUMINOUS PAVING, MN	8	89
18	79	4	CENEX LAUREL, MT	FISHER, SPEARFISH	L	BORDER STATES PAVING	6	89
19	12	7	CENEX LAUREL, MT	FISHER, SPEARFISH	L	BORDER STATES PAVING	6	89
20	14	6	HILLS MATERIAL, R.C.	HILLS MATERIAL, WASTA	L	HILLS MATERIAL	6	89
20	34	6	HILLS MATERIAL, R.C.	HILLS MATERIAL, WASTA	L	HILLS MATERIAL	6	89
21	44	10	CENEX LAUREL, MT	BIRDSALL, BLUNT	S	MCLAUGHLIN & SCHULZ	8	89
22	14	6	KOCH MARSHALL, MN	L. G. EVERIST, D.R.	S	WYCO CONSTRUCTION, D.R.	7	89
22	22	11	KOCK MARSHALL, MN	L. G. EVERIST, BROOKINGS	S	WYCO CONSTRUCTION, D.R.	8	89
22	28	6	KOCH MARSHALL, MN	L. G. EVERIST, BROOKINGS	S	WYCO CONSTRUCTION, D.R.	8	89
22	101	5	KOCH MARSHALL, MN	L. G. EVERIST, BROOKINGS	S	WYCO CONSTRUCTION, D.R.	8	89
22	212	7	KOCH MARSHALL, MN	L. G. EVERIST, ORTO, MN	S	WYCO CONSTRUCTION, D.R.	8	89
22	218	6	KOCH MARSHALL, MN	L. G. EVERIST, BROOKINGS	S	WYCO CONSTRUCTION, D.R.	7	89
23	28	8	KOCH MARSHALL, MN	LOCAL SOURCE , HURON	S	MCLAUGHLIN & SCHULZ	8	89
23	34	7	KOCH MARSHALL, MN	LOCAL SOURCE, HURON	S	MCLAUGHLIN & SCHULZ	8	89
23	45	5	KOCH MARSHALL, MN	LOCAL SOURCE, HURON	S	MCLAUGHLIN & SCHULZ	8	89
23	212	6	KOCH MARSHALL, MN	LOCAL SOURCE, HURON	S	MCLAUGHLIN & SCHULZ	8	89

Table 17. Median Size

Proj No	Road No.		Median Size		
		Design	Max	Avg	Min
1	44	0.181	0.23	0.199	0.17
1	50	0.181	0.236	0.236	0.236
1	50Z	0.181	0.299	0.245	0.197
1	1804	0.181			
2	18	0.181	0.24	0.197	0.158
2	19	0.181	0.165	0.165	0.165
2	44	0.181			
2	115	0.181			
3	25	0.142	0.177	0.167	0.158
3	239	0.142	0.169	0.169	0.169
3	253	0.142	0.201	0.17	0.142
4	19A	0.181	0.189	0.185	0.181
4	46	0.181	0.228	0.216	0.205
4	103	0.181	0.181	0.181	0.181
5	10	0.287	0.181	0.165	0.15
5	12	0.287	0.181	0.181	0.181
5	12Z	0.287	0.197	0.197	0.197
5	47	0.287	0.217	0.199	0.181
5	63	0.287	0.181	0.181	0.181
5	212	0.287	0.181	0.169	0.158
5	1804	0.287	0.204	0.18	0.158
6	28	0.142	0.134	0.134	0.134
6	37	0.142	0.161	0.147	0.134
6	212	0.142	0.142	0.142	0.142
6	212Z	0.142	0.118	0.118	0.118
6	281	0.142	0.161	0.139	0.118
7	14	0.287	0.169	0.169	0.169
7	14Z	0.287	0.177	0.169	0.161
7	14Z	0.287	0.177	0.169	0.161
7	73	0.287	0.161	0.161	0.161
8	53	0.287			
8	248	0.287			
8	248Z	0.287	0.181	0.167	0.154
9	47	0.287	0.158	0.158	0.158
10	22	0.142	0.22	0.2	0.181
10	28	0.142			
10	106	0.142			
11	79	0.181	0.256	0.212	0.173
12	12	0.287	0.177	0.177	0.177
12	12Z	0.287	0.177	0.177	0.177
12	63	0.287	0.177	0.177	0.177
12	63Z	0.287	0.185	0.185	0.185
12	1806	0.287	0.169	0.169	0.169
13	1804	0.181	0.248	0.222	0.197
14	11	0.181	0.276	0.237	0.201
15	38	0.181	0.284	0.261	0.24
16	18	0.181			

Table 17. Median Size

16	37	0.181	0.209	0.209	0.209
16	50	0.181	0.209	0.209	0.209
16	81	0.181	0.201	0.201	0.201
17	12	0.142	0.173	0.173	0.173
17	12Z	0.142	0.177	0.169	0.161
17	37	0.142	0.177	0.177	0.177
17	37Z	0.142	0.177	0.169	0.161
18	79	0.181	0.205	0.191	0.177
19	12	0.181	0.197	0.187	0.177
20	14	0.287	0.244	0.205	0.169
20	34	0.287	0.158	0.158	0.158
21	44	0.287	0.158	0.158	0.158
22	22	0.142	0.181	0.165	0.15
22	28	0.142	0.181	0.159	0.138
22	101	0.142	0.142	0.142	0.142
22	212	0.142	0.173	0.173	0.173
22	218	0.142	0.177	0.177	0.177
23	28	0.142	0.197	0.197	0.197
23	34	0.142	0.158	0.158	0.158
23	45	0.142	0.142	0.142	0.142
23	212	0.142	0.197	0.197	0.197

Table 18. Aggregate Gradations

Proj no	Highway no	Test no	0.5 in	0.375 in	#4	#10	#40	#200
					Percent Passing Sieve Size			
1	44	1	100	100	50	4	2	0.1
1	44	2	100	100	32	3	2	0.6
1	44	0	100	100	31	3	2	0.5
1	44	3	100	100	40	4	2	0.3
1	44	4	100	100	42	4	2	0.6
1	44	5	100	100	37	3	2	0.4
1	44	6	100	100	41	3	1	0.3
1	50	1	100	98	40	4	2	0.5
1	50	0	100	100	39	4	2	0.3
1	50	2	100	100	38	3	1	0.2
1	50	3	100	98	40	8	4	1.3
1	50	4	100	98	40	10	5	1.6
1	50Z	1	100	96	36	8	4	1
1	50Z	0	100	96	35	9	5	1.3
1	50Z	2	100	94	17	5	3	0.7
1	50Z	3	100	100	42	6	3	0.6
1	50Z	4	100	98	35	7	4	1.2
1	50Z	5	100	100	38	2	1	0.3
1	50Z	6	100	98	30	2	1	0.6
1	50Z	7	100	98	45	12	6	1.8
1	50Z	8	100	98	45	9	4	1.2
1	50Z	9	100	98	46	10	5	1.8
1	50Z	10	100	98	42	10	5	1.5
1	50Z	11	100	96	32	8	4	1.2
1	50Z	12	100	98	45	9	4	1.4
1	50Z	13	100	100	42	7	3	1.2
1	1804							
2	18	1	100	99	32	4	2	
2	18	2	100	99	33	4	2	
2	18	0	100	99	30	5	2	
2	18	3	100	99	32	4	2	
2	19	1	100	100	59	4	2	
2	19	0	100	100	60	3	2	
2	19	2	100	100	57	5	3	
2	19	3	100	99	52	4	2	
2	19	4	100	100	54	4	2	
2	44	1	100	99	34	4	2	
2	44	0	100	99	28	4	2	
2	44	2	100	99	34	5	2	
2	44	3	100	99	32	5	2	
2	44	4	100	99	34	5	2	
2	115	1	100	100	69	11	1	
2	115	0	100	100	68	10	1	
2	115	2	100	100	64	9	2	
3	25	1	100	100	62	14	2	

Table 18. Aggregate Gradations

3	25	2	100	100	59	13	1	
3	25	3	100	100	29	3	1	
3	25	4	100	100	56	11	2	
3	25	0	100	100	49	8	2	
3	25	5	100	100	49	9	2	
3	25	6	100	100	68	18	3	
3	25	7	100	100	58	12	2	
3	25	8	100	100	56	11	2	
3	25	9	100	100	58	12	2	
3	25	10	100	100	57	12	1	
3	25	11	100	100	56	12	1	
3	25	12	100	100	59	15	2	
3	45							
3	239	0	100	100	62	17	2	
3	239	1	100	100	60	18	2	
3	239	2	100	100	60	16	2	
3	239	3	100	100	57	14	2	
3	253	1	100	100	55	12	2	
3	253	0	100	100	64	20	3	
3	253	2	100	100	66	20	3	
3	253	3	100	100	60	13	2	
3	253	4	100	100	55	12	1	
4	19A	1	100	99	29	4	2	1.3
4	19A	0	100	99	29	3	2	0.5
4	19A	2	100	100	53	12	4	1.3
4	19A	3	100	100	45	8	3	1
4	46	1	100	100	39	2	1	0.2
4	46	0	100	100	40	2	1	0.2
4	46	2	100	100	32	2	1	0.3
4	46	3	100	100	35	2	1	0.3
4	46	4	100	100	40	5	2	0.4
4	46	5	100	99	35	3	1	0.5
4	46	6	100	99	30	3	1	0.4
4	46	7	100	99	39	5	2	0.4
4	103	1	100	100	56	5	2	0.7
4	103	2	100	100	47	5	2	0.6
4	103	0	100	100	46	5	2	0.4
4	103	3	100	100	55	8	2	0.6
5	10	1	100	100	60	9	1	0.7
5	10	2	100	100	62	14	2	0.8
5	10	3	100	100	69	20	3	0.9
5	10	4	100	100	62	16	2	0.6
5	10	5	100	100	62	17	2	0.7
5	10	6	100	100	59	14	2	0.7
5	10	7	100	100	50	10	2	0.8
5	10	8	100	100	59	14	3	0.8
5	12	1	100	100	52	9	2	1
5	12	2	100	100	54	9	2	1

Table 18. Aggregate Gradations

5	12	3	100	100	53	7	1	1
5	12Z	1	100	100	44	7	2	0.7
5	12Z	2	100	100	50	8	2	0.9
5	12Z	3	100	100	54	8	1	0.6
5	47	1	100	100	42	6	1	0.5
5	47	2	100	100	46	6	1	0.6
5	47	3	100	100	60	10	2	0.9
5	47	4	100	100	55	8	1	0.5
5	47	5	100	100	53	10	2	0.7
5	63	1	100	100	50	6	1	0.7
5	63	2	100	100	47	7	2	0.8
5	212	1	100	100	56	9	1	0.9
5	212	2	100	100	58	11	2	1.2
5	212	3	100	100	60	16	3	1.6
5	212	4	100	100	56	12	2	1.2
5	212	5	100	100	54	9	1	1
5	212	6	100	100	56	10	1	1
5	212	7	100	100	57	12	2	1.2
5	212	8	100	100	55	11	2	1.1
5	212	9	100	100	62	16	3	1.2
5	1804	1	100	100	40	6	1	0.4
5	1804	2	100	100	62	13	2	0.7
5	1804	3	100	100	45	6	1	0.4
5	1804	4	100	100	60	10	2	0.6
5	1804	5	100	100	61	9	1	0.6
5	1804	6	100	100	72	14	2	0.6
6	28	1	100	100	78	19	2	
6	28	2	100	100	79	20	2	
6	28	3	100	100	79	21	2	
6	28	4	100	100	77	20	3	
6	28	0	100	100	81	22	2	
6	28	5	100	100	80	20	2	
6	37	1	100	100	77	15	2	
6	37	2	100	100	78	13	2	
6	37	3	100	100	71	10	2	
6	37	4	100	100	76	13	2	
6	37	5	100	100	78	18	2	
6	212	1	100	100	75	11	2	
6	212	2	100	100	73	11	2	
6	212Z	1	100	100	79	21	1	
6	212Z	2	100	100	82	23	2	
6	212Z	3	100	100	80	22	2	
6	212Z	4	100	100	81	22	2	
6	281	1	100	100	75	11	2	
6	281	0	100	100	74	11	2	
6	281	4	100	100	76	12	2	

Table 18. Aggregate Gradations

6	281	2	100	100	73	12	2	
6	281	3	100	100	76	16	2	
6	281	5	100	100	79	20	2	
6	281	6	100	100	80	21	2	
7	14	1	100	100	63	12	2	1.8
7	14	2	100	100	62	13	2	1.7
7	14	3	100	100	62	13	2	1.7
7	14	4	100	100	53	11	2	1.9
7	14Z	1	100	100	61	10	1	0.7
7	14Z	2	100	100	64	13	2	1
7	14Z	3	100	100	65	11	1	1.4
7	14Z	4	100	100	60	14	3	2
7	14Z	5	100	100	63	12	2	1.5
7	14Z	6	100	100	66	11	2	1.6
7	14Z	7	100	100	70	13	1	1.2
7	14Z	8	100	100	69	14	1	0.9
7	14Z	9	100	100	66	13	2	1.1
7	14Z	10	100	100	64	13	1	1.4
7	14Z	11	100	100	63	11	2	1.6
7	14Z	12	100	100	67	16	3	2
7	14Z	13	100	100	64	13	2	1.5
7	14Z	14	100	100	65	11	2	1.6
7	14Z	15	100	100	57	11	2	1.6
7	14Z	16	100	100	66	14	3	1.6
7	14Z	17	100	100	66	14	3	1.6
7	14Z	18	100	100	65	14	2	0.9
7								
7	73	1	100	100	67	25	5	1.4
7	73	2	100	100	68	19	4	1.3
7	73	3	100	100	66	25	4	1
7	73	4	100	100	64	25	5	1.3
7	73	5	100	100	64	21	4	1.1
7	73	6	100	100	58	12	2	1
7	73	7	100	100	61	20	4	0.8
7	73	8	100	100	62	19	4	1.2
7	73	0	100	100	68	28	6	1.6
8	53	1	100	100	63	14	3	1.7
8	53	2	100	100	66	13	2	1.6
8	53	3	100	100	63	16	3	1.5
8	53	4	100	100	79	17	2	1.2
8	248							
8	248Z	4	100	100	64	12	2	0.9
8	248Z	5	100	100	66	15	2	1.5
8	248Z	6	100	100	51	8	2	1.1
8	248Z	7	100	100	59	13	3	1.5
8	248Z	8	100	100	64	10	5	1.3
8	248Z	1	100	100	64	17	3	1.6
8	248Z	2	100	100	65	12	2	1.4
8	248Z	3	100	100	69	18	3	1.6
8	248Z	9	100	100	55	17	5	1.7
8	248Z	10	100	100	61	18	5	1.4

Table 18. Aggregate Gradations

9	47	1	100	100	68	14	2	1.5
9	47	2	100	100	66	14	3	1.8
9	47	3	100	100	66	16	2	1.5
9	47	4	100	100	63	11	2	1.7
9	47	5	100	100	67	16	3	1.9
10	22	1	100	100	48	7	2	
10	22	0	100	99	35	5	1	
10	22	2	100	100	46	8	3	
10	22	3	100	100	49	13	2	
10	22	4	100	100	52	8	2	
10	22	5	100	100	46	7	1	
10	25	1	100	100	64	16	2	
10	25	0	100	100	66	18	2	
10	25	2	100	100	54	13	2	
10	25	3	100	100	54	10	2	
10	25	4	100	100	46	9	1	
10	28	1	100		55	10	3	
10	28	2	100		50	6	1	
10	28	0	100		52	8	3	
10	28	3	100		54	9	3	
10	28	4	100		44	6	2	
10	28	5	100		61	9	2	
10	28	6	100		51	9	2	
10	28	7	100		68	12	2	
10	28	8	100		92	8	2	
10	106							
11	79	1		100	32	11	4	4
11	79	5		100	100	28	7	4
11	79	0		100	100	37	37	3
11	79	2		100	100	49	11	3
11	79	3		100	100	56	14	3
11	79	4		100	100	52	12	3
12	12	1		100	58	11	3	1.8
12	12Z							
12	63	1		100	58	11	2	0.3
12	63Z	1		100	55	12	3	1.7
12	63Z	2		100	58	14	3	1.6
12	63Z	3		100	54	12	3	1.9
12	1806	1		100	59	13	2	1.3
12	1806	2		100	59	13	2	1.1
13	1804	1	100	99	29	4	2	
13	1804	7	100	100	42	8	4	2.9
13	1804	2	100	99	36	7	3	
13	1804	3	100	99	30	4	2	

Table 18. Aggregate Gradations

13	1804	4	100	99	46	13	4	
13	1804	5	100	99	38	7	3	
13	1804	6	100	98	31	4	2	
13	1804	8	100	100	39	5	2	1.7
13	1804	9	100	100	43	4	2	1.4
13	1804	10	100	100	42	3	1	0.9
13	1804	0	100	98	31	4	2	1.8
14	11	1		99	33	5	3	
14	11	2		100	35	6	2	
14	11	3		99	30	5	2	
14	11	0		100	30	5	2	
14	11	4		99	23	3	1	
14	11	5		99	25	4	2	
15	38	1	99	28	4	2		
15	38	0	99	26	4	2		
15	38	2	99	30	3	2		
15	38	3	99	22	3	1		
16	18							
16	37	2	100	99	39	5		
16	50	1	100	100	40	3		
16	81	1	100	98	44	3		
17	12	1		100	59	12	2	
17	12	2		100	50	10	3	
17	12Z	1		100	60	13	2	
17	12Z	0		100	60	13	2	
17	12Z	2		100	61	12	1	
17	12Z	3		100	56	12	1	
17	12Z	4		100	57	13	2	
17	12Z	5		100	65	16	2	
17	12Z	6		100	60	16	2	
17	12Z	7		100	63	11	1	
17	12Z	8		100	50	10	3	
17	37	0		100	49	8	2	1
17	37	1		100	46	10	2	1.3
17	37	2		100	53	12	2	1.4
17	37	3		100	47	11	2	1.4
17	37	4		100	54	11	2	0.8
17	37	5		100	46	9	2	1
17	37Z	1		100	62	12	2	
17	37Z	2		100	58	9	2	
17	37Z	3		100	66	13	2	
17	37Z	4		100	57	12	2	
17	37Z	5		100	63	15	2	
17	37Z	6		100	64	13	2	
17	37Z	7		100	54	7	2	
17	37Z	8		100	49	8	1	

Table 18. Aggregate Gradations

17	37Z	9	100	51	7	1	
17	37Z	0	100	64	14	2	
17	37Z	10	100	62	15	2	
17	37Z	11	100	66	14	3	
18	79	1	99	31	2	2	
18	79	2	100	33	3	2	
18	79	3	100	42	4	2	
18	79	4	99	53	8	3	
18	79	5	101	50	7	2	
18	79	6	100	43	6	3	1.5
18	79	0	100	44	5	3	1.5
19	12	1	100	44	5	3	1.7
19	12	2	100	49	5	3	2
19	12	3	100	50	7	4	2.2
19	12	4	100	44	5	3	1.7
19	12	5	100	46	1	3	1.7
19	12	6	100	47	6	3	1.6
19	12	0	100	48	6	3	1.7
19	12	7	100	50	5	2	1.3
19	12	8	100	52	5	3	1.3
20	14	1	100	34	12	5	2.5
20	14	2	100	35	15	7	3
20	14	3	100	40	18	8	3.9
20	14	4	100	39	18	8	4.2
20	14	0	100	42	19	9	4.7
20	34	1	100	66	23	4	3.1
20	34	2	100	67	21	4	2.8
20	34	3	100	66	17	3	2.1
20	34	4	100	64	18	3	1.8
20	34	5	100	66	18	3	1.7
20	34	6	100	63	17	3	1.7
20	34	0	100	58	11	1	1.4
21	44	1	100	54	10	2	0.8
21	44	2	100	52	8	2	0.9
21	44	3	100	52	8	2	0.9
21	44	4	100	55	10	1	0.9
21	44	5	100	57	10	2	0.9
21	44	6	100	57	10	1	8
21	44	7	100	53	9	1	0.5
21	44	8	100	54	9	1	0.4
21	44	9	100	56	9	1	0.4
21	44	10	100	59	10	1	0.6
21	44	11	100	59	10	2	1
21	44	12	100	54	8	2	0.9
21	44	13	100	58	8	1	0.9
21	44	14	100	58	9	1	0.7
21	44	0	100	54	3	2	0.7
22	14	0	100	64	8	1	
22	14	1	100	63	8	1	
22	22	2	100	72	16		2

Table 18. Aggregate Gradations

22	22	3	100	49	5		2
22	22	4	100	67	9		2
22	22	5	100	71	17		2
22	22	1	100	67	11		2
22	28	1	100	72	13		1
22	28	3	100	68	12		2
22	28	4	100	70	11		3
22	28	5	100	50	4		2
22	28	2	100	73	13		2
22	101	1	100	72	13		3
22	212	1	100	56	14	1	
22	212	2	100	56	13	3	
22	212	3	100	57	13	2	
22	212	4	100	61	14	3	
22	218	0	100	47	4		0.4
22	218	1	100	48	4		1
22	218	2	100	57	5		1
22	218	3	100	62	6		1
23	28	0	100	48	7	2	
23	28	1	100	49	8	2	
23	28	2	100	42	5	2	
23	28	3	100	46	5	1	
23	28	4	100	45	5	1	
23	28	5	100	44	3	1	
23	28	6	100	48	6	2	
23	34	1	100	63	13	1	
23	34	2	100	66	16	1	
23	34	3	100	63	14	1	
23	34	4	100	60	12	2	
23	45	1	100	65	14	2	
23	45	2	100	66	20	3	
23	45	3	100	68	20	3	
23	45	4	100	68	17	3	
23	212	1	100	55	12	1	
23	212	2	100	42	5	1	
23	212	3	100	47	8	2	

Note: "Z" after highway number indicates second project on same highway.

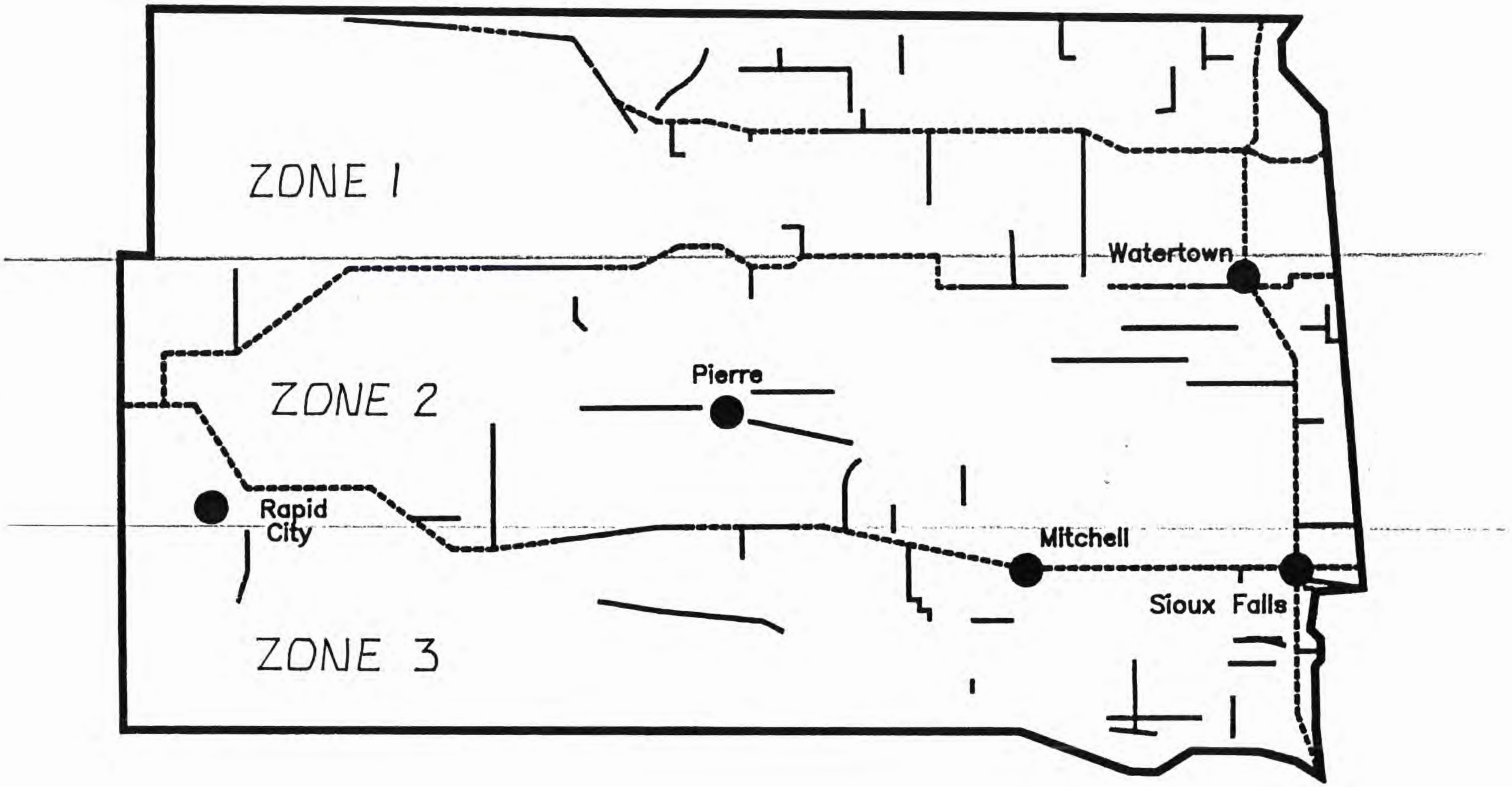


Figure 16. Climatic zones.