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DURABLE ASPHALT EMULSION SEAL COATS

Volume I: Research Report

October 1989

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FOREWORD

This report documents an investigation of seal coats, primarily chip seals. The study included a literature review, discussions with pavement technologists, interviews of State highway departments, and laboratory and field evaluations of selected projects. In addition, two other documents resulting from this investigation are available: volume II--appendixes to this report; volume III--a users manual which outlines the factors that should be considered when designing and constructing a chip seal project.

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16. Abstract This report documents an investigation of seal coats, primarily chip seals. The study included a literature review, discussions with pavement technologists, interviews of State highway departments, and laboratory and field evaluations of selected projects. Significant findings and recommendations are as follows:

- Construction factors are extremely important. Increasing awareness, knowledge and experience in this area should lead to fewer premature failures.
- Design methods vary and result in significantly different material quantities. Many agencies rely on rates based on historical data and experience.
- Performance measures, failure criteria, or factors affecting performance of chip seals are not significantly different betweenclimatic regions.
- Emulsion and residual asphalt viscosity should be directly considered in design, in specifications, and during construction. Emulsion viscosity can decrease substantially from production to time of construction.
- Statistically planned, controlled field projects which focus on isolated parameters are recommended for further research.

Other available documents are: volume II (Report No. FHWA-RD-89-231) -- appendixes to volume I; volume III (Report No. FHWA-RD-89-237) -- a users manual which outlines the factors that should be considered when designing and constructing a chip seal project.

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APPROXIMATE CONVERSIONS TO SI UNITS

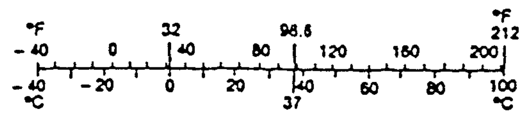
Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
	VOLUME			
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

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

Symbol	When You Know	Multiply By	To Find	Symbol
	MASS			
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
	AREA			
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
	VOLUME			
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
	MASS			
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
	TEMPERATURE (exact)			
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



* SI is the symbol for the International System of Measurement

(Revised April 1989)

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CHAPTER 1. INTRODUCTION

1. Problem Definition

Asphalt emulsions have been used for a wide range of applications in pavement construction. Introduced more than 80 years ago, they have been accepted only gradually into the paving community and primarily for various types of seal coats. The popularity of cutbacks tended to delay the growth of asphalt emulsions, but several incidents through the years have increased their acceptance. These included at least, (1) development of cationic emulsions, (2) the energy crisis in the mid-1970's, (3) the environmental protection movement, and (4) the advent of new binders such as polymer modified asphalt emulsions. Most of the growth in asphalt emulsion usage has occurred since 1973, but even so, these materials represent only about 10 percent of the asphalt used in pavements.[1] Although the potential for increased use of asphalt emulsions seems much greater, their limited utilization has been caused by uncertainties in the performance of some applications, especially when used as a seal coat.

Seal coats, as used in this report, include surface treatments (also referred to as chip seals), slurry seals, sand seals, and fog seals or combinations of these. The most popular seal coats are chip seals, but even so, they have had their problems. Some seal coats have performed quite well, but others have failed after only a few months of service. With an increasing need to "stretch" the maintenance dollar, many agencies that had rejected the use of seal coats, particularly chip seals, are now re-examining this option with the hope that research and development have advanced the state of the knowledge to produce reliable techniques at low costs.[2,3,4]

Historically, most seal coats were made with asphalt cutbacks or paving grade asphalts and worked well. By using proper procedures based on local experience and using asphalt binders with known properties, many thousands of miles of excellent seal coats were constructed. More recently, asphalt emulsions have been used extensively, but with inconsistent results. For example, in order to get good coating and wetting of aggregate, solvents are often used in asphalt emulsions. However, some solvents have caused softening of the underlying asphalt pavement with subsequent embedment of aggregate chips into the underlying pavement and a flushing situation resulted. This phenomenon is illustrated in figure 1.

Poor performance of asphalt emulsion seal coats can be caused by a number of factors; it can usually be traced to one and often several of the dominant factors influencing performance. For example, one or more of the individual materials that go into a seal coat may have deficiencies. A suitable set of tests for materials evaluation is an important consideration. Asphalt binders (residual asphalt) used in a chip seal must possess strength, adhesion, durability, and resistance to traffic forces. Tests and criteria need to be established for the properties of the asphalt. Figure 2 shows a typical aggregate particle in a chip seal and the resulting forces it must resist. The durability and toughness of the aggregate is extremely important, and represents a part of those factors important to achieving a successful chip seal.

Construction factors are also very important to the success of seal coats. The variables in construction practice are probably the most difficult to control because they are numerous, including at least the following:

- Equipment and methods.
- Type and condition of underlying surface.
- Control of traffic during construction.
- Volume and type of traffic as well as speed.
- Geometry.
- Weather.

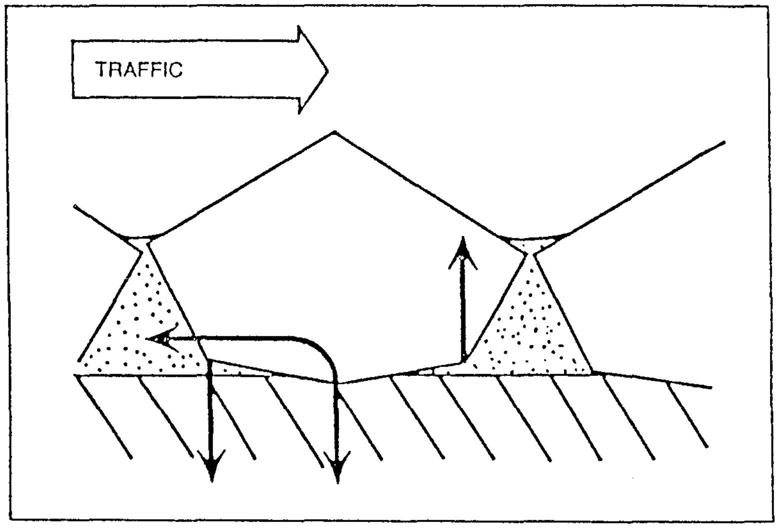


Figure 1. Aggregate embedment under traffic action.(5)

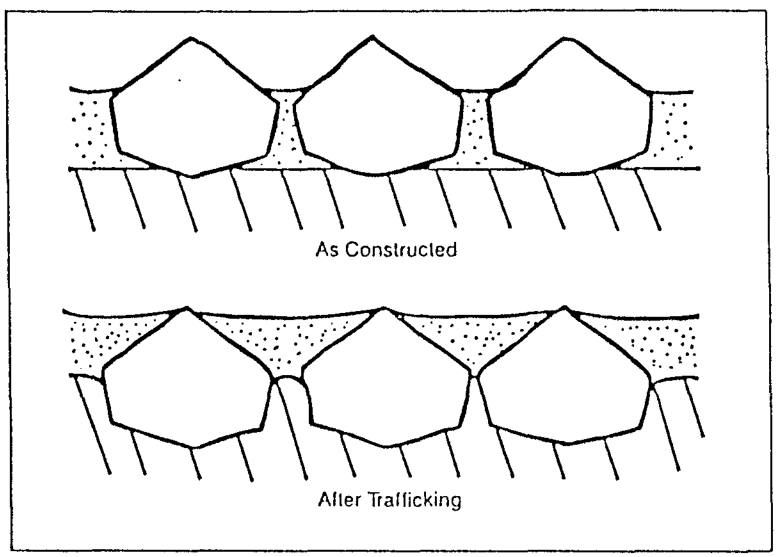


Figure 2. Schematic representation of stresses applied by wheel to a chip seal system.(5)

It has been suggested that many of the problems may be associated with inexperienced personnel. These would include designers, contractors, and inspectors alike. Because the construction of a good seal coat is somewhat of an "art," good training is necessary. It has been further suggested that most of the problems related to premature failure are construction related rather than materials related. This perception needs to be evaluated further since the design of the seal coat and materials are certainly an important consideration.

The research on seal coats has been somewhat limited. Quantifiable and well documented data relating materials and construction to performance is difficult to find. Most of the improvements have come through field trials where performance can be observed, but documentation and correlation with laboratory tests has often been overlooked or poorly researched and reported. For example, the evolution of chip seals has gone from single applications of asphalt emulsion and aggregate--to double asphalt and double chipping--to single asphalt and double chipping (see figure 3). In Europe, this evolution was made with conventional asphalt emulsion and more recently with polymer modified asphalts which have apparently been effective in achieving a level of performance not achieved with conventional binders.[5] Improved binders for slurry seals have also made it possible to achieve better skid resistance by allowing the use of larger aggregates as shown in figure 4. As a result of limited research, the presently available manuals and guidelines are primarily based on practical experience. The intent of this project was to develop improved guidelines based on rational investigation to <u>bridge the gaps</u> now existing.

2. Project Objectives

The objective of this study was to develop procedures and guidelines that will consistently yield durable asphalt emulsion seal coats. It included a comprehensive study of the factors that affect performance of asphalt emulsion seal coats. This was accomplished with information from:

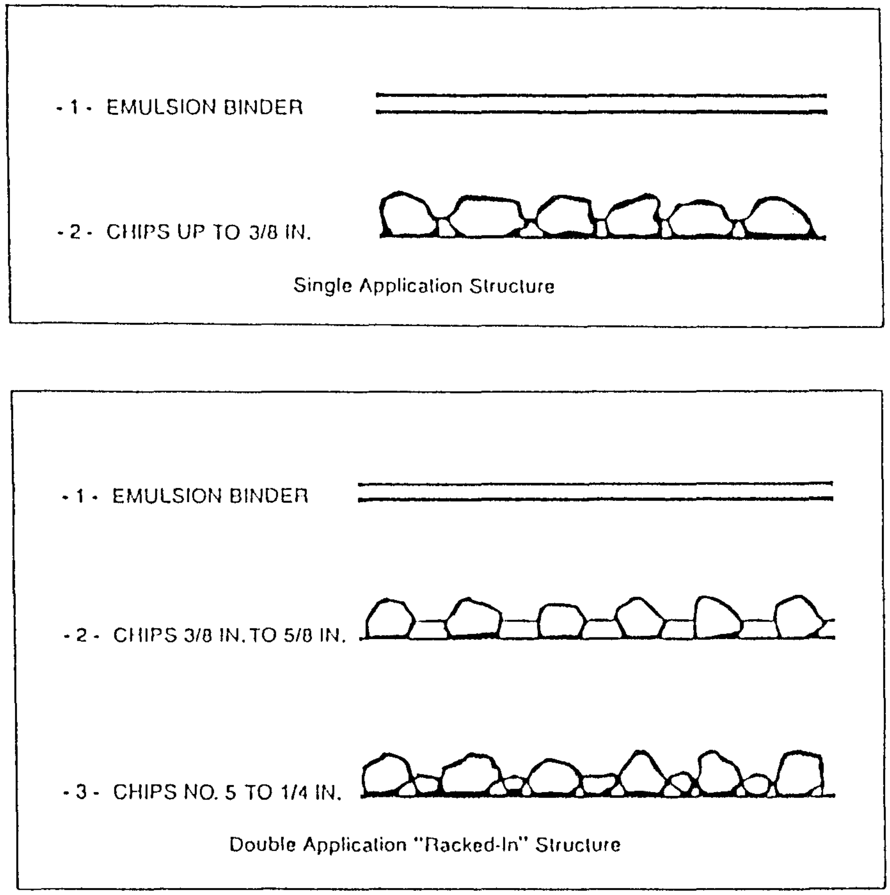


Figure 3. Recommended chip seal structures with modified asphalt emulsion.[5]

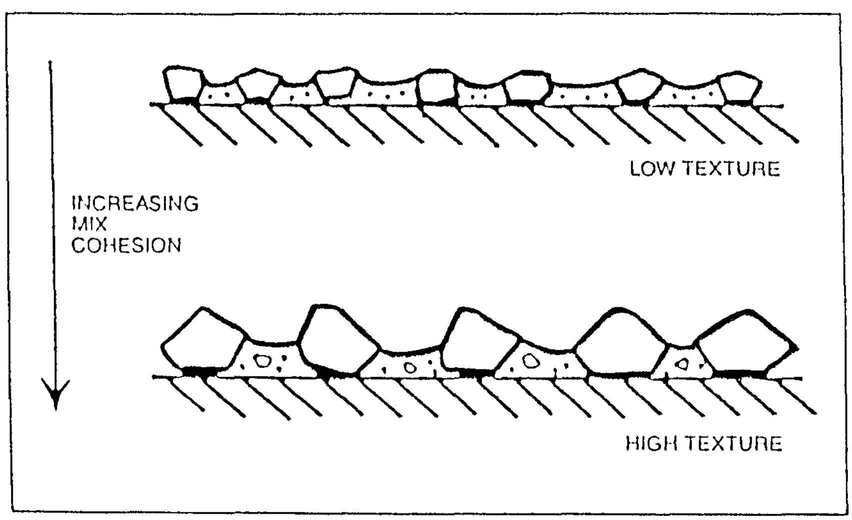


Figure 4. Relationship between mix cohesion and surface texture.[5]

- A literature search.
- Evaluation of successes and failures.
- Laboratory/field testing and evaluation program.

The ultimate use of these data was to develop improved tests, specifications, procedures and guidelines for the design and construction of asphalt emulsion seal coats. A major product was an easy-to-read users manual, intended for use by municipal, county, and State construction and maintenance engineers, roadway maintenance foremen, and contractors.

The primary intent of the study was to reduce the number of "early" failures of asphalt emulsion seal coats. For purposes of this study, "early" failure is one where the chip seal fails to perform its intended function during the first 12 months. In addition to reducing early failures, the output from the study should also enable the construction of emulsion seal coats with increased service life and reliability.

3. Study Approach

Though many reports, manuals, and papers exist which describe the design, construction, performance, and maintenance of seal coats, there are still a large number of early seal coat failures. This study was designed to:

- Identify the factors required to reduce the number of early failures.
- Enable the construction of emulsion seal coats with increased service life.
- Communicate to agency and contractor personnel the procedures to be followed to maximize the potential for satisfactory performance of seal coats.

The overall approach used to satisfy the project objectives is summarized in figure 5.

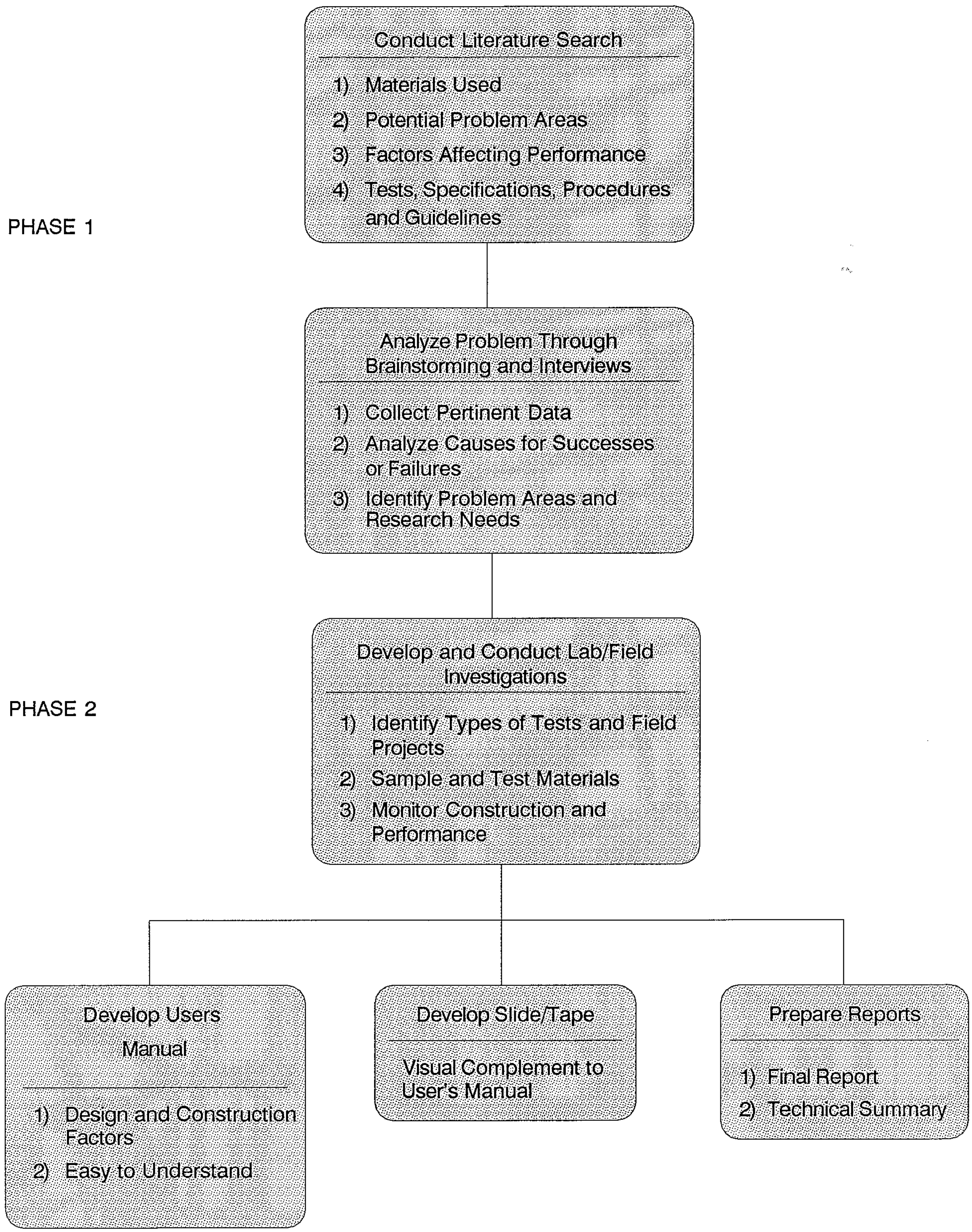


Figure 5. Study approach for seal coat investigation.

The first step was to conduct a comprehensive literature search. The items addressed included:

- Types of asphalt emulsion-aggregate systems used in seal coat applications.
- Potential problem areas that might result in early failure.
- Factors influencing the performance of asphalt emulsion seal coats.
- Tests, specifications, procedures and guidelines currently used for design and construction of asphalt emulsion seal coats.

The results of this effort are summarized in chapter 2 "Literature Review."

The next step consisted of a detailed analysis of the problem. This was accomplished in two ways:

- A brainstorming meeting between the principal investigators and project advisors.
- Interviews with agencies throughout the United States and Canada.

The brainstorming meeting was useful to determine:

- What data to collect and how to collect it.
- Who to obtain the data from.
- How much data must be collected to provide reliable answers.
- How to analyze data collected.

The follow-up interviews were useful in identifying:

- Problem areas leading to poor and inconsistent performance.
- Information identified with good performance.
- Information gaps which need additional research.

The results of these activities are presented in chapter 3 "Brainstorming and Interviews."

The final step in the investigation was to analyze the relationships of material properties and construction procedures to actual seal coat performance. This analysis was accomplished by conducting the following activities for selected seal coat projects:

- Performing preconstruction surveys of the original pavement prior to coverage by the seal coat.
- Observing and documenting construction conditions and procedures.
- Sampling project materials and conducting various laboratory tests.
- Performing post construction evaluation ratings of actual chip seal performance.

Results of the above activities are given in chapter 4 "Laboratory and Field Evaluations."

Overall significant findings and recommendations are presented in Chapter 5. A list of pertinent references and a bibliography are included at the end of this report.

A companion to this volume I report is a series of four appendixes grouped into volume II. The appendixes have been assembled to enable other researchers to evaluate the findings of this study in more detail and/or extend seal coat research.

APPENDIX A--LITERATURE REVIEW ABSTRACTS AND ANNOTATED BIBLIOGRAPHY
APPENDIX B--QUESTIONNAIRE, RESPONSES, AND ANALYSES
APPENDIX C--LABORATORY DATA AND FIELD NOTES
APPENDIX D--SUMMARY AND COMPARISON OF DESIGN METHODS

Appendix A lists pertinent references and abstracts obtained from two computer searches performed as part of the project. An annotated bibliography developed in another study is also included. Appendix B presents the questionnaire that was used to interview State highway departments; addresses of the State contacts are included. Questionnaire replies are given in appendix B as well as a detailed discussion of the statistical analysis performed thereon. Appendix C contains raw laboratory data and field notes which have been summarized and presented here. Appendix D discusses a number of design methods that have been used in the past.

In addition to volumes I and II, which constitute the research report, a manual was prepared entitled, "Guide to Durable Asphalt Emulsion Seal Coats" which represents volume III of this project. The intent of the manual is to summarize all factors which should be considered for design and construction of chip seal projects. Although the manual is presented in the form of a guide to better chip seals, many of the details of materials testing, design, and construction are left to other excellent existing manuals to avoid unnecessary duplication. Rather, this guide is focused on key factors that have the most impact on obtaining a successful chip seal. A slide presentation that parallels the guide is also available.

CHAPTER 2. LITERATURE REVIEW

A number of preliminary studies and background reviews were made at the beginning of the project. These were accomplished to provide the research team with current information on:

- Purpose and uses of seal coats.
- Types of seal coats.
- Problems with seal coats.
- Factors affecting performance.
- Guidelines for design and construction.

The studies included:

- An extensive HRIS/TRIS literature search (see appendix A).
- Personal contacts with asphalt emulsion manufacturers and their respective trade associations.
- A review of various guidelines for seal coats.

The sources of information explored as a part of this study are as follows:

Literature Search:

- Computer Searches (HRIS/TRIS).
- Transportation Research Board (TRB).
- American Public Works Association (APWA).
- Canadian Technical Asphalt Association (CTAA).

Contacts with Producers & Associations.

- Chevron USA.
- Asphalt Emulsion Manufacturers Association (AEMA).

- Eurobitume.
- Asphalt Institute (AI).
- International Slurry Seal Association (ISSA).

Review of User Agency Guidelines:

- USA.
- Canada.
- Europe.
- South Africa.
- New Zealand/Australia.

This chapter summarizes the results of the literature review effort.

1. Purpose and Uses of Seal Coats

Seal coats are applied to an existing bituminous surface for one or more of the following purposes:[4]

- Seal an existing bituminous surface against the entrance of air and water.
- Revitalize an existing dry or raveled surface.
- Provide a skid resistant surface.
- Increase pavement visibility at night.
- Reduce tire noise.
- Improve demarcation of traffic lanes or other geometric features.
- Attain a uniform appearing surface.

Little increase in load carrying capacity is obtained from the additional pavement thickness supplied by a seal coat; however, an effective seal may improve the load carrying ability of a pavement by preventing water access to the underlying materials.

Seal coats are only temporary solutions for badly fatigued or thermally cracked pavements. Further, seal coats cannot significantly correct the ride quality of rough pavements or repair badly rutted or corrugated pavements. When all is considered, seal coats can be invaluable in preserving a pavement. They have generally been used in pavements with traffic volumes carrying up to 5,000 vehicles per day per lane. The probability of success is, however, greatly increased on roadways carrying lower traffic volumes or decreased on roadways carrying higher traffic volumes.[6]

In Europe, the advent of polymer modified emulsions has permitted the use of seal coats (chip and slurry seals) on higher volume facilities (Motorways in United Kingdom, Autobahns in West Germany and primary highways in France).[5] Therefore, the use of seal coats on these type facilities could also be considered assuming necessary binder properties can be provided.

2. Types of Seal Coats

A seal coat is generally defined as a bituminous surface that results from one or more successive applications of a bituminous binder and cover aggregate applied to an existing paved surface.[4] In addition to conventional seal coats (surface treatments or chip seals) there are slurry, sand, fog and cape seals.

These various seals are summarized in table 1 and are described in more detail below.

a. Surface Treatments

Surface treatments can be single or multiple treatments of asphalt emulsion followed by aggregate. This treatment is a common practice worldwide, especially in areas where traffic volumes do not justify the cost of hot-mix asphalt surfacing. The Transportation and

Table 1. Emulsified asphalt seal coats.[7]

System	Description and Uses
Chip Seal	Single most important seal coat. Produces an all weather surface, renews weathered pavements, and improves skid resistance.
Slurry Seal	Used in airport and city street maintenance where loose aggregate cannot be tolerated. Seals and fills cracks and minor depressions, and improves skid resistance.
Sand Seal	Restores uniform cover. In city street work, it improves street sweeping, traffic lane visibility. It also enriches dry weathered pavements and reduces raveling.
Fog Seal	Renews old asphalt surface, and seals small cracks and surface voids.
Cape Seal	Combination of chip and slurry seals. Provides robust surface with good skid resistance and surface texture.

Road Research Laboratory, in its pavement design guide for tropical areas, recommends a double surface treatment in lieu of hot mix asphalt concrete (HMAC) for all pavements with cumulative traffic volumes of less than 2.5 million standard axles over the design period.[8] Likewise, in New Zealand, double surface treatments instead of HMAC are used on pavements that carry up to 20,000 vehicles per day.[9]

Surface treatments are sometimes distinguished from a chip seal according to the nature of the subsurface, e.g., aggregate or asphalt concrete, respectively.

Asphalt emulsion binders generally used for surface treatment operations are the rapid setting type (RS-1, RS-2, CRS-1, CRS-2). In recent years, polymer or latex modified asphalt emulsions have been used.

Also, so-called "high float" emulsions have proven to be advantageous in many situations.

b. Slurry Seals

A slurry seal is a mixture of a well-graded fine aggregate, mineral filler, asphalt emulsion and water.[10] It is used in both corrective and preventive maintenance of asphalt pavement surfaces. It does not, nor is it intended to, increase the pavement's structural strength.

The main advantages of a slurry seal result from its composite nature; it is a mixture of components made with equipment designed to consistently combine ingredients in prescribed proportions. Slurry seals can achieve the following benefits in a one pass operation:

- Fill existing pavement cracks.
- Stop raveling and loss of matrix.
- Improve skid resistance.

By changing its aggregate gradation, a slurry seal becomes a versatile material which can be used in different job situations. For example, slurry seals are generally grouped as follows:[11]

- <u>Type I (minus No. 8 sieve) seals</u> are used for maximum crack filling and protection.
- <u>Type II (minus No. 4 sieve) seals</u> are the most widely used. They are used to seal, correct raveling and to improve skid resistance.
- <u>Type III (minus 3/8 in sieve) seals</u> are used to correct severe surface conditions, as the first course in multicourse applications, and to impart skid resistance.

Emulsified asphalts used in slurry seals range from slow setting (SS): SS-1, SS-1h, CSS-1, CSS-1h to quick setting (QS) emulsion when early opening to traffic is required. In addition, considerable success has been achieved with natural latex or polymer modified asphalt emulsions in so-called "improved slurry seals" or "micropavements."

c. Sand Seals

A sand seal consists of a spray application of asphalt emulsion followed by a light covering of fine aggregate. It is primarily used to:

- Enrich a dry, weathered or oxidized surface.
- Prevent the intrusion of moisture and air.
- Develop a skid resistant surface texture.

Like conventional surface treatments, a rapid setting emulsion is normally used. Although the construction procedure is rather simple, sand seals are not as widely used as the surface treatments or slurry seals for roadway maintenance. They are more likely to be used in parking lots or residential driveways where a smooth surface is more appealing.

d. Fog Seals

A fog seal consists of a light sprayed application of an asphalt emulsion diluted with water on an existing surface. Slow setting asphalt emulsions or proprietary binder products are normally used in this application. Fog seals are normally used to:

- Renew old asphalt surfaces that become dry and embrittled with age.
- Seal small cracks and surface voids.
- Provide a construction seal to partially compensate for poor compaction.

Their use may prolong pavement life or delay the time when major maintenance or reconstruction is needed; however, many engineers believe that fog seals are largely cosmetic.

e. Cape Seals

A cape seal is the combination of a chip seal using aggregate 3/8 in or larger followed by a slurry seal. All materials are similar to those used with either a chip seal or slurry seal (Type II). Cape seals are expected to be more durable than conventional single treatment chip seals. They can especially aid in the prevention of chip loss.

3. Problems with Seal Coats

Performance problems identified with various types of seal coats are as follows:

a. Chip Seals or Surface Treatments:

- Loss of aggregate exposing the base asphalt.
- Bleeding (excess amounts of asphalt) resulting in a slippery surface when wet.
- Nonuniform longitudinal or transverse distribution of asphalt or aggregate resulting in accelerated wear of the seal.
- Loose or unbonded aggregate resulting in cracked windshields.

b. Slurry Seals:

- Premature wear due to poor mix design.
- Segregation of aggregate and liquid portion due to poor mix design.
- "Scabbing" due to improper cleaning of subsurface.
- Inadequate coverage causing accelerated wear.

c. Sand Seals:

- Problems are similar to those of chip seals, with the exception of flying chips.

d. Fog Seals:

- Excessive application resulting in slippery surface.
- Insufficient application with uneven appearance and lack of benefit.

e. Cape Seals:

- Problems can occur as associated with individual layers.
- System does provide what can be described as a "back-up" to premature failure.

Researchers have identified types and potential causes of distress of seal coats in Texas (see table 2).[4] That report and others proved to be of considerable use in this study.[3]

4. Factors Affecting Performance

The problems identified in the previous section can generally be attributed to one or more of the following:

- Material properties--emulsion and aggregate.
- Design quantities--emulsion and aggregate.
- Construction procedures--construction techniques, existing surface preparation, traffic control, inspection, etc.
- External conditions--type and volume of traffic, curvature or alignment, grade, climatic conditions, etc.

Table 3 summarizes some of the material properties which affect the performance of seal coats. For this study, table 3 served as a starting point to assist in identifying all factors affecting performance. Design considerations are discussed extensively later in this chapter. Tables 4 and 5 present construction and external factors. The remainder of this report focuses on chip seals due to their extensive use yet controversial performance.

Table 2. Types and causes of seal coat distress.[4]

Distress	Possible Causes
Streaking	Longitudinally distributed deficiencies in asphalt application due to: inoperative nozzles, incorrect nozzle angles, incorrect distributor bar height, low asphalt temperature, low pump pressure, incorrect fan widths at a given height, high distributor speed. These problems are particularly troublesome at spread rates below 0.1 gal/yd^2.
Corduroying	Uneven and bumpy aggregate spreader operation. Bent or warped roll base.
Incipient Bleeding	Underlying surface condition (too soft, inadequate preparation, excess asphalt not removed, base not compacted, primer incorrectly applied). Asphalt spread rate OK, but aggregate spread rate too low. Aggregate loss due to moisture problems.
Raveling	Asphalt spread rate too low. Aggregate loss due to moisture problems. Fast traffic allowed on surface too soon.
Transverse Joints (Bumps)	Overlap of asphalt at beginning and end of a shot.
Longitudinal Ridges	Too much overlap of asphalt and aggregate spread which results in excesses of one or both materials.

Table 3. Material properties affecting performance of seal coats.

Property	Comments
a) Asphalt Emulsion	
1. Viscosity	• At time of application. • Rate of set. • Temperature susceptibility.
2. Durability	• Rate of hardening. • Abrasion resistance.
3. Adhesion	• Rate of development of bond. • Bond in presence of water during and after construction.
b) Aggregate	
1. Strength	• Ideal aggregate is hard, clean, tough crushed stone or gravel. • LA Abrasion less than 35 is preferred.
2. Shape	• For chip seals, preferred shape is cubical. • Flat particles are to be avoided.
3. Size and Gradation	• Affects emulsion application quantity. • For chip seals, one size aggregate is best.
4. Texture	• Affects adhesion. • Usually obtained by crushing.
5. Durability	• Evaluated by sulfate soundness or wet degradation. • Good durability is essential.

a. Materials Properties Affecting Performance (see table 3)

(1) Asphalt Emulsions (refer to table 3). There are a number of grades of emulsion used for chip seals. Basically, asphalt emulsions are classified and labeled by electrical charge, setting rate, and

viscosity. For example, RS-1 denotes an anionic emulsion while CRS-1 represents a cationic emulsion; the abbreviations: RS, MS, SS relate to rapid set, medium set, and slow set emulsions, respectively; characters following the dash indicate the relative viscosities of the emulsion and the residual asphalt--1, 2, etc. represent characterizations of increasing viscosities. In addition, high float emulsions which provide thicker coating films include a designation of HF.

Viscosity. The asphalt emulsions, RS-1, MS-1, SS-1, HFMS-1, CRS-1, CMS-1 and CSS-1 have lower viscosities at the temperature of application. This can result in running or sagging on the grade, super elevations, or high crowns. The lower viscosities can also result in "waves" of emulsion in front of the aggregate spreader, especially with aggregates containing fines.

The higher viscosity products such as RS-2, MS-2, MS2h, HFMS-2, HFMS-2h, CRS-2, CMS-2 and CMS-2h show less tendency to sag on grades, super elevations and high crowns if the products are manufactured in the mid-range viscosity of their specifications. That is the reason why some agencies have modified their viscosity specifications, such as for CRS-2, from 100 to 400 seconds at 122 ^{o}F to 150 to 300 seconds at 122 ^{o}F. The upper range was lowered to reduce streaking. These higher viscosity products will also form "waves" with some fine graded aggregates.

It is uncertain if there is a relationship between rate of set and viscosity. Under similar weather conditions, set is generally associated with the formulation of the emulsion.

Set is affected by the electro-chemical reaction (ECR) between the emulsion and the rock. The ECR associates anionic emulsions better with limestones and cationic emulsions better with a wider range of aggregates of siliceous nature.

Setting time is also affected by:

- The type and amount of emulsifier and stabilizer used. The CSS-1, SS-1, and some of the HF emulsions are designed to have slower sets.
- The type, amount and point of combining of a solvent (cutter) in the emulsion affects the rate of set of the emulsions.
- The spread rate (quantity per square yard) can affect set and cure.

Temperature susceptibility is usually associated with the base asphalt. The harder (higher viscosity) asphalt would show a better resistance to the initial rock turning or roll-over under traffic in warmer weather conditions. However, these harder grades may lack flexibility and ductility in the cooler part of the year. Therefore, the grade of asphalt chosen is generally a compromise. Development work is underway in an attempt to flatten these temperature susceptibility curves, possibly with polymer modification.

Durability. Asphalt emulsions have the advantage of being stored and applied at relatively low temperatures, which reduces hardening. Heavier application rates and thicker films also slow hardening. However, the nature of a chip seal being open graded does expose the asphalt to air and water, thus accelerating aging.

Adhesion. The bond between the rock and the asphalt, and between the asphalt and the pavement is a function of the asphalt emulsion breaking. The break is a function of the type of emulsion used. Usually, the CRS (or RS) grades are considered the most rapid and the CSS (or SS) grades the slowest. However, in warm weather this time could be nearly the same. The cutter in an emulsion can aid adhesion if there is dust on the aggregate or when working in cooler weather conditions. But until the cutter evaporates, the full strength of the bonding may not develop.

A damp aggregate is desirable when sealing with an asphalt emulsion. Free water on the aggregate, however, can lower the viscosity of the emulsion. It is preferable to dampen the aggregate in the stock pile. Depending on the emulsion and the ECR with the rock, early rain can have little effect or can completely wash off the binder. Generally, however, the emulsions, particularly the RS or CRS grades, will set and have better early rain resistance than cutbacks. Most emulsions are made with emulsifiers and stabilizers which are anti-strip additives, and give the emulsion good resistance to later stripping.

(2) Aggregates (refer to table 3). Certainly the rock should be hard enough not to crush under original construction traffic and rolling, or under subsequent use. In addition it should be nonpolishing under traffic.

Both natural gravels and crushed rocks have produced satisfactory chip seals. The natural aggregates are used primarily for economic reasons and have a limited application. They have a tendency to roll over on grades. To "stick" these naturally existing aggregates require substantially higher application rates of the emulsion.

The crushed faces of a manufactured aggregate give an interlocking between particles and the flat faces give better contact between the aggregate, asphalt, and the existing pavement.

A wide range of aggregate sizes and gradations has produced satisfactory chip seals. A maximum size of 3/4 by 1/2 in is used where a coarse texture is desired. The 3/8- by 1/4-in size produces a finer texture. The volume of traffic can influence the aggregate choice. High volume traffic conditions favor the smaller sized rock because it is easier to stick and less likely to break windshields and headlights.

One-sized aggregate produces an attractive, free-draining mosaic. One-sized aggregate seals require heavier applications of asphalt. And they also have a tendency to turn under early traffic and frequently require an application of choke stone.

An intermediate graded cover stone contains sizes ranging from the maximum size through the 1/4 in with little or none passing the number 200 sieve. This is a very common grading specification. It generally requires less emulsion per square yard than the one-sized aggregate with the same maximum size.

A full graded aggregate cover stone is also used with the emulsions. The aggregate does contain some portions passing the 200 sieve. Generally, the HF or a CMS-2 emulsion is used with this cover stone. Because there are fewer voids, the emulsion application is reduced.

Pavement surfaces with finer aggregate seals have as good or better skid resistance characteristics in dry and in most wet conditions. Initially, crushed rock provides a rougher texture surface than the natural cover stone. However, many crushed rocks will polish smooth under traffic.

b. Construction Factors Affecting Performance (see table 4)

(1) Materials Handling and Storage

Aggregates. In one-sized aggregates there is no problem with segregation. With a more fully graded aggregate, the standard good practices of stockpiling should be followed. This starts with preparing a level uniform floor on which to build the stockpile. Then the stockpile should be built in layers rather than a cone. As the loader is filling the trucks, it should not be allowed to dig into the floor of the stockpile. This will prevent troublesome over-sized rocks on the seal coat project.

Emulsions. The short-time storage temperature of asphalt emulsion should be close to the spraying temperature, when relatively short haul distances are involved.

Table 4. Construction factors affecting performance of seal coats.

Factor	Comment
1. Materials Handling and Storage	• Maintain uniformity of aggregate • Check storage stability of emulsions
2. Construction Equipment	• Calibration is a must • Keep spray nozzles clean
3. Surface preparation procedures	• Distressed areas must be repaired • Seal coats will not correct all problems
4. Construction Procedures	• Spread rates and temperatures must be monitored • Uniformity of application should be checked • Chip spreader must keep up with distributor • Use proper rollers
5. Traffic Control	• Function of cure time, climatic conditions, etc.
6. Inspection	• Periodic checks of equipment spread rates • Monitoring construction procedures

Vertical tanks will generally have less surface area exposed to the air, and this is preferable when storing asphalt emulsions. When the surface of the asphalt emulsion is exposed to air in storage (particularly for extended periods), a skin will form. By floating solvent on this interface, the skin formation can be reduced or limited.

With horizontal or vertical tanks, it is desirable to fill the tank and load from the tank from the bottom. Filling the tank from the top can break up the skin, if it is present, into small chunks causing pumping problems and plugging nozzles.

Electric heat, steam or hot oil tubes, or flue heaters have been used to heat or maintain temperatures on emulsion storage tanks. It is critical to prevent overheating the emulsion and having "hot spots" adjacent to the heating tubes. Circulation during heating is desirable.

Anionic and cationic asphalt emulsions are not compatible. Co-mingling of these types can break the emulsions and make them unusable. Draining tanks or equipment and washing with solvent is required before changing grades.

Extended heatings of emulsions can evaporate part of the water from the emulsion, changing the viscosity and handling characteristics. Boiling or freezing will break the emulsion and make it unusable.

(2) Construction Equipment. The distributor controls the uniformity of the binder application and thus the uniformity of the chip seal. The thermometer, tachometer, and pump should be operating properly. The bar and its nozzles must be properly set to obtain a uniform spray. The nozzle size, spacing, and angle in relationship to the bar, determines the height of the bar.

Streaking is the most common result of nonuniform application. Streaking can occur if the emulsion is too cold or too viscous, the nozzles are not all at the same angle, the bar is not at the proper height, or the bar pressure is too high or too low for the length of the bar and the size of the nozzles.

The chip spreader should be adjusted to apply a uniform aggregate spread. However, a slightly heavier coverage is often set for the wheel paths of the chip spreader and truck. Corrugations can result if the auger roller is out of round or bent.

(3) Surface Preparation Procedure. If the chip seal is laid on an untreated surface (i.e., surface treatment), the top course should be

brought to the proper grade and a uniform texture. This surface can either be a tight surface or have a uniform layer of float aggregate.

On an existing asphalt pavement, the surface should be sound and clean. It should first be patched and broomed. If there are newly patched areas, they should be presealed or shot heavier. Some pavement conditions which may require special application adjustments are: an open or dry surface where a higher spread rate should be considered; a fat (flushing) pavement where it is difficult to choose the proper application rate because frequently the surplus asphalt in the original pavement will bleed into the new seal; darkly shaded areas which frequently require a heavier emulsion application.

(4) <u>Construction Procedures</u>. All equipment necessary for the project should be on the jobsite before the chip seal project begins.

There should be enough loaded aggregate trucks standing by to cover the entire length of roadway spread with asphalt emulsion.

The distributor should start and finish each shot on paper. The yield should be calculated after each shot to determine that the desired amount was applied. The amount desired can be determined by several design methods, as covered in a following section. In all cases, the goal is to produce a chip seal with the aggregate embedded in the asphalt emulsion from 50 to 70 percent. Too thin (low) an application of the emulsion generally results in rock loss, particularly of the larger sizes. Too thick (high) an application usually is not as serious if enough cover stone is used; frequently, more rock is bound to the pavement. There is, however, a possibility of over-embedment, resulting in flushing.

Rock spreading should follow immediately after the asphalt application. The rock should cover the asphalt while it is still fluid to obtain good embedment. The spread rate of the rock is predetermined by calculating the amount necessary to make the surface one stone deep. It can be checked by visually observing if 10 to 15 percent black (asphalt) shows through the newly laid rock, and there is no pickup by traffic. The chip spreader should be operated at a slow enough speed so as not to roll the rock. The aggregate should be spread on the first half of the roadway in such a manner that a 4 to 6-in strip (meetline) of asphalt is left exposed along the centerline. This meetline is reshot when the adjacent lane of asphalt emulsion is applied to promote chip retention along the construction joint. If there are areas where an excess of aggregate has been spread, it should be uniformly distributed on adjacent roadway or removed. Areas which have received too light an aggregate cover should be hand spotted. This should be accomplished before the rolling begins.

Choke stone, an aggregate graded finer than the primary chip rock, may be applied after the chip rock to prevent the new chip seal from being turned or rolled over under early traffic.

Rolling can be accomplished with either steel or pneumatic rollers. Generally, the steel roller is used with a seal coat on an untreated surface. Pneumatic rollers are preferred on seals over existing asphalt pavements. Rolling should proceed close behind the rock spreader. Rolling is to orient the rock to get the flat side down. The roller should be operated at slow speeds (4 to 6 mi/h) so the rock is set, not displaced.

Brooming of the surplus cover stone can be performed the next day or up to several weeks later, depending on the curing characteristics of the emulsion and the traffic conditions. Brooming is usually done with a rotary power broom. It should be done in the cool part of the day when the asphalt binder is stiffer.

(5) Traffic Control. Depending on the particular chip seal project, auto traffic and especially trucks traveling at relatively high speeds can cause premature chip loss. Traffic control protects the chip seal during the emulsion's tender period (curing time). This period

varies with the type of emulsion used and the air and pavement temperatures. Flaggers and signs help, but the only positive traffic control is a pilot car. A pilot car not only controls the speed, but it also controls the flow of traffic in different travel paths across the new chip seal to reduce flushing and improve compaction.

(6) Inspection. Measuring yields of asphalt and rock should be part of a continuous inspection procedure during the project.

A post construction inspection is desirable as well. This includes a general inspection of the overall appearance of the project. Several of the maximum size rock should be manually removed from the seal to determine if the desirable 50 to 70 percent embedment in the residual asphalt is obtained. If insufficient embedment has been obtained, a fog seal can be applied at this time to enrich the surface and tie down the cover stone.

c. External Factors Affecting Performance (see table 5)

(1) Traffic Type and Volume. The damage caused by fast-moving, braking, and turning traffic can be minimized by the initial traffic control with a pilot car. The use of choke stone will further reduce this potential for premature failure.

(2) Weather Conditions.

Hot Weather. High air and pavement temperatures can lead to traffic damage to a chip seal. The asphalt at elevated temperatures is less viscous and does not have its full strength and adhesiveness. Reducing traffic speeds helps. If this is not possible, choke stone may help reduce this damage. The choke not only fills the void between the larger rocks to keep them from turning, but some technologists believe that fines in the choke raise the viscosity of the asphalt.

Table 5. External factors affecting performance of seal coats.

Factor	Comment
1. Traffic--Type and volume	• Fast moving, braking and turning traffic can cause surface raveling leading to premature failure.
2. Weather Conditions	• Very high temperatures may lead to traffic damage.
	• Low temperature affects coating and rate of set.
	• Rainfall affects adhesion and rate of set.
3. Road Alignment	• Steep grades affect surface wear.
	• Horizontal curves, particularly in the shade, can promote early raveling.
4. Drainage	• Poor surface drainage is not corrected by seal coats.
	• Rutting and cross slope must be corrected first.

<u>Cold Weather</u>. Cold weather affects the binding characteristics of the asphalt by making it less tacky and increasing its viscosity. This results in a poorer bond between the pavement, asphalt, and the rock. Further it can reduce the embedment of the rock into the asphalt emulsion. An asphalt emulsion with more cutter like the CMS-2 is more tacky and under certain conditions is a good choice. A slightly heavier shot has also proven helpful. However a heavier shot may result in flushing and bleeding in warmer weather.

<u>Rain</u>. Chip seal construction should be postponed if there is rain or the threat of rain. If a chip seal is caught by an early rainstorm, there are several steps which can be taken to help save the seal, such as: close the roads to traffic (which is usually impractical); reduce the speed of the traffic; or apply additional cover stone.

(3) Road Alignment. Chip seals on steep grades frequently show wear; however, the smaller aggregates and the tighter seals seem to be less affected. Extra care should be practiced during construction operations on grades.

Curves are areas that experience high lateral shear stress. A tighter seal with a choke stone reduces this damage.

Shaded areas frequently require heavier emulsion application rates and/or an asphalt emulsion with more cutter.

(4) Drainage. Chip seals can only correct minor deficiencies in grade and smoothness of asphalt pavement. With the lower viscosity emulsions, they may sag into ruts, or other grade irregularities, producing nonuniform rock retention. Further, irregularities in the surface can hold water to form puddles or ice pockets.

5. Review of Current Guidelines for Design

The objective of the design of asphalt emulsion seal coats is to determine the type and quantities of materials to be placed in order to achieve a durable surface that will give good performance and serve the purpose for which it was intended. Specifically for chip seals, this involves determining the type and application rate of aggregate and the type and application rate of asphalt emulsion to accomplish these objectives. For multiple chip seals, an additional factor includes distributing the total amount of asphalt emulsion to successive layers. Construction guidelines provide procedures to combine these materials in the field in a way to maximize the probability of success.

There is no universally acceptable method for the design of chip seals using single or multiple layers of aggregate. The methods used by agencies to determine the optimum quantities of emulsion and aggregate to use on any particular project vary. Some calculate the appropriate quantities based on laboratory tests to determine material suitability and weight-volume relationships. These calculated rates are then modified in the field to achieve final spread rates. On the other hand, some agencies rely on historical application rates that have been associated with successful jobs in the past using materials similar in character. These agencies then depend upon the field experience of project engineers to adjust the spread rates to account for the variability in field conditions. Table 6 shows an example of equations that can be used to determine application rates. Laboratory testing is required to determine each of the parameters in the equations. Table 7 shows an example of simplified guidelines that were given in a recent publication.(12)

While there is a lack of uniformity in the specific methods of design, it appears that the general concept of design is more uniform across methods. The aggregate application rate for a single chip seal is predominantly felt to be "the amount which is required to form a blanket one stone in depth."(13) The application rate for successive applications in double and triple chip seals is that required to fill the voids between the large aggregate in the initial application. The application of asphalt emulsion is that required to fill the void spaces between the aggregate such that the aggregate is sufficiently embedded so that it will be firmly held in place under traffic. Asphalt quantity cannot be excessive, however, or bleeding of the chip seals will occur. Figure 6 demonstrates the principle of a one-stone blanket and aggregate embedment in asphalt.

Much of the framework for the following general discussion regarding design is taken from an excellent survey of seal coats performed in 1968.(6) This is a comprehensive literature review of the subject and includes an excellent review of design methods existing prior to 1967. Since that time, modifications to these design methods in North America have occurred, which are also discussed here.

Table 6. Example of design equations to calculate aggregate application rates.[9]

Unit of Measurement	Equation
English System (H measured in inches).	
BY WEIGHT	
Pounds per square yard	$C = 46.8(1-0.4V)HGE$ or $C = \frac{0.75(1-0.4V)HWE}{1-V}$
Square yards per short ton (2000 pounds)	$C = \frac{42.74}{(1-0.4V)HGE}$ or $C = \frac{2667(1-V)}{(1-0.4V)HWE}$
Square yards per long ton (2240 pounds)	$C = \frac{47.86}{(1-0.4V)HWE}$ or $C = \frac{2987(1-V)}{(1-0.4V)HWE}$
BY VOLUME	
Cubic feet per square yard (loose weight)	$C = \frac{0.75(1-0.4V)HE}{1-V}$
Square yards per cubic yard (loose weight)	$C = \frac{36(1-V)}{(1-0.4V)HE}$

Notes:

C = Number of pounds of cover aggregate to be applied per square yard.

V = Fraction of voids in the coverstone in its loose weight condition.

H = Average least dimension of cover aggregate in inches.

G = ASTM bulk specific gravity of the cover aggregate.

W = Weight of coverstone in its loose weight condition as measured by ASTM C29.

E = Wastage factor due to percent of coverstone lost due to whip-off by traffic and to unevenness of spread.

Table 6. Example of design equations to calculate aggregate application rates (continued).

Unit of Measurement	Equation
Metric System (H measured in Millimetres)	
BY WEIGHT	
Kilograms per square metre	$C = (1-0.4V)HGE$ or $C = \frac{(1-0.4V)HWE}{1-V}$
BY VOLUME	
Litres per square metre (loose weight)	$C = \frac{(1-0.4V)HE}{1-V}$
Square metres per cubic metre (loose weight)	$C = \frac{1000(1-V)}{(1-0.4V)HE}$

Notes:

C = Number of pounds of cover aggregate to be applied per square yard.

V = Fraction of voids in the coverstone in its loose weight condition.

H = Average least dimension of cover aggregate in inches.

G = ASTM bulk specific gravity of the cover aggregate.

W = Weight of coverstone in its loose weight condition as measured by ASTM C29.

E = Wastage factor due to percent of coverstone lost due to whip-off by traffic and to unevenness of spread.

Table 7. Example of simplified determinations of asphalt and aggregate materials selection and application rates.[12]

Chip Quality

Size: Chips should be uniform in size. For a single layer, 5/8 in chips are recommended. For a double layer, first use 5/8 in chips followed by a second application of 3/8 in chips.

Clean: No sand or rock fragments, such as found in crusher run material, should be present. There will be a slight amount of dust. The key word here is slight. If any dust is blowing up during the dumping or spreading process, it is too dirty. The dust will combine with the asphalt first and prevent the chips from being stuck down as they should. If in doubt, test a sample using a sieve analysis. There should be no more than 2 percent by weight passing the #200 sieve.

Asphalt

Application Rate: The oil should be sprayed at a rate of 0.35 gal/yd^2. This is about 4,500 gal/mi for a 22-ft wide road.

Temperature: If you are using emulsified asphalt, it should be heated to 100 ^oF to 140 ^oF at the point of spraying. If you are using a cut-back asphalt such as MC 3000, the oil should be heated to 225 ^oF to 275 ^oF at the point of spraying.

Chipping

Application Rate: Chips should be spread at a rate of approximately 40 lb/yd^2. This is about 260 tons/mi for a 22-ft wide road. Very small areas of [asphalt] will be visible through the chip cover. Excessive chip coverage is expensive and does not make a better job.

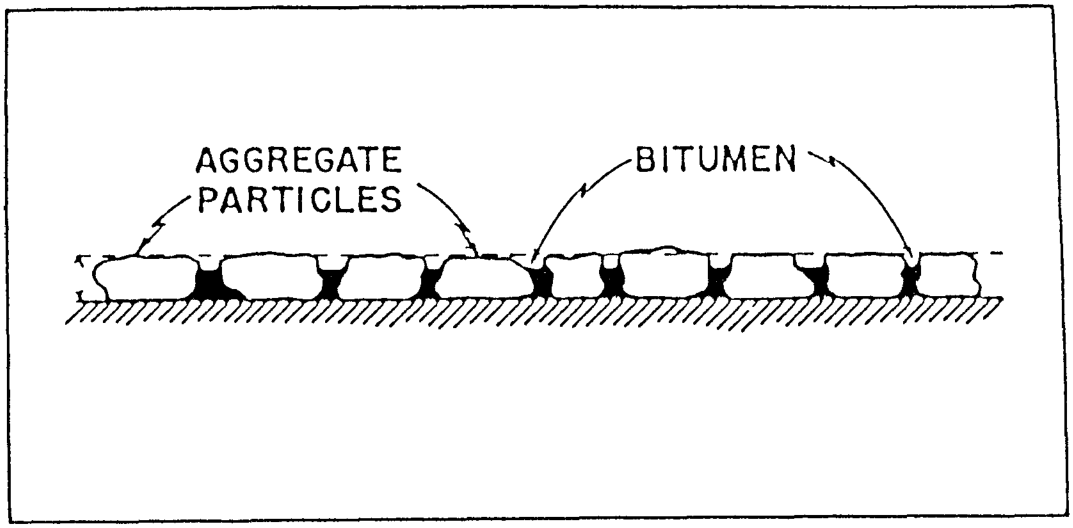


Figure 6. Illustrating the average least dimension of cover aggregate particles, and the ultimate positions of these particles in a surface treatment or seal coat after considerable traffic (the least dimension of each particle is vertical).[9]

The following sections present discussions of the factors related to the selection of amount and type of both aggregate and emulsion primarily for single chip seals. Included is a review of how various design methods treat each of the factors. Following that is a discussion of guidelines commonly found in construction specifications and in manuals in the United States and elsewhere. Specific information relative to design using particular methods is included in appendix D.

a. Determining the Amount of Cover Aggregate

Two major techniques exist for determining the amount of cover aggregate required. One method involves simulating the existing surface in a laboratory test and directly measuring the basic quantity required. The second approach is to calculate the spread rate based on the "average height or thickness of the aggregate layer." These two techniques and related factors are described in more detail below.

(1) Direct Method. Direct methods for determining the basic aggregate spread rate involve actually covering a board of known area with a sufficient quantity of aggregate which is placed with its least dimension upward so that complete coverage of the board, one stone in height, is achieved. Two methods described by Kearby and Mackintosh use a board test to directly determine the aggregate spread rate.[13,14,15] Design methods used by Texas and NITRR in South Africa also use this technique.[4,16] The Texas method is closely related to the Kearby method and the board test is identical. The NITRR procedure in South Africa uses a "modified tray table" to determine other parameters of the stone that is spread. The spread rate is a related parameter which is also determined.

(2) Indirect or Calculated Methods. The pioneering work done by Hanson in 1935 was the first attempt at determining the factors influencing the design of chip seals.[17] Hanson was the first to establish some fundamental principles of the relationship between aggregate and bituminous binder. Hanson developed procedures to calculate the spread rate based on his observations that the voids in aggregates prior to compaction will be 50 percent and the voids after compaction by both construction and traffic will ultimately be reduced to 20 percent. By identifying a thickness of the compacted aggregate, termed the "average least dimension" (ALD), the spread rate can be calculated. Others have followed similar procedures in calculating the amount of aggregate that will be required. McLeod extended Hanson's original work and developed a general equation suitable for both one-size and graded aggregates. Other agencies have incorporated some of McLeod's concepts and procedures including the Asphalt Institute and the Asphalt Emulsion Manufacturers' Association.[9,11,18] Alaska has recommended that the McLeod procedure be followed in the design of seal coats.[19]

Other researchers who have included calculated spread rates into their design methods include Hveem, Lovering, and Sherman.[20,21]

(3) Thickness of the Aggregate Layer. Probably the most diversity in the different design methods involves the determination of the "thickness of the aggregate layer." Different names have been applied to this physical characteristic and include:

- Average stone size.[22]
- Effective maximum size.[20]
- Average least dimension. (See references 9, 11, 17, 18.)
- Average mat thickness.[4,13,14]
- Mean particle dimension.[23]
- Spread modulus.[21]
- Median size.[24]
- Effective layer thickness.[16]

In his original work, Hanson actually measured the smallest dimension of at least 100 particles and averaged the results. New Zealand has automated this procedure somewhat but still measures each individual particle. Most design methods use characteristics of the aggregate gradation to arrive at the average thickness. For example, McLeod starts with the median size (size corresponding to 50 percent passing) and then modifies it using the flakiness index to arrive at the average least dimension. The spread modulus is a weighted average of the sizes passing certain screens. Pennsylvania uses the median size of the aggregate but it is plotted on a gradation chart where the sieve size is raised to the 0.45 power.[24]

(4) Factors Which Influence the Average Thickness of Aggregate. The main factors which influence the "average thickness of the aggregate" are primarily the aggregate gradation, particle shape and the hardness of the underlying pavement surface. Few design methods take particle shape into account. McLeod uses the flakiness index to determine average least dimension. Pennsylvania specifies that the number of thin, elongated pieces (max:min dimensions less than 5:1) be not more than 15 percent and has found good correlation between this value and acceptable flakiness

index values. New Zealand requires that the Average Greatest Dimension divided by the Average Least Dimension be a maximum of 2.25. In addition, the percentage of least dimensions within ±2.5 mm of the Average Least Dimension must be between 65 and 75.

(5) <u>Modifications of Design Spread Rate to Achieve Field Spread Rate</u>. All design methods recommend that a certain percentage of aggregate, in addition to that calculated, be applied to account for waste and whip-off due to traffic. The key factors which require this additional amount include handling, inaccurate spreading, or traffic. The percentages of additional aggregate required vary depending on the type of design method. Something between 4 and 10 percent is common. Many design methods allow this percentage to be selected by the designer.[11,18,24] Other design methods specify a recommended percentage based on the size of the aggregate or the expected traffic. One investigator cautioned very strongly against the use of excess aggregate for two reasons.[15] The first reason is that the loose aggregate can be a safety hazard when the rock is "whipped off" the surface. The second reason is that the excess aggregate can have a tendency to dislodge other aggregate. While the aim should be to carefully design so that excess chips are not used, he realistically concludes that approximately 4 percent should be sufficient to account for waste and imperfect workmanship.

b. Determining the Type of Aggregate

The determination of the type of aggregate is usually set forth by specification. For single chip seals the objective is to get durable, angular aggregate that is clean and nearly one size. For multiple chip seals, the size of the aggregate in successive layers should be such that the voids are filled. This discussion focuses on the factors important in selection of the quality, gradation and size of the aggregate.

(1) <u>Quality</u>. Most agencies are in agreement that the aggregate for chip sealing needs to be clean, strip-resistant, durable, abrasion-

resistant, and economical. However, the actual items specified and the numerical values assigned do vary among specifying agencies.

(2) Gradation and Size. The maximum size of aggregate in a single chip seal is chosen large enough to provide a surface texture which has adequate skid resistance yet not so large that the detrimental effects of an overly rough surface texture result.

The selection of the maximum-size aggregate is normally based on economic and traffic considerations. Large maximum-size cover stones require larger amounts of asphalt than small maximum-size cover stones. Normally a more effective seal can be provided with thicker films of asphalt. Field variations in applied asphalt quantities, which are of the order of 0.06 gal/yd^2, are much more critical for aggregates of small maximum size. It is common practice for States to select larger maximum-size aggregates for high traffic volume facilities. The large-size stone provides improved pavement surface drainage and thus reduces the potential for hydroplaning. However, tire pavement noise is usually higher with larger maximum size aggregate.

Certain designers have maintained that the aggregate should be as close to one size as possible. For example, typical New Zealand specifications for chips with average least dimensions between 5.5 mm and 12 mm require that a minimum of 65 to 75 percent of the aggregate have dimensions within $\pm$2.5 mm of the average least dimension. Australian specifications also typically have rather rigid specifications with respect to gradation.

In this country it has been felt that the production of this closely sized aggregate is too restrictive and both ASTM and AASHTO specifications allow a wider band in allowable sizes. Herrin, Marek and Majidzadeh state:[(6)]

Since surface treatments with the more restrictive one-size aggregates have had excellent service records, the designer has to decide whether to use a more expensive, closely controlled, one-size aggregate that will have good performance or to specify a cheaper, more open-graded aggregate that will probably have poorer performance. Many times this is a difficult decision to make. The decision should not depend on type of aggregate that has been customarily used in the past; it should be based on the conditions existing in the locality at the time the surface treatment is to be built.

c. Determining the Quantity of Bituminous Binder

It has been written that selection of the correct application rate for the binder is the single most important factor in successful chip sealing.(25) The fundamental principle in nearly all design methods is the required amount of asphalt needed to fill the voids between the aggregate to an optimum depth. This design principle was first stated 50 years ago by Hanson and "is so simple and logical that most of the later design methods also utilize this idea."(6) If too much asphalt is applied, bleeding results; not enough, and aggregate loss results.

The asphalt that is sprayed on the existing surface can go in three places: it can fill the voids between the aggregate particles and the texture of the existing surface; it can be absorbed by the aggregate; or it can be absorbed into the existing asphalt surface if the surface is aged and/or porous.

Designers have approached the problem of determining the volume of voids in the aggregate layer in a variety of ways. For example, Hanson and subsequently McLeod, assumed that the ultimate percentage of voids in the chip seal coat will be 20 percent, regardless of the maximum aggregate size. This is based on observations made by Hanson. Hanson also maintained that the initial void content after spreading was 50 percent. McLeod extended the work of Hanson and submits that the ratio of final void content for any aggregate to 20 percent is the same as the ratio of loose void content to 50 percent. Other design methods use the loose unit weight and the average thickness in the calculation of voids. The design method used by the NITRR in South Africa is one of the only ones that seeks a direct measurement of the void content with the aggregate in a similar position as it will be during construction.[16] The procedure used to determine void content is the modified tray test. The test equipment consists of a circular tray with an area of 0.05 m^2 and a wall height of 50 mm. A shoulder piece fits snugly on top of the tray and has the same internal diameter as the tray, and is fitted to a loose fitting cloth membrane. The purpose of the membrane is to keep the density sand from flowing into the voids between the aggregate.

Once the volume of voids is determined in these methods, the amount of asphalt required to fill the voids to some optimum depth of embedment is calculated.[9,13,17] Other engineers have used a formula based only on the average size of the aggregate. These methods assume constant percentage of voids and a constant percentage of voids to be filled. For example Hveem, Lovering and Sherman (1949) and Lovering (1954) determine the asphalt in this way.[20,21]

This optimum depth is generally considered to be a fixed percentage of the total average thickness of the aggregate. Hanson and McLeod both assume that 50 to 70 percent of the void space should be filled with binder. Most design methods have assumed that this embedment is a fixed percentage regardless of the size of the aggregate. However, Kearby, in his initial work, developed a relationship between the "Average Mat Thickness" and the "Aggregate Embedment Percentage."[14] This relationship was later modified by Benson requiring higher embedment percentages at lower mat thicknesses. It was further modified by Epps for synthetic aggregates and later extended to include other types of aggregate.[26] Figure 7 demonstrates these modifications of this curve over the past 35 years.

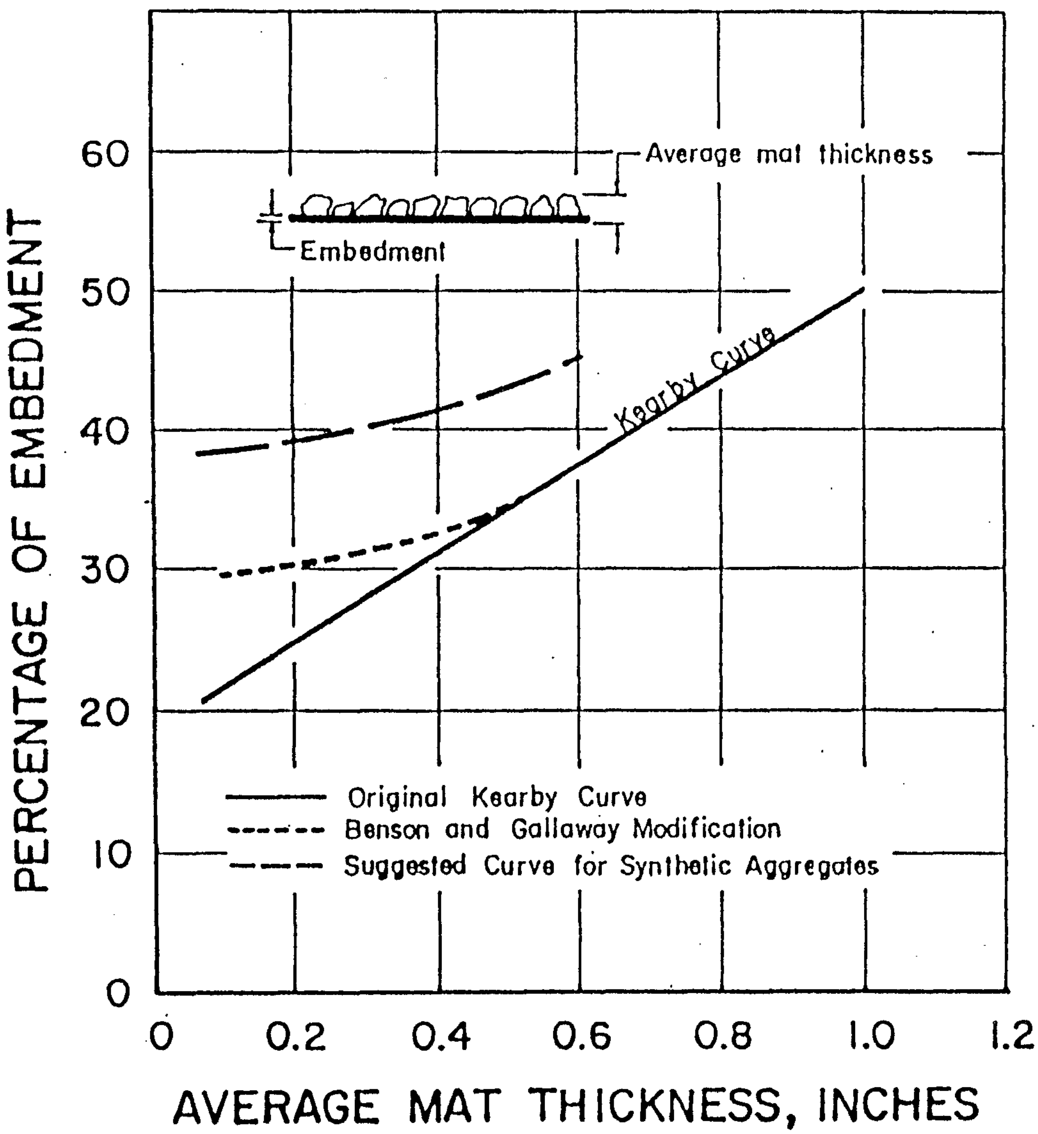


Figure 7. Modifications to Kearby's original curve.[4]

(1) Influence of Aggregate Shape. It would appear that aggregate shape should play a role in the determination of asphalt required for a successful chip seal. Aggregate shape plays a role in the volume of voids and since the volume of voids has a direct bearing on the amount of asphalt necessary, it should be a factor. Some design methods use the shape as a modifier of the thickness of the aggregate layer.(9) New Zealand limits the ratio of average greatest dimension to average least dimension so that nearly cubical particles are obtained. Rounded aggregates would tend to increase void contents; however, most agencies limit this effect by requiring rather high percentages of crushed faces.

(2) Influence of Aggregate Porosity. Few design methods ever account for the porosity of the aggregate. McLeod has suggested that slight increases be accommodated when a known absorptive aggregate is used. The early California Method included a correction based on a surface factor (K_c) and was one of the few to actually attempt to directly account for aggregate absorption. Many agencies try to limit the effect by specification, only allowing aggregates which meet certain limiting values of absorption.

(3) Influence of Traffic. Many design methods have adjustments that are required to take into account the level of traffic. All that include this factor reduce the amount of asphalt required when traffic levels increase. Texas assumes the theoretical rate is acceptable for traffic in excess of 1000 vehicles per day (vpd) per lane.(4) The field rate is increased by 5 to 20 percent in four steps as traffic is decreased from 1000 to under 100 vpd. McLeod adjusts the percentage of void space to be filled based on traffic. The theoretical value of 70 percent of the void space is considered acceptable for 500-1000 ADT. When traffic is less, the void space filled is increased to 80 percent. When the traffic is increased, the void space filled is reduced to 60 percent. Pennsylvania, the Asphalt Institute and the AEMA, all follow McLeod's recommendations.(24) A Canadian procedure uses a factor ranging from 1.02 to 0.72 to change the spread rate to account for traffic from less than

100 vpd to over 2000 vpd. In New Zealand, traffic factors range from 1.596 for less than 5 vpd/lane to 0.877 for 5000 vpd per lane in 20 steps.

(4) Influence of Existing Surface. The total amount of binder necessary is influenced in two ways by the existing surface. If the surface has small voids or cracks, then some asphalt will fill those small cracks and smooth the texture. In every case, the presence of these deficiencies in the pavement surface will require more asphalt than if it is in "perfect" condition. The condition of the pavement surface can lead to adjustments of the application rate, either requiring more or less asphalt than in the "perfect" condition. All design methods have factors to account for the condition of the existing surface. Most current methods, however, simply apply factors based on a visual assessment and application of adjustment factors. For example, the Texas procedure adjusts asphalt spread rates from -0.06 gal/yd^2 to +0.06 gal/yd^2, based on the existing surface condition.(4) McLeod adjusts from -0.06 to +0.09 gal/yd^2 for the condition of the existing surface. A Canadian procedure adjusts from -0.03 to +0.06 gal/yd^2. Since residual asphalt spread rates are typically on the order of .25 to .35 gallons/yd^2, these adjustments (up to 0.09 gal/yd^2) can amount to 25 to 35 percent of the total amount to be applied. In conversations, engineers have argued that because of this variation, the design methods are only approximations which should realistically be modified in the field. And since this modification is required anyway, perhaps the initial application rate could just as well be approximated by historical experience and then modified in the field to meet changing field conditions.

Some agencies, most notably New Zealand and South Africa, have devised methods in hopes of more rationally predicting the demand of the existing asphalt surface. For example, New Zealand uses the sand patch test to estimate the amount of voids in the existing surface that will be filled with asphalt. South Africa uses a ball penetration test to determine the hardness of the existing surface. This hardness is important both from the standpoint of oxidation of the asphalt (thus, increasing its demand) and the potential embedment of the aggregate into the underlying layer (thus, decreasing the necessary asphalt).

One item that is immediately evident is that the demand of the existing surface is not uniform across the width of the underlying material. This characteristic has been addressed in only one place that we are aware of. District 23 in Texas is presently the only agency that carefully controls the transverse variation of asphalt. To ensure correct application, the district furnishes the contractor with a set of nozzles that have been modified to give precisely controlled fan widths and quantities of sprayed asphalt. Nozzles with larger openings are installed in the spray bar over areas outside and between the wheel paths. Smaller aperture nozzles directly over the wheel paths dispense a smaller amount of asphalt. The district has been using this technique for more than 10 years, and is pleased with the results. Although it takes more time and careful control must be exercised, substantial evidence is accumulating which indicates that these controls will prolong the life of the seal coat.

(5) Influence of the Percentage of Residual Asphalt. All design methods give the residual amount of asphalt required. Asphalt emulsions are typically 30 to 35 percent water which is present when the emulsion is applied but eventually lost during breaking and setting. Engineers do not agree on the adjustment to the application rate necessary because of the volume change due to the loss of the water.

McLeod is at one end of the spectrum. He argues that the total residual asphalt amount is required. Therefore, the calculated residual asphalt, taking into account all the other factors previously discussed, should be increased by dividing it by .65 to .70, depending on the particular emulsion. The resulting quantity is the required asphalt emulsion application rate. Others argue that because of certain characteristics of the emulsion, the application rate can almost be identical to that for asphalt cement and no correction for the water in the asphalt emulsion needs to be made. An interesting "Discussion" of this point is found in McLeod's 1969 AAPT paper.(9)

Many engineers prefer a "middle ground" on this issue. For example, Pennsylvania uses a factor of .75 to adjust for the residual amount. Texas uses an approach where this adjustment is related to the season of construction.

(6) <u>Influence of Temperature and Volume Change of Material</u>. All design methods assume application rates (volumes) at 60 ^{o}F. Spray temperatures of the emulsion will be higher and therefore a correction is required so that the volume sprayed at an elevated temperature will translate to the required volume at 60 ^{o}F. Standard tables showing temperature-volume corrections for emulsified asphalts are typically used for this process.

d. Design of Multiple Chip Seals

Multiple chip seal design typically consists of charts and tables. McLeod reported that based on a review of published literature including work by ASTM, AASHTO, Bureau of Public Roads, Federal Aviation Agency, County Roads Board, National Association of Australian State Road Authorities, Tagle and Benson, and the Asphalt Institute, all have methods which recommend application quantities for each layer.(9) Some are semi-empirical while others are theoretical.

McLeod's investigation of these methods indicated a lack of agreement in predicted quantities. He presents a general design method in which consideration is given to each of the following important factors:

- Gradation of cover aggregate in each layer.
- Reorientation of the cover aggregate under traffic, and therefore recognition of the need for determining each cover aggregate's Average Least Dimension.

- Traffic volume to be carried.
- Fraction of residual asphalt in the asphalt binder.
- Asphalt binder correction for the textural characteristics of the surface to which the seal applied.
- Correction for the loss, if any, of a portion of the asphalt binder into the cover aggregate.

The design method presented by McLeod and adopted by the Asphalt Institute is discussed in appendix D.(11)

Key assumptions of this method include the following:

- The size of each successive layer should be approximately one-half the size of the preceding layer.
- The total quantities of binder and cover aggregate are obtained by assuming that each layer is to be designed as though it were an independent single application and summing to determine the total.
- No additional aggregate is placed to account for wastage in any of the aggregate layers.
- The grade of asphalt to be used for the multiple chip seal should be approximately one grade softer than that required for a single chip seal.
- The correction of binder application rate for the existing surface should only be made for the first layer of a multiple chip seal. The binder application rate for subsequent layers should not include this correction factor.
- The distribution of the total asphalt binder to the layers of a multiple treatment are related to the temperature at the time of construction and more importantly the time of the season.

The NITRR in South Africa has also presented a design method applicable to double chip seals.(27) They have found good relationships between the total equivalent layer thickness and the sum of the equivalent layer thicknesses of each layer determined individually. In addition, they have determined a relationship between the void content of the composite and the void content of the individual layers. The design procedure then consists of designing a double chip seal in the same manner as a single chip seal but using the equivalent layer thickness and void content of the composite.

e. General Guidelines Found in the Literature

It is useful to review some general guidelines that are found in the literature. This section summarizes selected guidelines developed and used by various agencies throughout the world. These and others have been carefully reviewed as a part of this study.

(1) AEMA. In 1981, the Asphalt Emulsion Manufacturers Association developed a series of Performance Guidelines for use with asphalt emulsions. Included in this publication are guidelines for:

- Asphalt emulsions.
- Emulsion mixes.
- Chip seals, slurry seals and fog seals.
- Maintenance mixes and recycling.
- Construction equipment.

The guidelines for chip and slurry seals carefully layout procedures for:

- Selection of materials.
- Proportioning of ingredients.
- Construction equipment and procedures.
- Preparation of existing surfaces.
- Traffic control.

This manual should provide an excellent starting point for the development of improved guidelines.[18]

(2) Alaska Department of Transportation and Public Facilities. Connor conducted a detailed investigation of bituminous surface

treatments, the purpose of which was to identify probable causes of early failures and to offer recommendations to improve their performance.[3] The results of this 2-year study indicated that most of the failures were attributed to:

- Improper construction techniques such as low asphalt content or dirty aggregate.
- Construction during poor climate conditions.
- Poor base or surface preparation.

Other factors which were found to contribute to poor performance included late season construction and the use of unsound aggregate. No significant differences in performance could be found between cutback and emulsified asphalts. Recommendations to improve performance included:

- Changes in gradation, particularly the No. 200 sieve.
- Limiting the construction season.
- Use of McLeod's procedure to determine aggregate and asphalt spread rates.
- Training of field personnel.

In a follow-up study completed in 1984, Connor reported on a field study which implemented the findings of the 1981 study.[3,19] The results indicated:

- The percentage of material passing the number 200 sieve should be less than 0.5 percent.
- A 50 ^{o}F minimum pavement temperature should be maintained.
- McLeod's procedure provides a good estimate of spread rates.
- Proper training of field personnel improves chances for success.

(3) Canada. Chip seals are also used extensively in Canada. For example, in Saskatchewan, policy requires their use on all paved surfaces to delay the need for structural rehabilitation.[28] Specific guidelines have been established for:

- Selection of materials.
- Spread rates.
- Construction procedures.

Much of the chip seal work done in Canada, however, has been with high float emulsified asphalts. Reportedly, high-float emulsions permit the use of dirty and moist aggregates and have resulted in acceptable chip seals with minimum design and construction controls.

(4) New Zealand. Excellent sources of information for chip seals are reports prepared by the New Zealand Ministry of Works. Two of these include:

- Sealing Manual.[29]
- Sealing Site Supervisors Course.[30]

The first report describes, in detail, procedures for selecting materials and desired proportions and for constructing chip seals using asphalt cements, cutbacks and emulsions. The second report are the notes for a training course for line supervisors. It includes:

- Pre-site work checks.
- On-site supervision.
- Needed records.

This second report is an excellent source of information for quality control and inspection, and it is written specifically for field supervisors.

(5) Pacific Northwest (California, Idaho, Oregon, Washington). Chip seals are widely used in this region of the U.S.[2] At present, CRS-2 emulsions are most widely used. However, problems such as rock loss, streaking and bleeding have been reported if:

- Proper spread rates are not employed.
- Adequate traffic control is not provided.
- Maintenance calibration of equipment is not periodically performed and strictly enforced.
- Construction procedures are not changed when the aggregate gradation or type of emulsion are changed.

The sealing program in Oregon during the past 40 years is summarized below.

- 1940-1960: In the early years, Oregon had an active sealing and oiling program which was greatly reduced in the late 1960's because of complaints of general damage.
- 1970-1980: During this period, Regions 4 and 5 increased the amount of sealing primarily using hot asphalt.
- 1982: Through some early pavement management studies, it became evident that timely and high quality chip seals played a major role in extending pavement life. This fact was particularly significant because of the premature raveling of many of Oregon highways. Chip sealing was proposed at that time to become a major part of Oregon's preservation program.
- During 1982-83: Through a Tri-state program between Oregon, California, and Idaho, information was exchanged on methods and procedures to obtain a good chip seal.
- 1983 to 1985: Oregon, California and Idaho were moving their sealing program from low volume to high volume highways including the Interstate. At the same time, the rubber, latex and polymer emulsions were being introduced in all three States.
- 1984 and 1985: Oregon likely placed more polymer seal than any of the western States except New Mexico. During this 2-year period, approximately 1,000 miles on the State system were sealed.
- 1984: A technical Committee was set up to develop new specifications for chip seals using emulsions. This Committee worked closely with California, which was developing a similar program, as well as Idaho. This specification was completed and used for the first time during the 1984 construction season.

- Spring, 1985: During this period, an effort was made to evaluate three formulas for calculating chip seal emulsion rates, and chip seal aggregate rates. These formulas and procedures came from Idaho, the Association of Asphalt Paving Technologists (AAPT) and FHWA material.

- 1986: At the present time, revision of Oregon's chip seal specifications and procedures is underway.

  From the above efforts, excellent records are available from many chip sealing projects including several done by contract. Since these projects were completed during the 1984/85 seasons, it is now possible to determine whether they were successful. By and large, the vast majority of them have been successful; however, there are a few failures. A comparison of the technical data and actual seal condition should provide input for such a study. The State Highway Division strongly encourages that the research be done in this area.

(6) <u>Texas State Department of Highways and Public Transportation</u>. Chip seals have been successfully used on Texas highways for many years. In the 1970's Texas conducted an extensive study to evaluate the performance of chip seals and the factors affecting their performance (see table 2).[4] The study culminated in a manual to provide guidelines for the design and construction of chip seals. The manual was developed specifically for field engineers, laboratory personnel and field inspectors responsible for the design and construction of seal coats. Specific items covered include:

- Selection of materials for different applications and climatic conditions.
- Determination of spread quantities for asphalt and aggregate.
- Preparation of existing surfaces.
- Calibration of equipment.
- Construction procedures.
- Guidelines for inspection and sampling.

Also included in the report is an evaluation form used to inspect field projects.

(7) United Kingdom. The use of emulsified asphalts for road maintenance and construction has increased dramatically in the past 10 years in the UK (and in the rest of Europe).[1] Both the Transport-Road Research Laboratory (TRRL) and the Road Emulsion Association Limited (REAL) have developed guidelines for the use of asphalt emulsions in surface dressings, slurry seals, and fog seals.[31,32]

The guidelines include information on:

- Selection of type and amount of materials.
- Construction procedures.
- Equipment maintenance and calibration.

In addition, the work by Heslop describes the use of modified emulsions for chip seals.[33] The use of emulsions in the UK and the rest of Europe is also summarized in a paper by Hicks.[1]

6. Review of Current Guidelines for Construction

Most engineers knowledgeable in the design and construction of asphalt emulsion chip seals agree that the construction phase is one of the most crucial aspects of attaining successful performance. Most of the manuals that have been written by agencies to promote successful chip sealing direct the information to the field inspector for jobs that are performed under contract. These manuals emphasize the importance of quality workmanship, well-functioning and calibrated equipment, knowledgeable field personnel and a basic understanding of the parameters that influence success or failure of a single or multiple chip seal.

The key steps involved in the construction process include:

- Scheduling the work relative to weather conditions.
- Preparing the existing surface.
- Spraying the emulsion.

Table 8. Weather guidelines for construction seal coats.

Agency	Weather Guidelines	
	Atmospheric Temperature	Pavement Temp.
Alaska	Greater than 60 °F	Greater than 60 °F
California	Greater than 60 °F	Greater than 80 °F
Indiana	Greater than 60 °F	Greater than 60 °F
Oregon	Greater than 65 °F in the shade	
Pennsylvania	Greater than 60 °F	Greater than 60 °F
Texas	Greater than 50 °F and rising	Greater than 60 °F
Asphalt Institute	Greater than 50 °F and rising	
Chevron	Greater than 50 °F and rising	
AEMA	Greater than 50 °F and rising	
Ontario, CAN	Greater than 50 °F and rising	
Alberta, CAN	Greater than 50 °F and rising	

- Spreading the aggregate.
- Rolling the aggregate.
- Brooming the surface.
- Controlling the traffic.
- Adjusting for field conditions.

It is difficult to separate any of these factors as being more important than the others as each, if done improperly, can contribute to a failure. If any can be separated out, it is spraying the emulsion at the appropriate rate. As has been evident from a discussion of the design methods, there exists no uniform method for determining just what that application rate should be; however, it has been clear from a review of the literature, and discussions with knowledgeable individuals that this is crucial to successful performance.

Each of the steps involved in constructing asphalt emulsion chip seals will be discussed in detail in the following paragraphs with a review of guidelines practiced by various agencies.

a. Scheduling the Work Relative to Weather

Weather is an extremely important factor in the construction of chip seals using asphalt emulsions. In particular, rain during or soon after a chip seal project will almost certainly ruin it. Cool weather has a tendency to cause the emulsion to not break for a significant period of time; therefore, careful traffic control is necessary. Very warm weather will cause the emulsion to break quite rapidly, making close coordination of the construction equipment and sufficient rolling equipment imperative. Table 8 shows general weather guidelines given by a number of sources. In addition to these temperature guidelines, most agencies mention that work is not to be performed if rain is anticipated. Some agencies, such as Pennsylvania, indicate how long to delay placing the chip seal if rain is anticipated (usually 24 to 48 hours). Other agencies limit the construction, usually from May or June through September. One district in

Oregon limits the construction season from July 1 through September 15. Another agency allows construction during borderline weather conditions if the aggregate is heated sufficiently.

b. Preparing the Existing Surface

Generally, the objective for preparing the surface is to establish as uniform a surface as possible. Typically, all rich patches should be removed and all holes, depressions, and other defective areas should be repaired. The surface should be clean and dry. New patches need to be cured prior to chip sealing by spraying with a diluted asphalt emulsion, after which they should be covered with sand and opened to traffic.

c. Applying the Emulsion

The application of the asphalt emulsion is extremely important. Specifications usually require certification of the equipment, ranges of application rates and other language which limits the amount of area that can be sprayed at any one time. Specifications typically identify the range of application temperatures suitable for spraying. The important property which needs to be determined is the viscosity for spraying in order to get uniform distribution of binder. Texas specifies a recommended viscosity of 100 to 125 centistokes and requires the contractor to provide a temperature viscosity relationship for the material which is going to be sprayed. The contractor is then required to keep the temperature of the material within $\pm 15\ ^{o}F$ of the temperature at which the desired viscosity is achieved. Texas is probably the only agency that approaches the specification of spray temperature in this fashion.

Many of the guidelines stress that careful monitoring of the equipment and the construction procedures for spraying the emulsion are essential for a good project.

d. Spreading the Aggregate

Factors affecting the selection of aggregate type, gradation, and maximum size have been discussed earlier in the report. Generally the aggregates used for single and multiple chip seals in the U.S. and Canada have a wider grading than those found in New Zealand, Australia and South Africa.

The aggregate needs to be spread almost immediately behind the emulsion distributor. Generally, specifications have language such as "immediately following the application of the emulsified asphalt." The important point is that the aggregate needs to be spread on the emulsified asphalt before the emulsion breaks. Normally, aggregate should be spread with a self-propelled continuous feed aggregate spreader for best results.

e. Rolling the Aggregate

The purpose of rolling is to reorient the aggregate particles into a denser state while the asphalt emulsion is still fluid. This action causes the aggregate to be well embedded into the binder and will help to keep it in place under the action of traffic. Guidelines for rolling from a variety of agencies and other sources suggest that pneumatic-tired rollers are preferred to steel-wheeled rollers. Some agencies require a minimum number of rollers for a particular job. Generally enough rollers are required so that two to three complete coverages of the aggregate are made before the emulsion "sets."

It is interesting that recent research has been done in New Zealand to investigate the optimum number of roller passes needed.(34) The conclusions were:

- Significant improvements in texture reduction were obtained between one and three passes of the rollers.

- Slight reduction in texture occurred between three and six roller passes.
- Variation in roller weights or speeds produced little discernible differences in rolling effectiveness as measured by the techniques used.
- Little chip reorientation occurred after the third pass of the roller.
- Normal trafficking had a very pronounced effect on chip reorientation.

This would tend to suggest that three complete roller coverages (as generally practiced in North America) would be sufficient, and careful control of traffic would be helpful in achieving chip reorientation.

One final note is that the New Zealand specifications relate the rolling time to the volume of binder spread. Their experience is that the number of roller passes are virtually impossible for one person to measure if three rollers are on site. Three is a very common number of rollers which would result in following North American specifications: one 11 ton roller hour is required per 2000 liters of binder. This is translated to one 10 tonne roller hour per 1435 yd^2 when the application rate is approximately .37 gal/yd^2. In addition, the requirements are such that the initial rolling needs to be completed within thirty minutes on each section prior to continuing on to the next section. The New Zealand guidelines point out that far less rolling is required for emulsions but still must be monitored carefully.

f. Brooming the Surface

Brooming is used to remove excess aggregate from the surface to minimize the damage to vehicles. Typically, a light brooming is applied early the morning of the day following the initial application of asphalt and aggregate. California uses latex modified emulsions in order to allow brooming prior to the end of each day's work. Generally the guidelines are to broom as soon as possible but at a time when the binder is hard enough so that the aggregate will not be dislodged by the brooming operation.

g. Traffic Control

Positive and effective traffic control is a key part to a successful project. Provision is made in all specifications for control of traffic. Factors important to the degree of traffic control required include:

- Type of traffic.
- Volume of traffic.
- Characteristics of roadway.
- Weather (temperature and humidity).

(1) Type of Traffic. The type of traffic is very important. Slow moving passenger vehicles are actually beneficial for a fresh chip seal and controlled traffic should be allowed on it as soon as practicable. The passenger vehicles are effective in reorienting particles. Heavy trucks with multiple axles are a natural enemy of a fresh chip seal and care should be taken in allowing these vehicles to cross over it. This highlights the need for careful control of the construction vehicles since fully loaded aggregate trucks need to use the fresh chip sealed roadway even prior to rolling.

(2) Volume of Traffic. High-volume traffic needs to be carefully controlled. Many agencies require the use of pilot cars to control traffic during the day. Some agencies require pilot car control of traffic around the clock until the binder has had an opportunity to become sufficiently "set."

(3) Characteristics of Roadway. If the section is such that stop-and-go traffic is likely on a fresh chip seal, it is important that careful control of traffic be exercised. Any traffic movements which place additional stress on the completed chip seal (starting or stopping or short radius turns) need to be carefully controlled.

(4) Weather. Weather influences the breaking characteristics of the asphalt emulsion and therefore controls the degree to which traffic needs to be controlled. A special situation arises when there is a possibility of rain. It is imperative that traffic be kept completely off a fresh chip seal constructed with asphalt emulsions and subjected to rainfall. It is likely that failure will occur anyway but by allowing traffic on it, most of the aggregate will surely be lost.

McLeod has provided several excellent guidelines for opening newly constructed chip seals to traffic based on weather considerations.[9] During hot sunny weather, the most critical time to open a new chip seal is between mid-day and later afternoon. The best time to open a new chip seal to traffic is just after dark. Afternoon temperatures can be hot, leading to high pavement surface temperatures, low binder viscosity and subsequent aggregate rollover when opening to traffic. On the other hand, temperatures have usually retracted by nightfall, increasing binder viscosity and enabling the newly constructed seal to withstand traffic forces.

7. Tests to Evaluate Materials and Field Performance

a. Aggregate Tests

The mineral aggregate in a chip seal is expected to:

- Transmit the vehicle load to the underlying surface.
- Provide a skid resistant surface.
- Resist abrasion from moving wheel loads.
- Resist the deteriorating effects of weather exposure.

In addition, cover aggregates sometimes are used to improve light reflection from the roadway and/or to provide a demarcation of shoulders or other limited traffic areas.

Laboratory tests have been developed to measure aggregate properties that relate to these desired performance properties. In addition, test methods are conducted to provide information required for chip seal design and construction. These tests are associated with weight-volume calculations (specific gravity, loose unit weight, etc.).

Table 9 summarizes aggregate specification requirements from four specifying agencies: ASTM, California, Nevada, and Texas. (See references 35, 36, 37, 38.)

(1) Strength and Abrasion Resistance. The most popular strength and abrasion resistance test in the United States is the Los Angeles Abrasion Test. Tests for the presence of clay lumps and friable particles are also used by some agencies to identify (largely by visual examination) aggregate that may "break down" during construction or under the action of traffic.

(2) Durability. Durability tests, or those tests which measure the resistance to the action of weather and time (freeze-thaw cycles, wet-dry cycles), vary considerably by specifying agency. The sodium and magnesium sulfate soundness test is the most popular durability test used in the United States. Film stripping tests, cleanness and the presence of deleterious materials are utilized by some public agencies to identify potential adhesion problems between the asphalt and aggregates. An aggregate freeze-thaw test is specified by Texas for lightweight aggregates only.

(3) Skid Resistance. Tests to define skid resistant properties of aggregates are used by some States. Requirements on crushed faces or crushed particles is an attempt to measure this quality. A polish value test is utilized by Texas to ensure that the aggregate has the desired resistance to the polishing action of traffic. Some States approve aggregates by source. Field skid tests are used to identify those aggregates which will provide the desired friction under traffic.

Table 9. Typical aggegate requirement.

Specifying Agency	Strength and Resistance to Abrasion	Durability	Skid Resistance	Other
ASTM[35] D1139	LA abrasion (C131) Clay lumps and friable particles (C142) Lt. wt. pieces (C123)	Sulfate soundness (C88)		Unit wt. & voids (C29) Sieve analysis (C136) Specific gravity (C127, C128)
California[36] Section 37	LA abrasion (211)	Film stripping (302) Cleanness value (227)	Crushed particles (205)	Free from dirt or other deleterious substances Gradation
Nevada[37] Section 408	LA abrasion (T233) Degradation (T232)	Stripping (T209)	Fractured faces (T230)	Gradation (T206)
Texas[38] Item 302, 303, 304	LA abrasion (410-A) Pressure slaking (431-A)	Deleterious materials (211-F) Freeze thaw (432-A)	Crushed faces (143-A)	Gradation (200-F) Flakiness index (224-F) o Unit wt (404-A)

(4) Size. Sieve analysis tests provide information which defines the maximum size of the aggregate and the size distribution of the aggregate. Single-size aggregates are considered to be the most desirable, but availability and cost often result in specifications that allow multiple-size aggregates.

A number of other tests are required to design seal coats: unit weight of loose aggregate, specific gravity, and flakiness index. These tests are called for in the three commonly used design methods in the United States: Australia, California, and Texas.[11,4] The flakiness test is used to define shape characteristics of the aggregate. The desired aggregate is angular, rough surface textured and blocky.

(5) Laboratory-Field Correlation. Correlations between field performance and laboratory tests and the associated specification limits are not well defined in the literature. Most of the laboratory tests were developed over 50 years ago and were only generally correlated to field performance (i.e., based on general observation), if documented performance was even available, to justify the established criteria. Stripping, cleanness, freeze-thaw and polish value are tests that were developed in the last 20 to 30 years. Extensive field correlation data is not readily available in the literature.

b. Chip Retention Tests

Chip retention during construction, after the first few hours and days of construction, and at the onset of cool or cold weather is a major performance problem associated with chip seals. At present, aggregate loss is controlled by selection of asphalt, aggregates and their application quantities during the design process and use of acceptable construction techniques. These techniques are not sufficient to control aggregate loss on many projects.

A literature review indicates that a number of stone retention tests have been used for research purposes.[39] Test methods developed by the road and paving industry specifically for testing and evaluating stone retention include:

- Multiple aggregate pull-out (figures 8, 9, 10).
- Variations of the Vialit (figure 11).
- Scuff (figures 12, 13).
- Centrifuge (figure 14).
- Full-scale Traffic (Trafficulator) (figure 15).

Ideally, a chip retention test method should predict field performance and simulate actual loading and environmental conditions. None of the above tests has all of the desirable features.

(1) <u>Multiple Aggregate Pull-Out Tests.</u>[40,41] These tests measure the force necessary to pull aggregates out of a binder. Load-deformation data can be recorded. Job aggregate and binder can be used.

(2) <u>Vialit Test</u>.[42] This laboratory test was developed in France in the early 1960's and has recently been tried in South Africa, Canada and the United States. A field version of this test was recently developed by Chevron, USA. The test measures aggregate retention under impact loading.

(3) <u>Scuff Test</u>.[43,44] A large tire scuff tester has been used by Chevron. Smaller versions of this test have been used to evaluate slurry seals. Shear forces are induced by the turning of a rubber tire with a normal load. The force necessary to turn the tire is measured and/or the damage inflicted upon the chip seal is visually assessed. A brush test, which creates shear force developed by brushing the surface of a chip seal, has been used in Texas. Stone retention is measured.

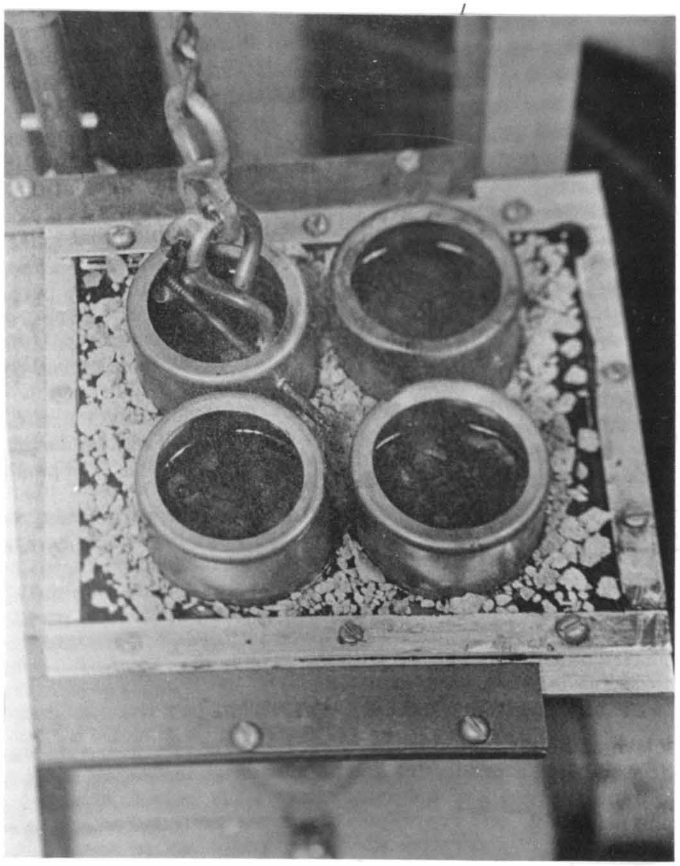


Figure 8. Mold arrangement and connection.(40)

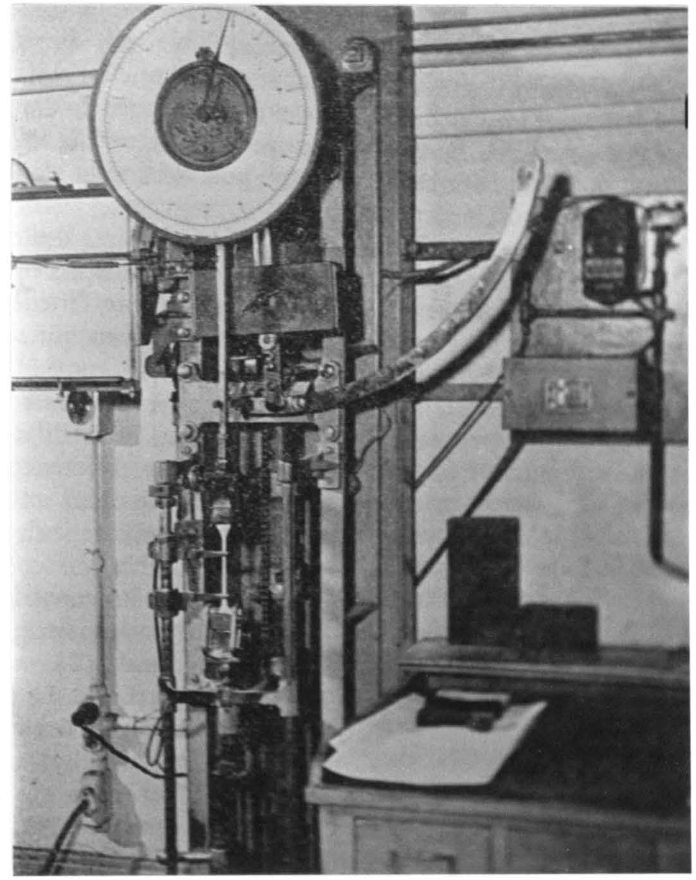


Figure 9. Assembly of test equipment with 4-in mold.(40)

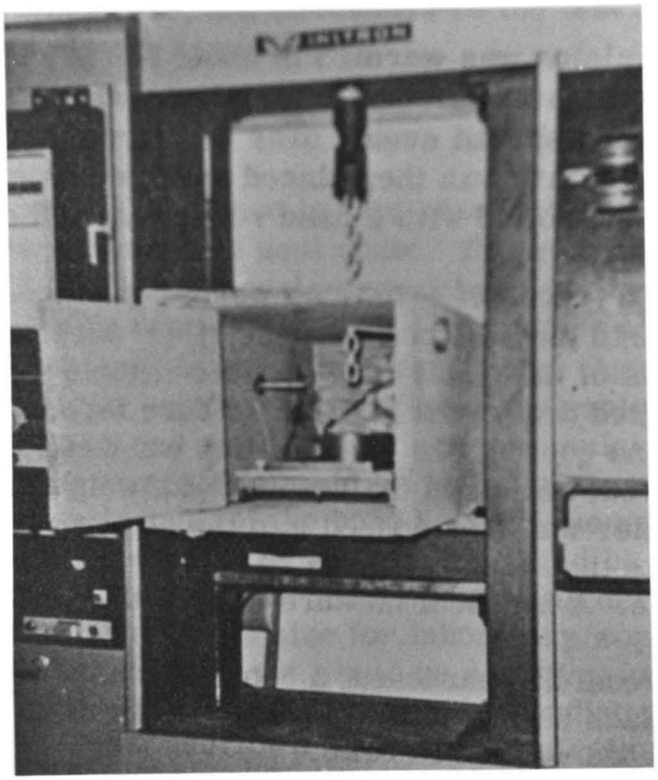


Figure 10. Testing machine and temperature box for tenacity test (setting and durability of asphalt emulsions).(41)

Figure 11. Modified Vialit test used by University of Nevada-Reno.(39)

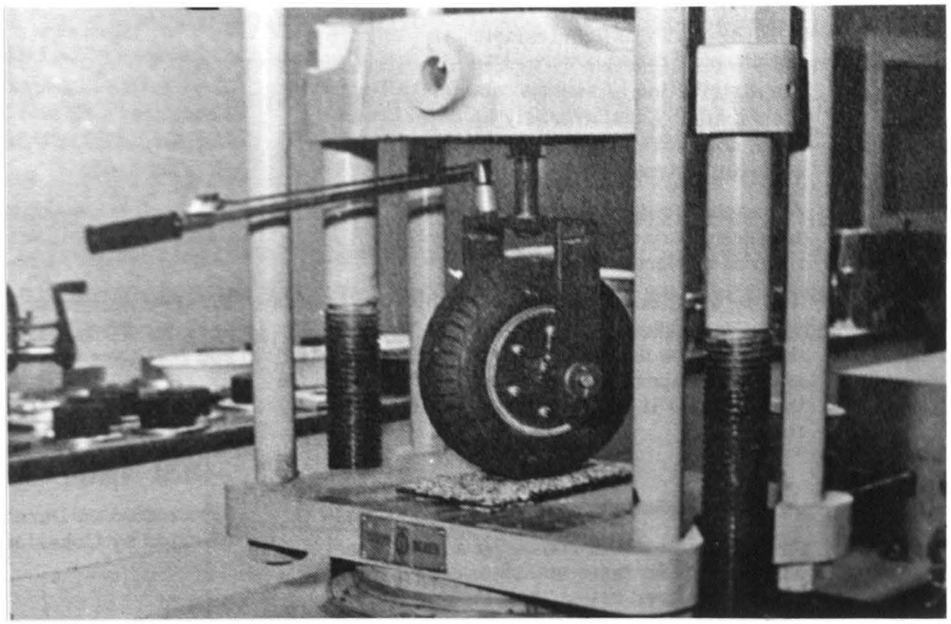


Figure 12. Scuff test.(43)

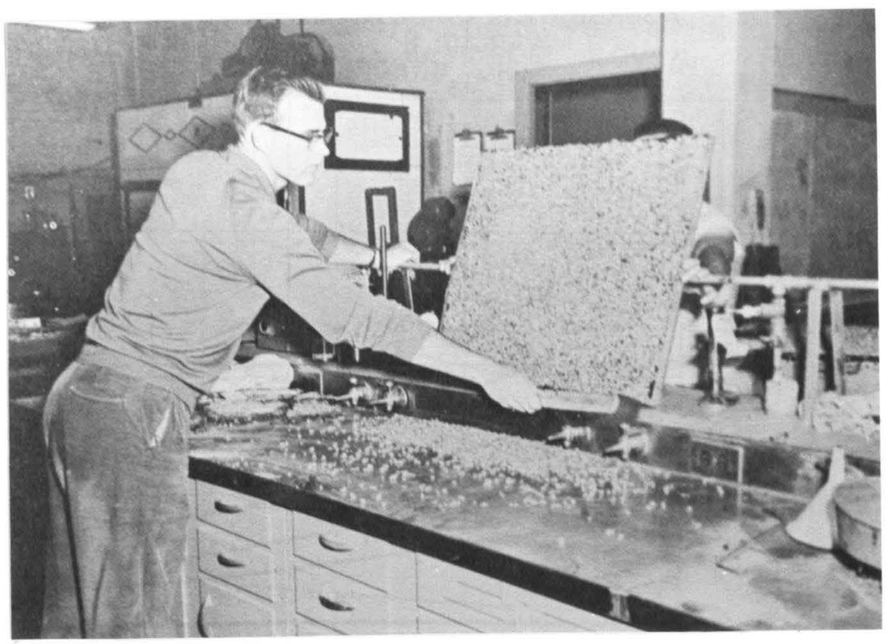


Figure 13. Brush test.(44)

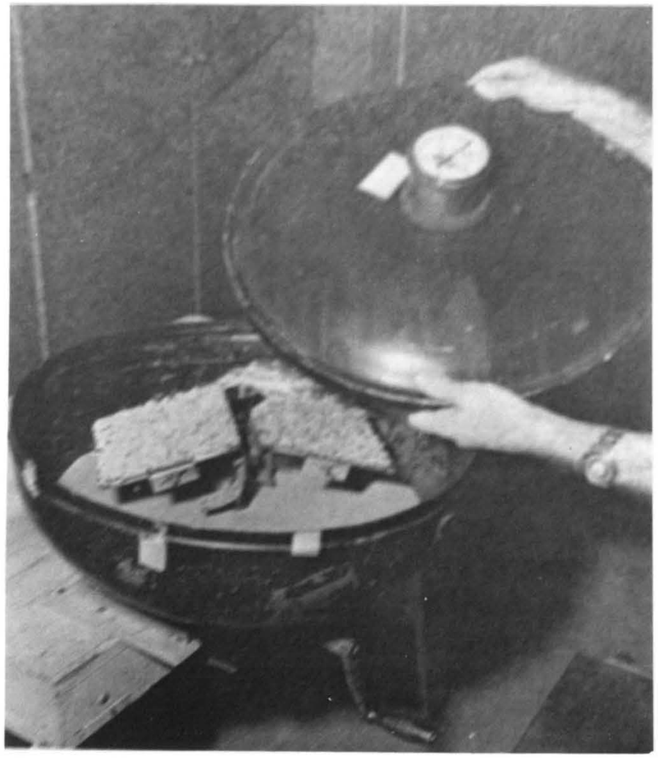


Figure 14. Centrifuge test.(45)

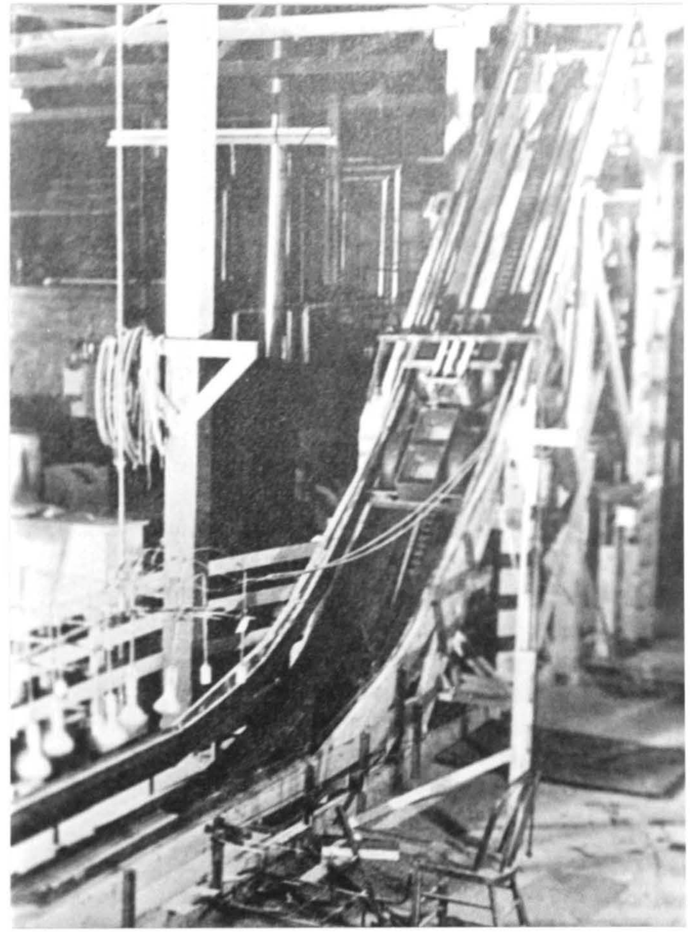


Figure 15. Trafficulator.(43)

(4) Centrifuge.[45] California has experimented with a centrifuge to develop tensile forces in laboratory-fabricated chip seals. Stone retention is measured.

(5) Trafficulator.[43] A device developed by Chevron which simulated vehicular traffic. Stone retention is measured.

(6) Other Tests. A number of tests have been developed in the coating and adhesive industries to measure binder properties. These tests do not allow the use of job aggregates.

8. Previously Reported Findings and Needs

It is interesting to note previously reported findings, gaps in knowledge and research needs. The following lists of findings and research needs are compiled from work performed over 20 years ago and provide an interesting historical perspective in the progress made to better design and construct seal coats.[6]

a. Findings

(1) By reviewing existing literature, one readily notes the inconsistencies in terminology relating to seal coats and surface treatments. It is evident that no universal definitions exist. There is an apparent need for widely acceptable terms which would facilitate communication among engineers dealing with surface treatments.

(2) Although some surface treatments have performed poorly, there are records of a number of surface treatments that have had excellent performance. Such desirable performance has not been limited to warm weather regions. Canada, Sweden and many other cold weather countries have produced excellent performing surface treatments. In addition, good performance has not been limited to surface treatments carrying only light traffic volumes. Many treatments have performed quite satisfactorily under medium to heavy traffic.

(3) Surface treatments are not recommended for heavy, high-speed traffic, as such traffic tends to readily displace the cover aggregates.

(4) The major restrictions for good surface treatment construction are as follows: (a) weather conditions during construction must be favorable as the temperature of the air and road surface and the presence of moisture greatly influence construction of a good surface treatment; (b) the underlying surface must be stable, clean, and dry before application of the bituminous binder material; and (c) the application of bituminous binder must be rigidly controlled in order that the "optimum" amount may be placed correctly.

(5) Surface treatments fail predominantly by (a) flushing or bleeding of the binder due to the presence of excessive amounts; (b) loss of aggregate caused by insufficient amounts of binder; and (c) streaking produced chiefly by the nonuniform application of bituminous material. All of these major types of failure are related to the bituminous binder and can be eliminated by careful design and construction practices.

(6) Surface treatments serve several important functions such as providing an abrasion and skid-resistant surface. However, this type of construction does not appreciably strengthen the pavement and will not allow an increase in the existing traffic loads.

(7) The gradation of the aggregate is very important. A closely controlled, one-size aggregate is considered the best type of cover material to use. In most areas, this type of aggregate is generally more expensive than aggregate with greater amounts of overage and underage, but the resulting increase in performance may warrant its use.

(8) Asphalt cements retain the cover aggregate better than any other type of bituminous material. However, adhesion between this bitumen and the aggregate is more difficult to obtain and the stone should be applied as soon as possible after the asphalt cement has been sprayed on the road surface.

(9) It appears that the basic principles set forth by F.M. Hanson in 1935 form the basis for the majority of current design methods.

(10) The quantity of aggregate has not been considered to be a critical factor so long as the surface is completely covered. Because of this, considerable variation in the "spread" amount has been allowed. This should not be the case as too much excess can be very detrimental.

(11) It appears that the different design methods indicate a wide variation in the amount of bituminous material to be used. This is even more critical than it seems since there is an optimum amount of binder required, and since little variation from this amount can be tolerated.

(12) There is no desirable analytical method of obtaining the type and grade of bituminous material to be used. McLeod has suggested one approach, but it still leaves many important design factors to be evaluated empirically by the engineer.

(13) There is no analytical method for designing multiple-layer surface treatments. At present they are "designed" primarily from experience.

(14) There has been little research, either in the laboratory or on actual field test sections, related to the various factors that influence the performance of surface treatments. It is possible, however, that much unreported research data do exist. This apparent lack of research information has caused many of the current design and construction practices related to surface treatments to be developed over the years by trial and error.

(15) Many engineers believe that since surface treatments are inexpensive and relatively simple to construct, care is not required during their construction. This usually results in a lack of control and/or necessary supervision of construction and subsequently produces poorly performing surface treatments.

b. Research Needs

(1) General Need. Although not strictly a research project, there is one area in which there is a dire need: standardization of terminology related to surface treatments. Because of the wide variation in usage throughout the world, it would be desirable for a national or international group to define the terms for common use. Then, even though it would be a greater problem, the definitions should be widely adopted by all engineers.

(2) Materials

(a) Type and magnitude of the forces which are applied to the aggregate in a surface treatment by moving wheel loads.

(b) Method of correlation of rheological and failure characteristics of bituminous binder to actual field conditions.

(c) Means for developing the best adhesion between the aggregate and the binder, since little strength is developed by aggregate interlock and aggregate friction.

(d) The feasibility of using gravel or crushed gravel as cover aggregate.

(e) The size of aggregate needed in relation to the traffic conditions.

(f) Gradation and top size of both the first and second layers of aggregate that are used in double surface treatment construction.

(g) Interlocking effect of the second layer of aggregate in a double surface treatment.

(h) Importance of reducing the size of the aggregate in the second application of a double surface treatment.

(i) Most suitable type and grade of bituminous binder needed, considering the aggregate, temperature and other influencing factors.

(3) Design

(a) The development of an analytical method to determine the influence of an aggregate shape factor on the amount of aggregate needed.

(b) The correct specific gravity to convert the quantity of aggregate from cubic feet per square yard to pounds per square yard.

(c) The feasibility of converting the quantity of aggregate determined by the test-board method to the average size of the aggregate.

(d) Means of computing the volumes of the voids between the aggregates as influenced by (i) size of the aggregate, and (ii) shape of the aggregate.

(e) The relationship between the volume of the voids between the aggregate in a layer one stone thick and the voids in the aggregate in bulk quantity.

(f) The maximum and minimum amounts that the aggregates can be embedded in the bituminous binder.

(g) Determination of the extent of aggregate penetration into the underlying surface so that a reduction in the amount of bituminous quantity can be made.

(h) Additional study on the influence of the physical condition of the aggregate (wet or dusty) and determination of acceptable limits.

(i) An analytical means, such as McLeod suggests, to determine the type and grade of bituminous binder to be used.

(j) A design method for double surface treatments which includes (i) the quantity of aggregate needed in the second application, and (ii) the quantity of binder needed, as it is not the same as two single surface treatments.

(k) A design method for "graded" aggregate, i.e., aggregates with an appreciable amount of overage and underage, especially the manner for including the fine aggregate in the design.

(4) <u>Construction</u>

(a) The most desirable way of measuring the serviceability and determining the performance of surface treatments. This probably means the use of more mechanical instruments to eliminate the human error in judgment.

(b) The means of producing, economically, one-size aggregates with little overage or underage.

(c) Means of determining the amount of bituminous binder that will be absorbed into the underlying surface.

(d) Determination of how much compaction (passes of the roller) is needed to produce the minimum vertical aggregate dimension under various conditions.

(e) Determination of desirable traffic speeds during the early life of the surface treatment.

(f) Although not strictly a research project, a means is needed to educate the construction personnel as to the best practices for surface treatment construction.

(g) Test sections, built under controlled construction conditions, are needed to evaluate design features and construction techniques.

CHAPTER 3. BRAINSTORMING AND INTERVIEWS

The literature review was extended through a brainstorming session between the project team members and interviews of State highway departments. In addition, results of the brainstorming session and interviews helped to outline critical areas which should be considered in the subsequent laboratory and field evaluations. This chapter summarizes the brainstorming and interview activities.

1. Brainstorming Session

Project team researchers with expertise in pavement technology as well as seal coats participated in the brainstorming session. Table 10 represents the factors affecting chip seal performance as prioritized by the project researchers. Findings from the literature review were combined with the researchers' personal knowledge of and experience with chip seals to develop the ranking order. The following criteria were used:

- Which factors directly relate to performance?
- Which properties are not as important as others?

As project researchers were prioritizing factors which affect chip seal performance, several "rules of thumb" were also expressed which are often used in designing, constructing and monitoring chip seals. These comments were recorded and summarized in table 11, providing useful suggestions.

Finally project members discussed the effectiveness of examining projects previously constructed and using them as case histories to attempt to refine the factors affecting performance. However, preliminary trials to obtain case history information had indicated that the information useful for this project was spotty at best. Therefore, the use of any statistical procedures on the resulting data would probably

Table 10. Primary factors affecting performance of seal coats ranked in order of importance.

Aggregate	Asphalt Emulsions	Construction
1. Cleanliness	1. Type -- RS, MS, CRS, CMS	1. Weather
2. Type (geologic)	2. Amount (spread rate)	2. Spread Rate a) asphalt emulsion b) aggregate
3. Gradation	3. Temperature/viscosity relationships of emulsion for spraying	3. Construction timing
4. Moisture content	4. Temperature/viscosity relationships for residual base asphalt	<u>Secondary Factors</u>
5. Shape and texture	5. Wettability (coatability)	4. Time of year
6. Amount (spread rate)		5. Quality Control Procedures
<u>Secondary Factors</u>		6. Traffic control
7. Porosity/absorption		7. Construction equipment a) type b) calibration
8. Abrasion resistance		8. Existing surface a) preparation b) condition
9. Soundness		9. Materials handling and storage
10. Adhesion characteristics		

Table 11. Brainstorming ideas for a check list or rules of thumb in seal coat construction.

1. Estimating the moisture in the aggregate. Saturated surface dry is about right. Best to water the stockpile, not the truck.

2. Cleanliness of aggregate. How much dust can you rub off in your hands? Can we calibrate or estimate various percentages of dust? In extreme cases if too dirty, the stockpile will stand with vertical faces.

3. Asphalt emulsion uniformity and quantity. Streaking - adjust single, double, triple overlays of spray fans. For estimating on the roadway: throw rock chips (more than one bounce means too little asphalt emulsion, use penny on edge as a gauge (about 3/32 in is the right spread rate, could make a throw-away cardboard gauge, could use example photographs in a field guide.

4. Checking asphalt emulsion spread rate. In addition to checking with pads across the roadway, a calibration curve should be developed for the truck tank. Also, can estimate spread rates from charts such as those published in the Technology Transfer newsletter from Olympia, WA.

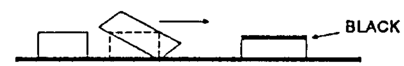
5. Breaking of asphalt emulsion. Need method to estimate other than turning from brown to black because a "skin" forms first and may be misleading.

6. Timing of aggregate application. How soon following asphalt emulsion application? Probably best is as quickly as possible to allow best aggregate coating.
Rock must be added sooner in hot weather when using asphalt emulsions. (This is the opposite for cutbacks, which permit delayed rock application because of the lower viscosity in hotter weather). Normally, rock is applied as soon as possible except when graded aggregate (Eg. 3/8 minus) is used and there is danger of pushing a wave of asphalt emulsion ahead of the rock as it hits the surface. Make sure there is enough aggregate on the jobsite in trucks to cover the asphalt spread.

7. How much aggregate embedment in the fresh asphalt emulsion? Suggested 40-50% just following construction and 70% ultimately after curing.

8. Estimate number of rollers required on job site. Speed of roller should be faster than walking speed (3-4 mi/h), probably about 4-6 mi/h is appropriate. If faster, the roller may pick up stones.

9. How soon to roll? Stones should not be picked up. Example photograph showing stone rolled over by traffic.

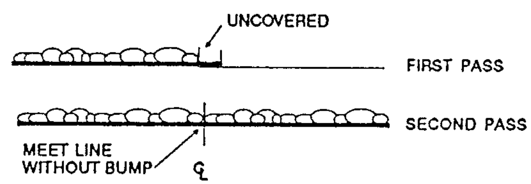


10. How soon to broom? Whether to broom at all? Depends on several factors: size of aggregate, amount of loose rock, speed and volume of traffic. Generally broomed very early the next morning after construction.

11. When to allow traffic on road? Use test vehicle (agency vehicle) after choke stone applied (if any). Ideas under investigation include microphone in wheel well of test car, box to collect loose stone behind wheel of test vehicle, modified vialit test, etc. Best to use pilot car and 20-25 mi/h speed limit in the beginning.

12. Traffic speeds? What speed and for how long? Best to use a pilot car and 20-25 mi/h speed limit until rock pick-up is minimal.

13. Overlap at meet line (joint between adjacent passes). Best to show in photographs. Idea is to leave approximately 3-4 in uncovered with aggregate (because it is thinner coverage at end of distributor bar), then the additional asphalt and the aggregate will be placed on the adjacent pass.



have been inappropriate. The project team agreed that some means of obtaining field information regarding factors that affect success or failure was important. In addition, having the information in a format appropriate for statistical testing was also considered important.

One method suggested to satisfy both concerns was a carefully prepared and tested questionnaire. The entire team agreed that, given all the factors involved, this would yield more useful information than an approach involving case histories.

2. Interviews

A questionnaire was developed to interview engineering, construction and maintenance personnel of State departments of transportation. Responses to the questionnaire were summarized and analyzed statistically.

a. Questionnaire

The questionnaire was designed to allow agency personnel to complete it quickly yet obtain the following information:

- General information on seal coats including emulsion and aggregate types, use criteria, design and construction guidelines, test procedures and quality control methods.
- Identification of performance measures such as aggregate loss, bleeding, tire wear or noise, etc.
- Identification of failure criteria (i.e., when the seal coat no longer performs its intended function).
- Identification of the factors most affecting seal coat performance (e.g., aggregate, asphalt emulsion and/or construction instructions).
- Any other issues that the individual would like to "write-in" on the form.

Preliminary versions of the questionnaire were sent to engineers in counties, States and foreign countries to elicit feedback regarding the format as well as obtain useful information based on their knowledge of chip seals. From responses to these "trial runs," the questionnaire was revised into its final version for official distribution. Appendix B in volume II contains a copy of the finalized questionnaire.

b. Statistical Analysis and Agency Selection

It was planned to statistically analyze the questionnaire responses in order to assess the significance of the answers. Some of the responses were not conducive to statistical analysis. However, questions regarding performance measures, failure criteria, and factors affecting performance were formatted to provide quantitative answers which allow statistical analysis; questions were answered using numerical scale evaluations (0 to 10 or 0 to 100).

Further, it was considered important to collect data from the different climatic regions in order to determine, if possible, the influence climate has on chip seal parameters. This would help to extend findings to the entire U.S. where justified. Table 12 lists the States selected for interviewing and their associated climatic regions are listed below. Personnel contacts are given in appendix B.

Eight State agencies responded to the questionnaire; Georgia did not respond. In the end, States were categorized into three of the four climatic regions: Wet--Freeze, Wet--No Freeze, and Dry--Freeze. While it is realized that some States are actually located within several climatic regions, only three environmental regions were included because it was felt that these three environmental regions covered most of the United States with the exception of the low deserts of Arizona and California, and the coastal regions of Southern California.

Table 12. Conditions useful to the selection of State agencies for collecting information.

		TEMPERATURE	
		FREEZE	NO FREEZE
PRECIPITATION	WET	Virginia Pennsylvania Indiana Maine	Washington Texas Virginia Georgia
	DRY	Washington California Arizona	California Texas Arizona

Environmental regions were "fixed," that is, the three regions were selected purposely to cover the regions of interest in this investigation. The agencies are "random"; that is, Pennsylvania, Maine and Indiana supposedly represent the entire Wet--Freeze region; Washington, Texas, and Virginia supposedly represent the whole Wet--No Freeze region; and California and Arizona supposedly represent the whole Dry--Freeze region. "Supposedly" is used because these agencies were not drawn at random in a statistical sense, but the seal coat project team believed that these agencies were typical of the agencies in those regions. In the analyses, the agencies were treated as the random component for statistical analysis.

The agencies located within each environmental region provide geographical dispersion which allows broad inferences to be drawn from the data. The assumption is made that the agencies selected for this study represent the agencies in those environmental regions and are, therefore, called "random." This quality of randomness of the agencies then allows inferences to be made regarding the responses so that statistical probability statements from the analyses of the data obtained are valid.

The "inference space," that geographical area and time constraint within which the results of this study apply, is the continental United States in the years 1986 and 1987. In other words, the assumption is made that the sample has been forced to be broad enough (geographically) that these results apply for the entire continental United States.

The above comments provide the basis for statistical analyses of the data. There are, generally speaking, two types of statistical analyses: Parametric (classical statistics) and nonparametric (distribution free statistics). The parametric statistical procedures, which require knowledge of the distribution of the responses, are more powerful and will show significant effects more readily than nonparametric statistics for the same number of responses. Hence, it is desirable to use the classical analysis approach if the data can be shown to have the required distributional properties.

The statistical analysis procedures consisted of three major parts. First, calculations and tests were performed to determine if the data complied with assumptions necessary for an analysis of variance. Next, the data were tested to see if a systematic variation existed that could be attributed to climatic region. Finally, tests were performed to determine whether the means of the values scaled off the form were statistically "different." This difference would imply a ranking of importance of or difference in performance measures, failure criteria, and factors affecting performance.

c. Interview Results

The following section summarizes the interview results. Complete responses to the questionnaire are given in appendix B of volume II.

(1) <u>General Questions</u>. General information regarding mileage within the jurisdiction, mileage sealed and types of materials used is given in table 13. Total mileage under the jurisdiction of the agencies queried ranged from 5000 in Maine to 70,000 in Texas. Similarly, it was found that the total mileage chip sealed each year ranged from less than 100 to 10,000. Typically cationic emulsions, both rapid and medium set, plus high float emulsions are used across the United States. Some cutbacks and asphalt cements also are still apparently used. All types of aggregates are used for seal coats.

All the agencies have standard specifications which treat this type of construction. It is indicative of the renewed interest in seal coating that several have recently updated their specifications in this area.

As would be expected, the decision to use a seal coat over some other form of rehabilitation is typically made based on judgment by engineers or maintenance personnel. Type and percent of cracking, amount of raveling, traffic volume and type, future plans for the roadway and available funds are factors which all play a role in the decision-making process.

Typically, seal coats are placed over old seal coats. Three of the agencies reported seal coats placed over all types of bituminous surfaces.

Most of the agencies are not hesitant to place seal coats on roads with traffic volumes over 1000 ADT, though two indicated that most frequently the seal coats are placed on roads with lower traffic volumes.

Table 13. Summary of general information on seal coats.

Agency	Centerline Miles of Roadway	Miles of Seal Coats Constructed per Year: Chip	Slurry	Other	Grades of Emulsion Used	Types of Aggregate Used
Arizona	6,000	150	10	--	CRS-2	Basalt, granite
California	15,184	1,300	20		CRS-2,RS-2 w/latex	No Response
Indiana	11,600	460		Sand seal	AE-90,AE-150, RS-2	Crushed: limestone, dolomite,gravel; slag, natural sand
Maine	5,400	0	0	Shoulder seal	HFMS-1,HFMS-2	Various natural sands
Texas	71,000	10,000	0	--	CRS-2,RS-2,HFRS-2 HFRS-2P,CRS-2P	Limestone,sandstone, ryolite, synthetic
Pennsylvania	44,000	2,900	0	--	E-2(RS-2),E-3(CRS-2) AC-2.5	Limestone, dolomite, sandstone,argillite, gravel,slag,diabase gneiss,quartzite,etc.
Virginia	62,000	9,737	1661	--	CRS-2,CMS-2	Siliceous gravel, granite,limestone, dolomite
Washington	7,000	500	0	0	CRS-2,CMS-2 MC-800	Basalt,andesite, granitics.

The criteria for selection of materials (e.g., emulsion type and aggregate) were somewhat varied. Previous experience, cost and availability are probably the most common reasons. The final decision in many cases is at the discretion of the local engineer.

Most agencies responded that initial application rates for materials are calculated based on the results of laboratory tests. Most indicated that these rates serve as guidelines and that rates are typically modified in the field. Interestingly enough, two agencies responded that in some cases, rates are chosen based on historical data and infrequently modified in the field.

Most agencies run standard quality control tests on materials to ensure compliance with the specifications for aggregates and emulsions. These include gradation, abrasion, percentage of crushed faces, presence of dust or clay-like material (cleanliness), degradation and stripping for aggregates. Standard tests for emulsions include viscosity, settlement, particle charge and percent residue.

During field operations, most agencies visually evaluate the breaking of the asphalt emulsion. Most agencies check the actual emulsion and aggregate spread rates by calculating the total amount sprayed and spread over a known surface area. One agency specifically mentioned State test methods for distributor and chip spreader calibration. Finally a question was asked as to any specific inspection and quality control "procedures" utilized by the agency. Since construction control is such a crucial part of the success or failure of chip seals, the answers given to that question are as follows:

- Monitor pavement and air temperatures.
- No construction control procedures used.
- Aggregate inspected for percent embedment. Traffic piloted at controlled speeds, minimum surface/air temperature. Survey completed after construction.

- Check calibration of distributor and chip spreader, yield test on aggregate application rates, check pneumatic tire roller for weight and tire pressures.

- Check spray bar for proper asphalt distribution. Occasionally vary rate across the pavement based on different conditions in and outside wheel paths. Make sure rolling is adequate. Vary asphalt rates between dry and flushed sections. Hold traffic off as long as possible and/or control traffic on new seal.

- Visual on-site inspection.

- None other than Asphalt Institute, ES-12.

- General inspection procedure - nothing else specific. Simply trying to achieve good, uniform rock embedment (50 to-70 percent) with no wasted rock and no visible joints.

(2) Scale Evaluation. The second portion of the interview form concerned a listing of performance measures, failure criteria and factors affecting performance. Respondents were asked to indicate on a continuous scale associated with each item either a level of importance or a measure of failure, depending on the item being answered. The performance measures, failure criteria and factors affecting performance that were included in the form resulted from the project brainstorming session.

A key item resulted from the statistical evaluation. The respondents were grouped by climatic regions. The data was analyzed to determine if the hypothesis that regional effects were insignificant could be rejected. The statistical outcome was that this hypothesis for the performance measures, failure criteria, and factors affecting performance could not be rejected; thus, climatic effects were determined to be insignificant.

The hypothesis decision had important implications from the standpoint of this project. It indicated that monitoring of projects (performance measures) throughout the different regions could be conducted in a similar manner. It also meant that the factors which affect performance and the failure criteria do not necessarily vary in a systematic way between climatic regions. Further, training materials highlighting these factors could be confidently developed for dissemination across regional boundaries.

The following is a discussion of the responses in each of the three areas: performance measures, failure criteria and factors affecting performance.

(3) Performance Measures. The results of the survey regarding performance measures are shown in table 14. The numbers indicate the importance placed by each of the respondents on the item as to its contribution in determining whether or not the chip seal is performing satisfactorily.

Table 14. Results of interview form for performance measures.

PERFORMANCE MEASURES	Agencies									
	PA	ME	IN	TX	WA	VA	GA	CA	AZ	AVE
A. Aggregate Loss	95	95	81	87	90	95	75	89	85	88
B. Appearance	71	49	81	52	60	89	45	53	64	63
C. Asphalt Bleeding	95	95	89	89	90	96	85	89	82	90
D. Corrugation	55	62	80	56	70	94	60	55	71	67
E. Flying Rock Damage	95	8	79	72	100	95	45	89	87	74
F. Surface Texture	73	49	41	61	60	84	60	39	71	60
G. Tire Noise	4	9	40	41	40	52	45	7	50	32
H. Tire Wear	4	9	40	23	30	52	25	7	50	27

The eight measures were ranked as shown below. The groups were determined based on a qualitative evaluation of the responses. As documented in appendix B, statistically, one can say with certainty that the factors for tire noise and tire wear were rated lowest of all.

Group I	Group II	Group III
• Asphalt bleeding.	• Corrugations.	• Tire noise.
• Aggregate loss.	• Appearance.	• Tire wear.
• Flying rock damage.	• Surface texture.	

(4) Failure Criteria. In the questionnaire, each respondent was asked to describe in a short statement the conditions that would differentiate between success and failure. The responses to that question were as follows:

- Loss of chips in wheel paths or bleeding causing a lowering of the frictional resistance.
- Loss of cover aggregate - Aggregate is placed too late or seal is contaminated with dust and chips do not stick. Seal flushes - Seal is applied at a too heavy rate and surface becomes "fat" with low skid residence qualities.
- Loss of aggregate resulting in lower friction levels. Bleeding from improper design or application with loss of friction. For success, aggregate adheres approximately 8 years with good friction during this period.
- "Failed" condition is when bleeding/flushing and/or aggregate loss reach a point where slippery conditions are observed.
- When a seal has lost 20 to 30 percent of initial retained aggregate; when bleeding or flushing results in 20 to 30 percent of wheel path areas being completely flushed; when skid values reach an unacceptably low level for the given section of roadway; when cracks are no longer sealed.
- Failure occurs when entire wheel paths have lost cover aggregate. If a project achieves the end result, i.e., waterproofing of old surface or restoration of skid resistance, then it is deemed a success.
- Sufficient aggregate loss or embedment to cause friction loss or markedly reduce the service life of the pavement.
- Visual loss of aggregate or excessive asphalt on surface.

As can be seen in the responses, each person rated loss of aggregate and excess asphalt on the surface as conditions which would be used to determine success or failure. What is interesting to note is that although flying rock damage was considered an important factor in determining performance, not one person indicated that an unacceptable number of complaints due to flying rock damage alone, would cause a project to be judged a failure. Conceivably, one could experience this damage without necessarily having detrimental aggregate loss (in terms of chip seal performance) if aggregate spread rates were high and brooming was not accomplished in a timely manner.

Each person was then asked to indicate the percentage of area in which rock loss or bleeding would have to occur in order to define failure. In discussing this question with one individual, the point was made that, depending on the location of the area exhibiting rock loss or bleeding, though the area might be small, repair measures might still be taken. The intent of the question was to determine that if general rock loss or bleeding was occurring, what percentage of loss would constitute "failure."

The results are given in table 15. Based on the average of the responses, the data suggests about 30 to 35 percent aggregate loss is acceptable within the wheel paths and a slightly larger amount, 45 to 50 percent, is acceptable outside the wheel paths. Less asphalt bleeding appears to be acceptable. The data suggests that if only 20 to 25 percent of the area experiences excessive asphalt problems, failure is said to occur.

Finally, skid resistance is an important measure for failure.

Table 15. Results of interview form for failure criteria.

FAILURE CRITERIA	PA	ME	IN	TX	WA	VA	GA	CA	AZ	AVE
	Agencies									
AGGREGATE LOSS IN:	Percentage of area									
Outer Wheel Path	47	60	20	30	20	11	90	10	15	34
Inner Wheel Path	47	70	21	31	20	12	90	10	14	35
Between Wheel Path	47	95	7	44	50	45	60	1	45	44
Centerline	47	95	7	45	65	74	40	1	50	47
SEV. OF ASP. BLEEDING IN:										
Outer Wheel Path	26	35	10	35	20	3	70	10	10	24
Inner Wheel Path	26	35	10	36	20	4	85	10	10	26
OTHER FAILURE MEASURES:	Measure of importance									
Skid Resistance	98	95	70	74	100	99	80	83	92	88
Appearance or Text.	76	40	70	43	55	91	60	34	50	58

(5) Factors Affecting Performance. The results of the interview forms for factors affecting performance are shown in table 16. The following conclusions are drawn based on a qualitative assessment of the data displayed in the table.

The factor appearing to be most important in determining performance is the emulsion application rate. This factor was brought out time and time again in the literature and was echoed by the respondents. Of the other factors associated with the materials, only aggregate cleanliness and gradation seemed to rank high. Other material properties were not considered as important. Perhaps one interpretation of this

Table 16. Results of interview form for factors affecting performance.

FACTORS AFFECTING PERFORMANCE	Agencies									
	PA	ME	IN	TX	WA	VA	GA	CA	AZ	AVE
AGGREGATE										
Amount	72	75	32	82	90	96	75	90	58	74
Cleanliness	98	89	62	55	100	97	60	90	69	80
Gradation	71	89	77	71	90	96	60	90	68	79
Moisture Content	98	44	22	50	65	96	55	90	60	64
Shape And Texture	71	58	80	55	60	95	85	42	75	69
Geological Type	10	41	26	55	50	63	75	41	67	48
ASPHALT EMULSION										
Amount (gal/sq yd)	95	90	91	91	100	96	90	92	74	91
Temp vs visc emul	72	72	82	69	65	95	55	45	40	66
Temp vs visc asphalt	85	72	13	50	75	95	55	70	40	62
Type of Grade	54	100	36	69	85	90	60	41	40	64
Coating Ability	95	75	85	60	75	94	80	20	60	72
CONSTRUCTION PROCEDURES										
Construction Timing	89	90	85	80	90	93	90	90	86	88
Field Application Amts	89	92	85	85	100	97	90	88	63	88
Application Uniformity	88	88	89	85	90	97	75	89	75	86
Weather	88	72	90	77	70	96	80	100	85	84
Time of Year	87	72	90	65	80	93	90	80	83	82

trend is that existing specifications are apparently satisfactory in providing aggregate that has sufficient durability and stability, and asphalt emulsions that are suitable for seal coating.

Conversely, every item associated with construction was ranked high by all the respondents. This reinforces the general conclusion that the success or failure of a seal coating program will many times depend upon the field experience of the contractors and inspection personnel.

CHAPTER 4. LABORATORY AND FIELD EVALUATIONS

1. Introduction

The purpose of this part of the research investigation was to study and establish the relationships of material properties and construction procedures to actual chip seal performance. This analysis was accomplished by the following activities:

- Performing preconstruction surveys of the original pavement prior to coverage by the chip seal.
- Observing and documenting construction conditions and procedures.
- Sampling project materials and conducting various laboratory tests.
- Performing post construction evaluations of actual chip seal field performance.

Chip seal projects in five different States were included in the study: Washington, Oregon, Nevada, Pennsylvania and Texas. Projects ranged from regular contract work to extensive research projects. Due to the diverse objectives and scopes of the projects, variations in laboratory and field documentation are provided herein. The following sections give a general description of the project; preconstruction, construction, laboratory and post construction activities; and findings or performance correlations (where possible) related to each project.

2. Washington

A regular, contract chip seal project was constructed in July 1988 on State Route 31 in Pend, Oreille County of northeast Washington. This area is classified as a "Dry--Freeze" region.

The project consists of a two-lane road comprising a structural section of multiple past surface treatments on top of an asphalt concrete pavement. The roadway experiences an ADT (per lane) of 142, of which 10 percent is trucks (mainly logging). The pavement appears to be underdesigned for its present traffic loading as evidenced by significant levels of rutting.

a. Preconstruction

Preconstruction evaluations made in the field are included in appendix C of volume II. Specific characteristics that were noted which may affect chip seal performance are:

- Prevalent medium to high severity rutting.
- Bleeding and high aggregate embedment (90 to 100 percent) in rutted areas.
- New, smooth rehabilitative patch in one lane.
- Higher traffic loads (loaded log trucks) in the southbound lane.
- Generally low traffic volume.

b. Construction

Observations made and data collected during project construction are contained in appendix C of volume II. Some of the more salient items are listed below:

- Favorable curing conditions (i.e., temperature, sunshine/cloud cover, wind, etc.).
- Tight spacing maintained between construction operations; one minute separated both emulsion spraying and aggregate spreading, and aggregate spreading and rolling.
- Ten minutes elapsed between aggregate spread and initial rolling of the center portion of the travel lane.
- Significant amount of dust due to dirty aggregate.
- Choke stone spread and rolled approximately 13 minutes after chip spread.

- Rollers and aggregate trucks driven over fresh chip seal at excessive speeds (approximately 30 to 40 mi/h); some aggregate pick-up was noted.

- Pilot car traffic control (approximately 25 mi/h); low levels of public traffic.

- Initial aggregate embedment depth = 30 to 40 percent.

- Setting rate of chip seal was delayed in a shaded portion of roadway.

- Fifteen minute delay occurred between emulsion application and aggregate spread on a portion of the test section due to coordination error between aggregate haul trucks and the rest of the construction operations.

- Brooming operations conducted early the following morning.

c. Laboratory Testing

(1) Individual Material Properties. Two types of asphalt emulsion and two aggregate types were used on the project. Rapid and medium set cationic (CRS-2 and CMS-2) asphalt emulsions were sampled. Samples of the chipping aggregate and choke stone were obtained. Tables 17 and 18 list the emulsion and aggregate properties.

Table 17. Properties of asphalt emulsions from Washington chip seal project.

Test	ASTM No.	CRS-2	CMS-2
Residual Asphalt by Evaporation, %	D244	69.1	68.2
Residual Asphalt by Distillation, %	D244	66.6	--
Viscosity @ 122 ^{o}F, SFS	D244	167*	168**
Penetration of Residue @ 77 ^{o}F, 100g/5sec., dmm	D5	112	--

* Average of 5 samples; range 104 to 213; std. dev. = 41.
** Average of 2 samples; range = 137 to 199.

Table 18. Characteristics of aggregates from Washington chip seal project.

Test	ASTM No.	Chip	Choke Stone
Bulk specific gravity	C127	2.653	NA
Bulk specific gravity, SSD	C127, 128	2.681	2.668
Apparent specific gravity	C127, 128	2.729	2.780
Absorption capacity, %	C127, 128	1.06	2.40
Unit weight, pcf	C29	107	NA
Sieve Analysis:	C117, 136		
Cumulative Percent Passing, %			
1/2 in		99.8	100
3/8 in		57.0	100
No. 4		6.9	81.9
No. 8		3.4	53.9
No. 16		<1.0	37.1
No. 30		<1.0	26.3
No. 50		<1.0	18.5
No. 100		<1.0	12.9
No. 200		1.5	9.1
Average least dimension:			
Median size		3/8 in	NA
ALD, in.		0.315	NA

(2) Design Quantities. Using the material properties from tables 17 and 18, construction application quantities were calculated based on two design references: Asphalt Institute and Texas Field Manual on Design and Construction of Seal Coats.[11,4] Table 19 presents these design quantities for asphalt emulsion and aggregate, as well as the target field quantities recommended by Washington State Department of Transportation (WSDOT) specifications. Application ranges for emulsion and aggregate are given in WSDOT specifications and are based on aggregate size and gradation.

Table 19. Comparison of asphalt emulsion and aggregate quantities: design versus field construction.

	Asphalt Institute	Texas	Target Field Construction
Asphalt Emulsion:			
CRS-2, gal/yd^2	0.45	0.22	0.42
CMS-2, gal/yd^2	0.45	0.23	0.42
Aggregate Chip, lb/yd^2	33	16	33
Choke Stone, lb/yd^2	--	--	6

(3) Chip Seal Properties by Vialit Testing. A modified Vialit test method was used to measure properties (chip retention) of the materials in combination (i.e., actual chip seal samples). Test samples were prepared by fabricating a chip seal sample on a steel plate, then subjecting the sample to selected conditioning. Chip seal samples were tested by first inverting the sample for 10 seconds over a pan on a scale (collecting dislodged chips and weighing them); second, by immediately placing the inverted sample on a support device (remaining inverted), followed by a steel ball impacting the backside of the plate three times within 10 seconds, collecting dislodged chips and weighing them; and finally, calculating the total percentage of chips which were dislodged or retained. More detailed information is provided by Paulsen.(39)

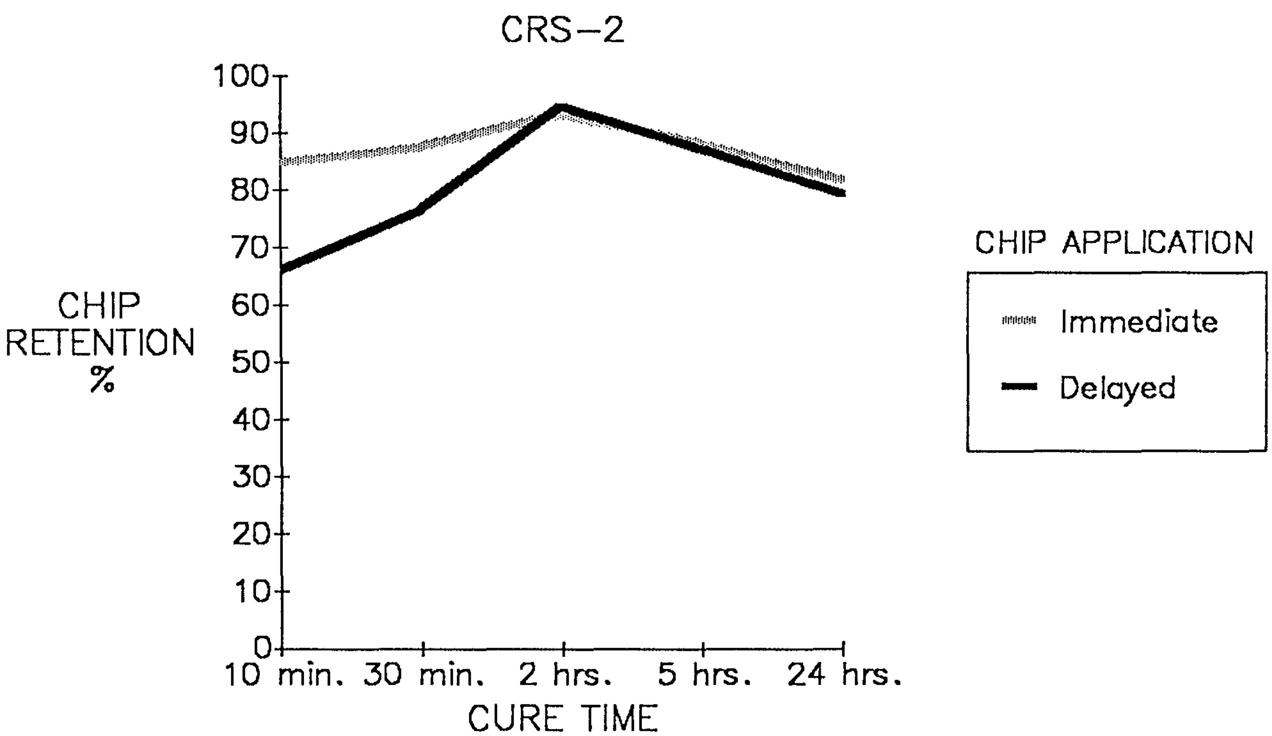
Samples were constructed to simulate field test sections. The same material quantities were applied and the samples were rolled with a loaded pneumatic tire. A 15-minute delay between emulsion application and aggregate spread was incorporated in the preparation of some samples to simulate the delay observed at one point in the field. Samples were fabricated and allowed to set at a temperature of 77 ^{o}F and relative humidity of approximately 30 percent. A report by Stroup-Gardiner contains more specific information on sample preparation and testing.(46)

Modified Vialit test results are contained in appendix C of volume II. Further comparisons are presented graphically in figures 16 through 19.

Figure 16 compares chip retention of samples made from each emulsion during the 10-second inversion portion of the test method. Two conclusions can be drawn from the figure. The ultimate retention percentages (assuming full set at 24 hours) indicate 10 to 20 percent of the applied aggregate quantity did not adhere to the asphalt emulsion. This amount of waste roughly corresponds to that observed in the field after brooming operations and is in excess of the surplus recommended by most design methods. The second conclusion pertains to the reduced retention percentage for the "delayed" CRS-2 samples at initial set times of 10 and 30 minutes. The results suggest reduced chip retention due to an increase in emulsion viscosity during the 15-minute delay, decreasing the binder's ability to effectively coat the rock and develop adequate adhesion.

Had the delay occurred along the CRS-2 portion of the project, subsequent chip retention problems may have occurred in the field. Fortunately, the section of the project experiencing the delay was constructed with CMS-2 emulsion; no problems were observed in the field, which is confirmed by the CMS-2 results depicted in the bottom graph of figure 16. Figure 17 illustrates the same trend (effect of delay) as measured after the impact portion of the test method; the retention percentages shown, account for all dislodged chips (i.e., both the invert and impact portions of the test).

Figure 18 shows the slower setting characteristics of CMS-2 samples after 10 minutes of set and increased retention of fully set (24 hours) CMS-2 samples, possibly due to better coating action.



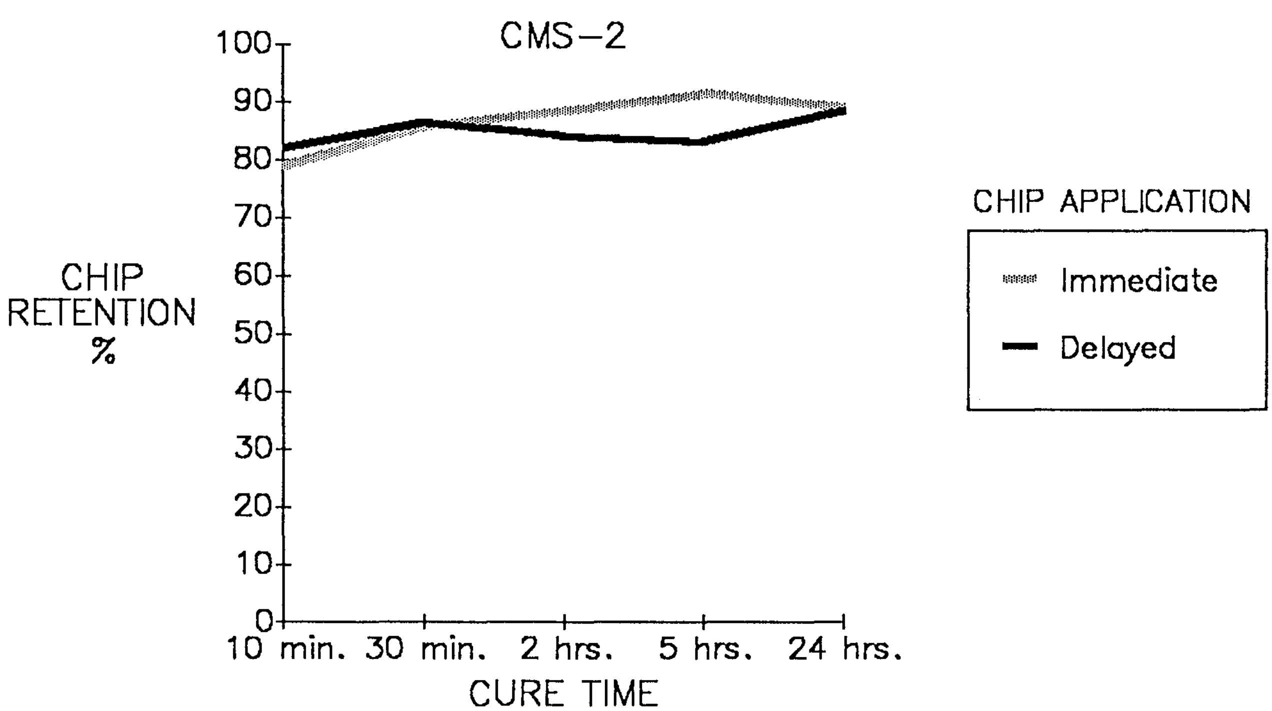


Figure 16. Effect of cure time and chip application timing; Washington Vialit (invert) test results.

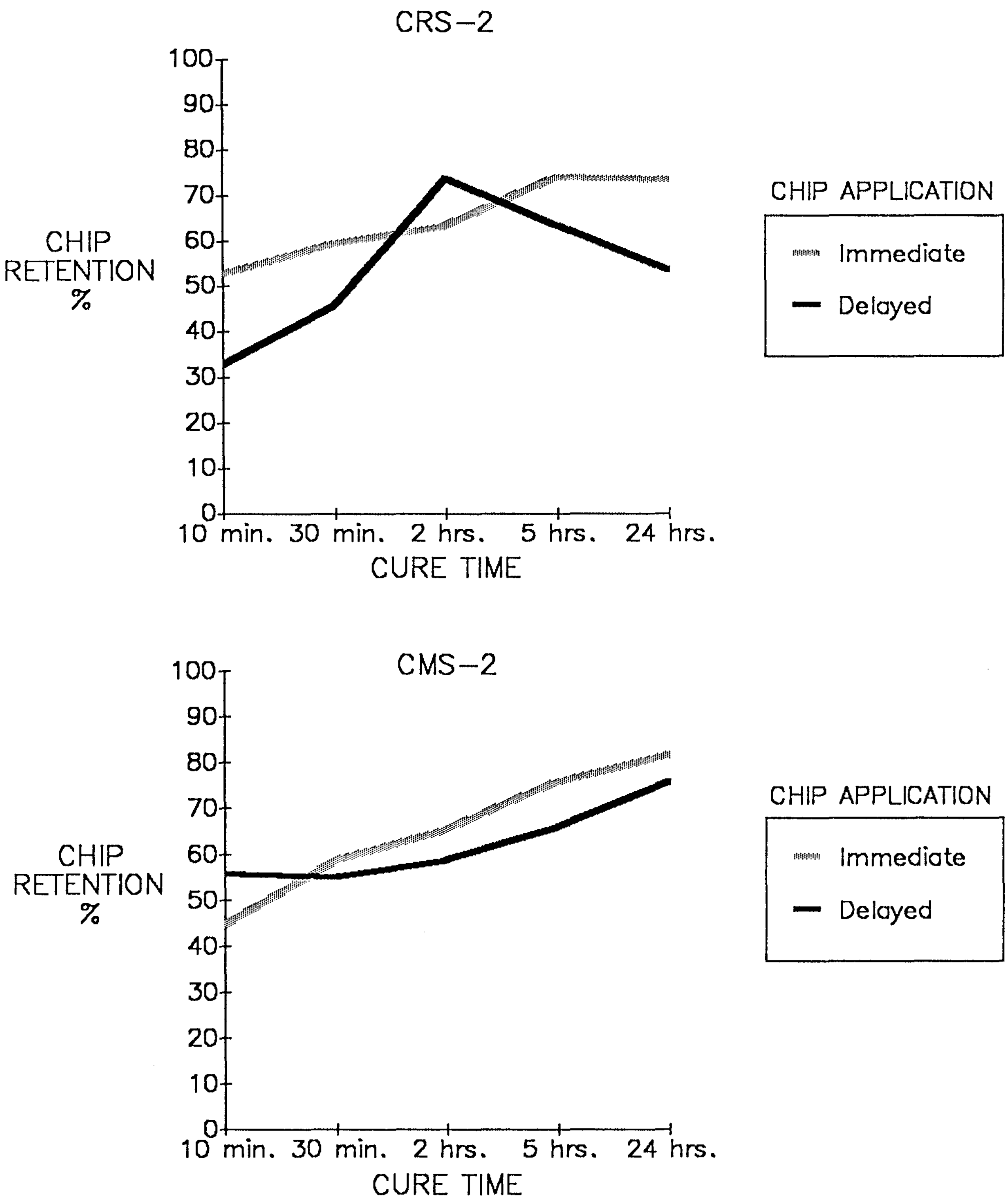


Figure 17. Effect of cure time and chip application timing; Washington Vialit test results.

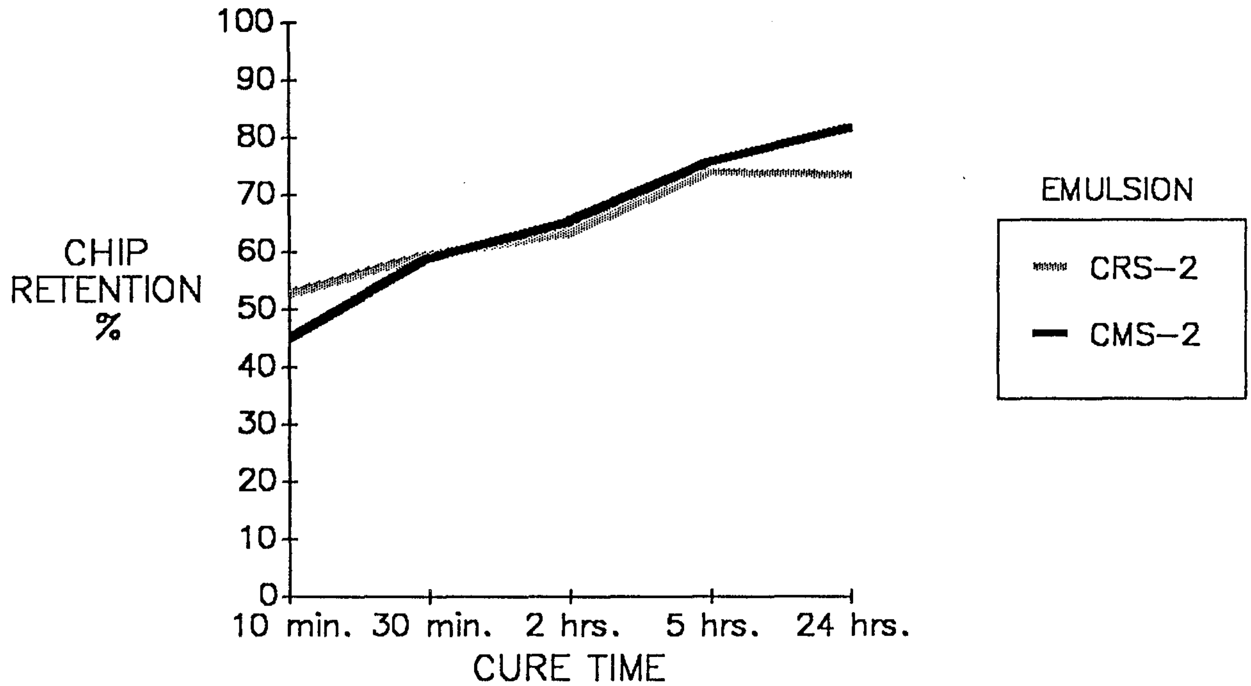


Figure 18. Washington Vialit test results, CRS-2 vs CMS-2.

Figure 19 presents cold temperature response of the base asphalt binder used in the CRS-2 and CMS-2 emulsions as measured by the modified Vialit test. The results indicate brittle failure occurring at temperatures around 30 ^{o}F.

d. Postconstruction

Postconstruction evaluations of the chip seal sections were performed at various time periods after construction. This information is recorded in appendix C of volume II. Performance characteristics from each time period are given below:

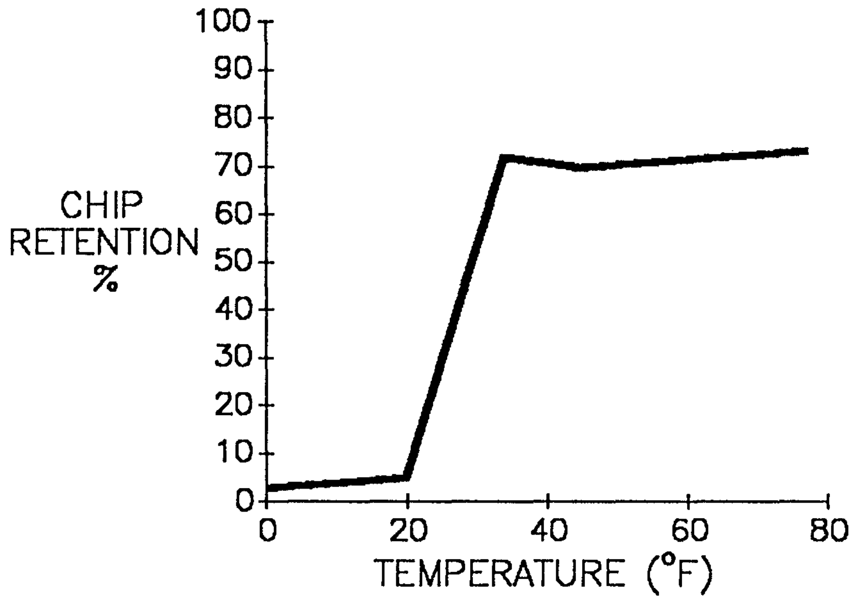


Figure 19. Effect of cold temperature.

(1) One Day After Construction

- Overall condition: 8 = good.
- Aggregate embedment was estimated at 30 to 40 percent.
- High chip seal tenacity was observed during cool morning temperatures.
- Aggregate chips in wheel paths (rutted areas) exhibited higher embedment depths than stones in between wheel paths. The embedment difference was likely due to chips in the wheel paths being subjected to more traffic, thus effectively orienting them to their least dimension; and/or, higher effective asphalt coverage in rutted areas caused by flow of the emulsion after spraying.

(2) Four Months After Construction

- Overall condition: 7.5 = good.
- Original pavement distress and the rehabilitative patch were not showing through chip seal.

- Raveling observed near centerline of roadway, along longitudinal construction meetline.

- Small spot (approx. 18-in diameter) exhibiting severe bleeding as a result of oil leakage from truck observed during construction.

- Aggregate embedment depth = 45 to 70 percent; higher embedment in the inner wheel paths of southbound lane.

- Chip seal had been plowed for snow removal at least once without chip loss.

(3) <u>One Year After Construction</u>

- Overall condition: 6.5 = fair.

- Aggregate embedment depth = 50 to 80 percent; higher embedment in the inner wheelpath of southbound lane.

- Inner wheelpath of southbound lane was flushed due to higher traffic loads and previous rutted, flushed condition.

- Chip loss, although spotty, began to show along the portion of the test section that was shaded during construction.

- No evidence of performance problems associated with portion of section that experienced delayed aggregate application during construction.

e. Findings

The data presented herein suggests the following conclusions:

- Overall, the Washington test sections have performed satisfactorily, although they are subjected to a relatively low volume of traffic.

- Rutting in the wheelpaths and the associated high aggregate embedment/bleeding condition is a repetitious problem. Use of different size spray nozzles located on the spray bar above the rutted wheelpaths, such as practiced in Texas, might mitigate this problem.

- The pre-existing rehabilitative patch in the section did not adversely affect performance.

- The dirty aggregate, which was measured to be slightly out of specification (1.5 percent passing the #200 sieve versus specification of allowable 0 to 1.0 percent), did not appreciably affect chip seal performance.

- The observed delay in aggregate application along a portion of the test section did not detrimentally affect chip seal performance, probably due to the use of the slower setting CMS-2 emulsion along this portion of the project. Had CRS-2 emulsion been used, chip retention problems may have been observed as suggested by the modified Vialit laboratory test results.

- Although some aggregate pick-up was observed as a result of the rollers and aggregate trucks being driven over the fresh chip seal at excessive speeds, these activities did not noticeably affect ultimate chip seal performance.

- After 1 year of service, a portion of the test section which was shaded during construction is beginning to show slightly increased chip loss when compared to other areas. However, the magnitude of this distress is not considered significant at this time.

- Emulsion viscosities were in specification; although they were on the low end, aggregate rollover problems were not observed during construction.

- The residual asphalt penetration was in specification; although it was on the low end, chip loss, due to brittle failure of the binder, was not observed.

- Field material quantities were similar to those calculated by the Asphalt Institute design reference.

- Aggregate spread quantities were somewhat excessive based on field observations and confirmed by the modified Vialit test in the laboratory.

- The modified Vialit test was sensitive to the different setting characteristics of the two emulsions (CRS-2 and CMS-2) used on the project.

- Although temperature records were not maintained during the life of the project, chip loss due to brittle failure of the binder was not observed, nor was it expected based on cold temperature modified Vialit testing, the climatic conditions of the region, and the relatively low traffic levels.

3. <u>Oregon</u>

An experimental chip seal project was constructed in Oregon to study the effectiveness of polymer-modified binder systems. There is a trend toward using polymer-modified asphalt to improve early chip retention, the belief being that these binders may be more "forgiving" over a wide range of conditions.

The project was placed on State Route 22 in Marion County of west central Oregon. This location is classified as a "Wet--Freeze" area. Ten chip seal sections were constructed end-to-end across the full width of the roadway, thus producing both eastbound and westbound test sections. Eight sections were placed with different modified asphalt emulsions, and two sections were placed with an unmodified CRS-2 emulsion to serve as controls. In addition, a CRS-2 calibration section was constructed first to adjust initial design application rates based on field observations. Secondary or alternate test sections of modified emulsions were constructed after the primary sections to purge the remaining emulsion from distributor trucks.

The roadway is a two-lane highway with a structural cross-section of 5 in of asphalt concrete (of which the top 1.5 in is an open graded overlay) above 10 to 17 in of aggregate base. The highway endures an ADT per lane of 12,100 (1988) of which approximately 8 percent is heavy timber trucks.

An extensive report documenting the investigation is forthcoming from the Oregon Department of Transportation (ODOT).[47]

a. Preconstruction

Preconstruction evaluations of each emulsion field section are included in appendix C. Important observations are summarized below:

- The westbound lane (subject to heavy truck loading) exhibited alternating areas of low to medium severity alligator cracking in the wheel paths.
- The more lightly loaded eastbound lane showed alternating areas of low severity alligator cracking.
- Slight raveling was observed in the wheel paths of both lanes and the overall surface texture was rated as coarse.

- Low severity rutting associated with the alligator cracking was noted in some sections.

- Other forms of pavement distress such as bleeding, transverse cracking, patching, etc. were nonexistent or considered to be insignificant.

- CRS-2(P1) and CRS-2K emulsion sections were to be placed on grades of 2 to 4 percent.

b. Construction

The following remarks were derived from observations made by both the authors and ODOT personnel:

- Adjustments were made to initial application rates for each emulsion to compensate for original pavement conditions and other factors. Most of the changes occurred in the eastbound lanes so that subsequent application rates in the westbound lanes (containing the evaluation sections) were more uniform. Nevertheless, there were large variations in application rates as shown in table 20.

  The aggregate application rate was in excess of that normally recommended by design, primarily due to a change in the design rate based on field observation (final target rate was 30 lb/yd^2). In spite of the final target application rate, large disparities in aggregate quantity were measured (see table 20).

  Actual field quantities in table 20 were measured in the field with aggregate collection pans and emulsion collection cloths, and were also calculated from weight differences of emulsion distributor trucks.

- CRS-2R eastbound lane test section experienced delays of aggregate application during which the exposed emulsion broke. Chips were still spread and rolled over the broken emulsion.

- Streaking was observed on HFE-100S test sections. This nonuniform binder application was attributed to the viscous nature of the emulsion rather than clogged spray nozzles.

- Steel-wheeled rollers were used to roll the chip seals instead of pneumatic tired rollers. Most observers felt that the rolling process and equipment were not effective in orienting chips to their least dimension.

Table 20. Oregon chip seal project field application data.

EMULSION PRODUCT	APPLICATION TEMPERATURE (°F)	FIELD QUANTITIES: EMULSION APPLICATION (gallon/square yard) BY CLOTH	FIELD QUANTITIES: EMULSION APPLICATION (gallon/square yard) BY TRUCK WT.	FIELD QUANTITIES: CHIP APPLICATION (lbs/sq yd)
CRS-2, East End, EB	130	0.382	0.354	20.7
CRS-2, East End, WB	130		0.477	
Polysar, EB	140	0.441	0.396	26.7
Polysar, WB	140		0.436	
Polysar, ALTERNATE	140		0.409	
CRS-2R, EB	165	0.435	0.396	31.0
CRS-2R, WB	165		0.587	
CRS-2R, ALTERNATE	165		0.378	
HFE-100S, EB	170	0.416	0.402	31.7
HFE-100S, WB	170		0.462	
HFE-100S, ALTERNATE	170		0.424	23.7
HFE-90, EB	175	0.472	0.456	23.9
HFE-90, WB	175		0.422	23.9
HFE-90, ALTERNATE	175		0.487	
Ductilad, EB	133		0.236	21.0
Ductilad, WB	133		0.506	33.7
Ductilad, ALTERNATE	133	0.273	0.502	38.7
Neoprene, EB	132	0.467	0.503	27.9
Neoprene, WB	132		0.469	38.5
Neoprene, ALTERNATE	132		0.485	31.6
CRS-2(P1), EB	140	0.406	0.443	36.2
CRS-2(P1), WB	140		0.430	34.9
CRS-2(P1), ALTERNATE	140		0.469	35.2
CRS-2K, EB	136	0.497	0.518	33.2
CRS-2K, WB	136		0.559	36.6
CRS-2K, ALTERNATE	136		0.475	32.4
CRS-2, West End, EB	130		0.361	
CRS-2, West End, WB	130	0.454	0.409	27.3

- An inexperienced distributor operator applied the Ductilad emulsion and encountered several problems during the initial test section application.

- A heavy shot (0.57 gal/yd^2) of CRS-2K emulsion was necessary due to the material's low viscosity. The CRS-2K sections were also constructed with unscreened aggregate (i.e., chip and choke stones combined together in first aggregate spread) due to depletion of the original job stockpile.

- Test sections were opened to traffic after different elapsed time intervals since test sections were constructed in series but traffic control was lifted at one particular time for the whole project.

- Remedial choking and sweeping operations were performed on several sections due to chip loss. These activities were continued as necessary for up to 24 hours after original construction; they were largely ineffective.

c. Laboratory and Field Testing

(1) Individual Material Properties. Tables 21 and 22 present binder and aggregate properties, respectively. The aggregate material represented by the grading in table 22 was rescreened using material retained on the 1/4-in sieve for chip rock and the material passing the 1/4-in sieve for choke stone.

(2) Design Quantities. Table 23 lists material quantities initially proposed for test sections and those calculated by the Asphalt Institute and Texas methods. The initial CRS-2 control emulsion application rate (0.44 gal/yd^2) and aggregate spread quantity (17.2 lb/yd^2) were determined based on a design method recommended by McLeod.[48] These design quantities were then observed in the field during construction of calibration sections; the aggregate spread rate was subsequently changed to 30 lb/yd^2. Proprietary (polymer-modified) emulsion spray rates were recommended by the suppliers; it is unknown whether the recommended target rates were based on experience or a particular design method.

Table 21. Emulsion and binder laboratory test results as tested by Oregon Department of Transportation.

Test	CRS-2	POLYSAR	CRS-2R	HFE90S	HFE100S	DUCTILAD	NEOPRENE	CRS-2P1	CRS-2K
EMULSION									
Viscosity, sec @ 122 °F (D244)	271	85	16	43	101	135	144	98	48
Particle Charge (D244)	pos.	pos.	pos.	neg.	neg.	pos.	pos.	pos.	pos.
Sieve (D244)	0.3	0.35	0.15	2.5	11.4	0.44	0.55	0.25	0.15
Distillation, % (D244)									
oil	0.3	0.4	1.1	1.3	1	0.8	0.4	0.4	0.2
residue	66.8	67.4	60.1	68.3	71.2	69	68.5	71.6	74.8
RESIDUE									
Penetration, dmm @ 77 °F (D5)	146	130	181	112	98	96	89	175	146
Softening Point deg °C (D36)	40	43	43.5	54.5	53.3	46.5	46	43.5	44
Ductility, cm (D113)									
@ 39.2 °F	75+	75+	29	10	29	17.5	29	50+	50+
@ 77 °F	100+	100+	100+	100	100+	100+	100+	100+	100+
Tensile Stress, kg/sq cm @ 800% elongation, 39.2 °F, 50 cm/min	3.8	8.8	8.8	15.7	8.8	8.8	19.6	7.9	7.2
Torsional Recovery, %	3.6	10.9	0	5.4	27.8	7.3	18.2	6.4	20
Toughness, in-lb	10	42	15	17	23	41	57	11	46
Tenacity, in-lb	1	29	6	2	9	18	31	4	34

Table 22. Aggregate properties as tested by the Oregon Department of Transportation. (ASTM test designation given in parentheses.)

PROPERTY	ASTM METHOD	TEST RESULT	
Loose Unit Weight	C29	91 lb/ft^3	
Cleanness Value	N/A	89	
Average Least Dimension	N/A	0.24 in	
Flakiness Index	N/A	11.4	
Specific Gravity	C127	2.66 Bulk	
		2.80 Apparent	
Absorption Capacity	C127	1.87	
Sieve Analysis	C117 C136	Size	% Pass
		1/2 in	100
		3/8 in	95
		1/4 in	8
		#4	2
		#10	2
		#40	1
		#200	1
Abrasion Loss	C131	14.2%	
Elongated Pieces	D693	1.4%	

Table 23. Design quantities of materials from Oregon chip seal project.

	QUANTITY (gal/yd²)		
Emulsion	Initial Project Target	Asphalt Institute	Texas
CRS-2	0.44	0.38	0.35
Polysar	0.44	0.38	0.35
CRS-2R	0.44	0.43	0.37
HFE-90	0.45	0.38	0.35
HFE-100S	N/A	0.36	0.34
Ductilad	N/A	0.37	0.34
Neoprene	0.45	0.37	0.35
CRS-2(P1)	0.45	0.36	0.34
CRS-2K	0.47	0.34	0.33

	QUANTITY (lb/yd²)		
Emulsion	Initial Project Target	Asphalt Institute	Texas
Aggregate	17.2	26	19

(3) Chip Seal Properties by Vialit Testing. Several versions of the Vialit test method were used to measure chip seal properties.[39,47,49]

ODOT used a Vialit test procedure in the laboratory which closely resembled the original method.[42, 47] The results are shown in table 24.

A modified Vialit test method was used to evaluate chip retention of the various binder systems.[39] Basically, samples were prepared in the laboratory closely simulating field conditions. Table 25 lists the material quantities applied in the laboratory. Emulsion rates were

Table 24. Vialit test results by ODOT.

Emulsion	Chip Retention @ 5°C (%)	Chip Retention @ -22°C (%)
CRS-2	32	0
Polysar	100	66
CRS-2R	100	39
HFE-100S	100	51
HFE-90	100	31
Ductilad	92	70
Neoprene	23	1
CRS-2 (P1)	100	99
CRS-2K	100	92

Table 25. Laboratory material application rates for modified Vialit testing.

Emulsion	Application Rate (gal/yd^2)
CRS-2	0.31
Polysar	0.33
CRS-2R	0.36
HFE-100S	0.34
HFE-90	0.37
Ductilad	0.29
Neoprene	0.39
CRS-2 (P1)	0.35
CRS-2K	0.42
Aggregate	19 lb/yd^2

adjusted from those in table 20 to account for substrate differences between the smooth, nonporous steel Vialit sample plate and the rough, porous original pavement surface in the field. The aggregate quantity was determined by covering the sample plate with as many chips as possible, yet maintaining a layer thickness of one stone. The aggregate quantity remained constant for all samples and was not adjusted to reflect field conditions.

Figure 20 summarizes the modified Vialit test results. As shown, the relative chip retention characteristics of each emulsion when tested at 80 ^{o}F and 17 percent relative humidity are given. Performance of the emulsions can be divided into four groups:

- HFE-100S and CRS-2K emulsions set very rapidly with 90 percent or greater chip retention after 30 minutes of cure time.
- Polysar, HFE-90 and CRS-2 (P1) emulsions provided slower setting rates but ultimately reached high levels of retention after 3 hours of cure time.
- The Neoprene, Ductilad and unmodified CRS-2 emulsions, as a group, produced lower chip retention values over all cure times.
- The CRS-2R emulsion exhibited extremely low chip retention for extended cure times; thus it is off the scale and not shown in figure 20.

It is important to note two factors which influence the interpretation of the results in figure 20. First, the relative difference between any two points is only statistically significant at a 95 percent confidence level for cases where the data points are sufficiently separated and/or where the respective standard deviation ranges (+/-1 standard deviation) do not significantly overlap as shown in figure 21. Otherwise, the relative performance between emulsions should be considered nonexistent, regardless of the graphical implications. Second, the results in figure 20 are confounded by the different emulsion application rates that were used on the project. Emulsion application rate affects aggregate embedment depth which is believed to significantly influence aggregate retention. Therefore, the relative chip retention performance of the emulsions shown in figure 20 is a function of both binder type and aggregate embedment depth.

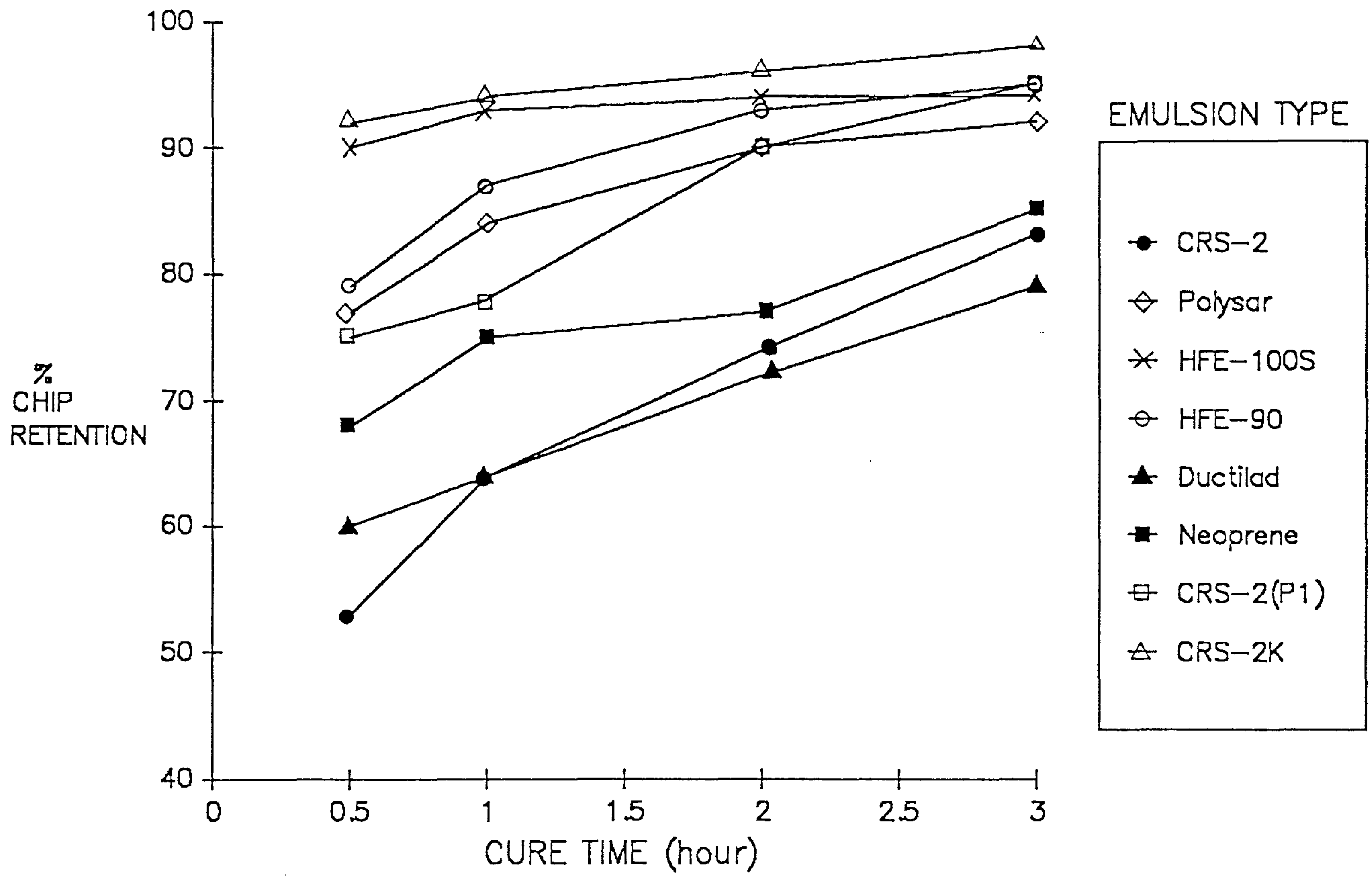


Figure 20. Average Oregon emulsion chip retention vs cure time.

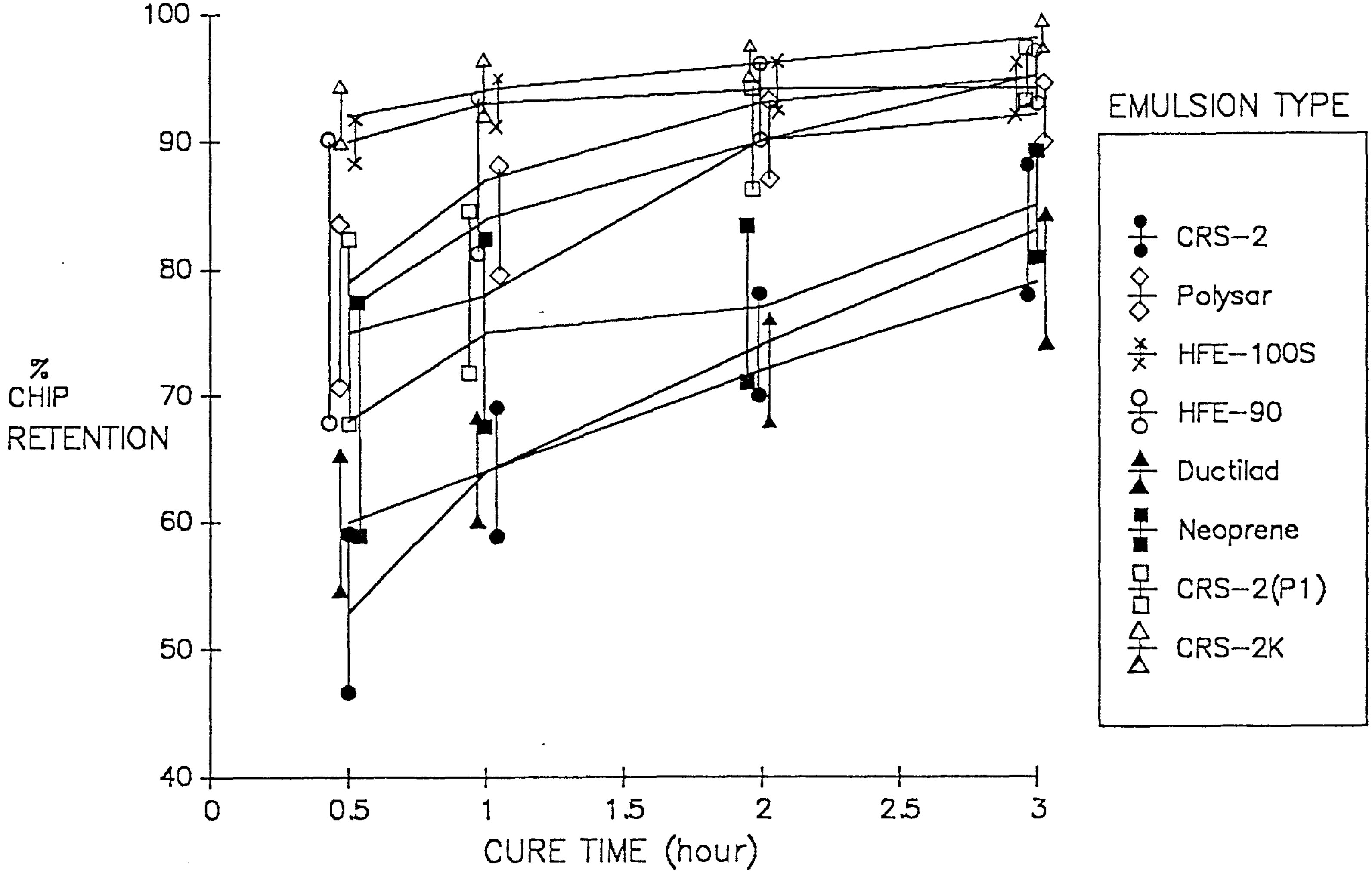


Figure 21. Variance (+/- one standard deviation) of emulsion chip retention.

Modified Vialit testing of chip seal materials both in the laboratory and field, and modified surface abrasion testing in the laboratory were conducted by a consultant to the Oregon project.[49] Data are tabulated in appendix C.

Modified laboratory Vialit test results are presented in figure 22. Sample preparation, testing apparatus, and curing procedures differed from the methods and equipment described in reference 39. Most importantly, the application rate for all emulsions was held constant at 0.40 gal/yd^2. In addition, a 23.8 lb/yd^2 aggregate application rate was used in contrast to the 19 lb/yd^2 rate. The authors feel that 23.8 lb/yd^2 was excessive by approximately 10 percent; therefore, the retention percentages reported in reference 48 were modified accordingly. The results shown in figure 22 incorporate this manipulation of the data.

Figure 22 depicts curing rates of the different binders over roughly the first hour. For clarity, the lines have been plotted as "best fits" through the data points provided in appendix C. Significant trends indicate the following:

- HFE-100S, Ductilad and CRS-2(P1) emulsions have relatively low initial retention values but rapidly increasing chip retention as a result of setting characteristics.
- CRS-2, Neoprene and CRS-2K emulsions provided relatively greater initial chip retention but did not significantly improve over the course of the hour of cure.
- Polysar and HFE-90 emulsions were similar to the first group (CRS-2, Ductilad and CRS-2(P1)), although they started lower and maintained relatively lower retention values throughout the cure period.
- The CRS-2R emulsion produced extremely low results.

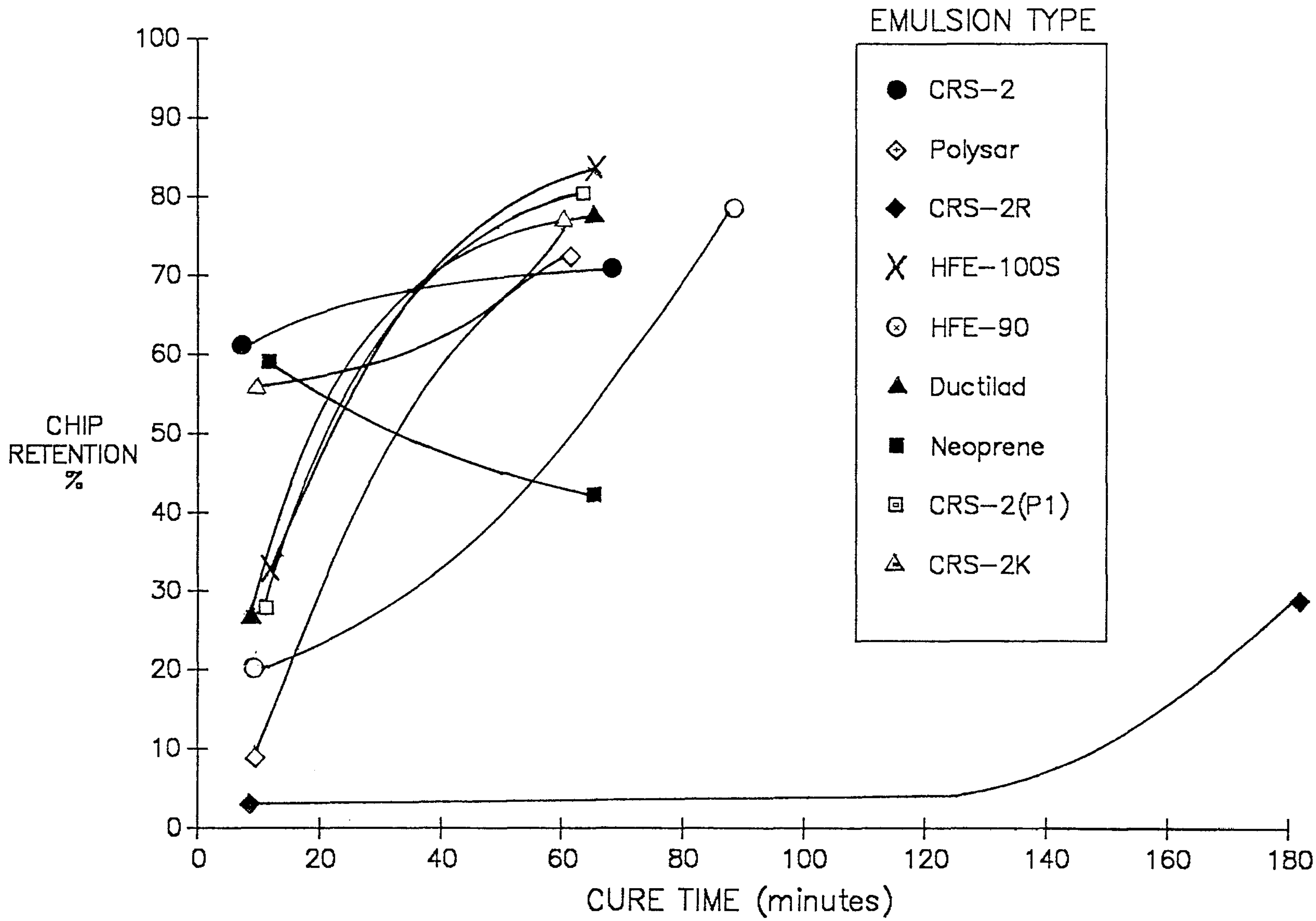


Figure 22. Oregon Vialit (lab) test results.

- In comparison with the other modified Vialit laboratory results (figure 20), only the relatively high rankings of HFE-100S and low rankings of CRS-2R (which is not shown in figure 20 due to its low value) correlated.

Vialit samples tested in the field were subject to exactly the same preparation and curing conditions present during construction of the experimental test sections. The test results are contained in appendix C and shown in figure 23. Once again, the results depicted in figure 23 have been recalculated to account for excessive aggregate application rates utilized in the field.

Figure 23 illustrates the following results:

- The CRS-2 emulsion started out with a very low chip retention value but gained strength quickly.
- Both high-float emulsions (HFE-90 and HFE-100S) were shown to decrease in strength after 1.5 hours of curing.
- The CRS-2 (P1) emulsion produced lower retention values overall, especially at early cure intervals.
- Again, the CRS-2R emulsion provided substantially lower retention values and was slow to set.
- In comparison with the laboratory Vialit studies (figures 21 and 22), the poor performance of CRS-2R was confirmed. In terms of ranking, relative similarities were shown for CRS-2K (figure 23 vs. figure 21) and, for CRS-2, Polysar, HFE-90 and Ductilad (figure 23 vs figure 22).

Finally, additional lab testing was conducted on the chip seal materials with a "Modified Surface Abrasion Test." See reference 49 for details with respect to sample preparation, sample conditioning, test equipment, and testing procedures. The test uses continuous impact by small steel balls to simulate the action of traffic and its detrimental effect on the durability of a fully cured seal coat. Binder fatigue seems to be the failure mechanism by which chip loss occurs in this test. Modified surface abrasion test results are given in appendix C and depicted herein by figures 24 through 27.

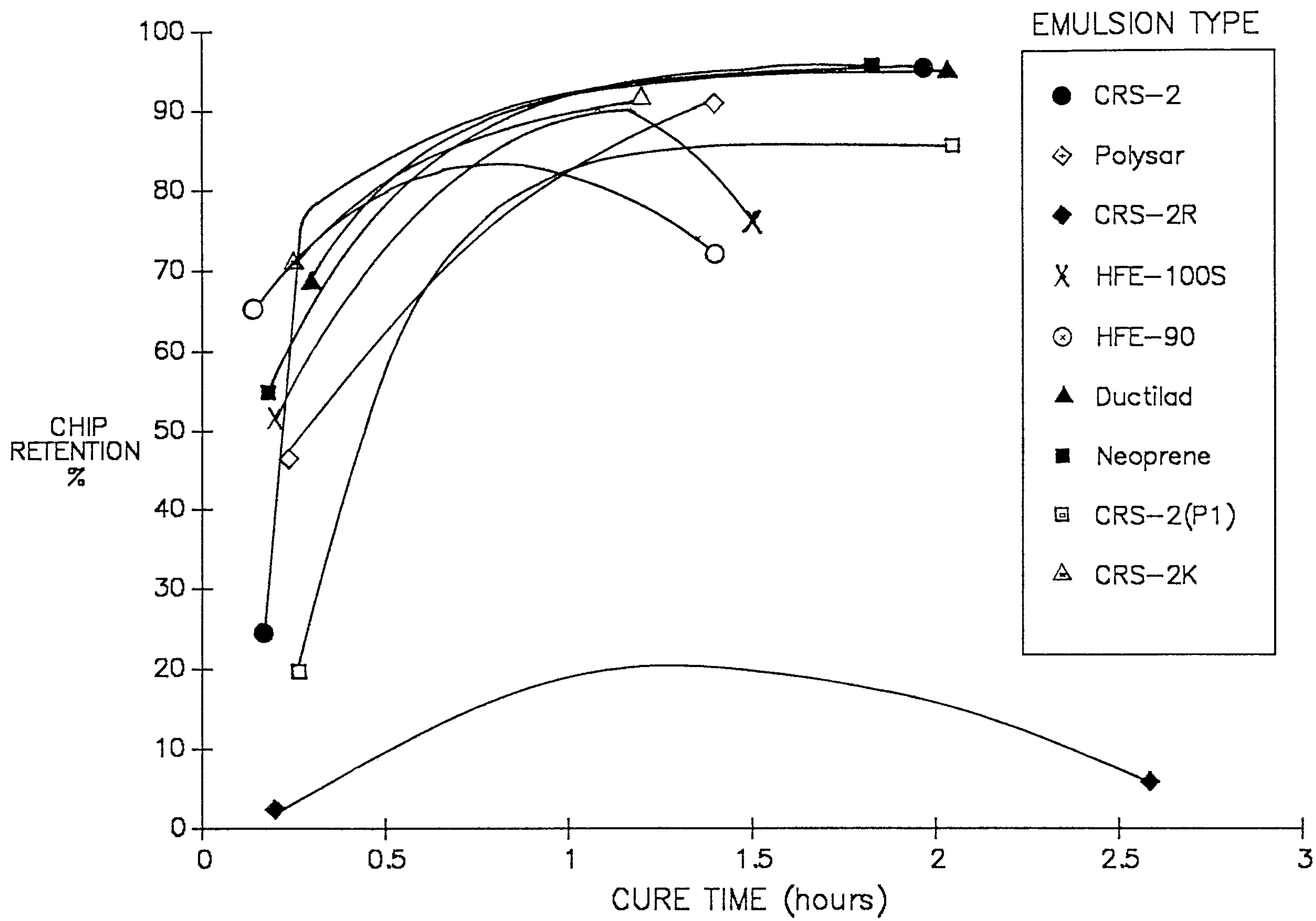


Figure 23. Oregon Vialit (field) test results.

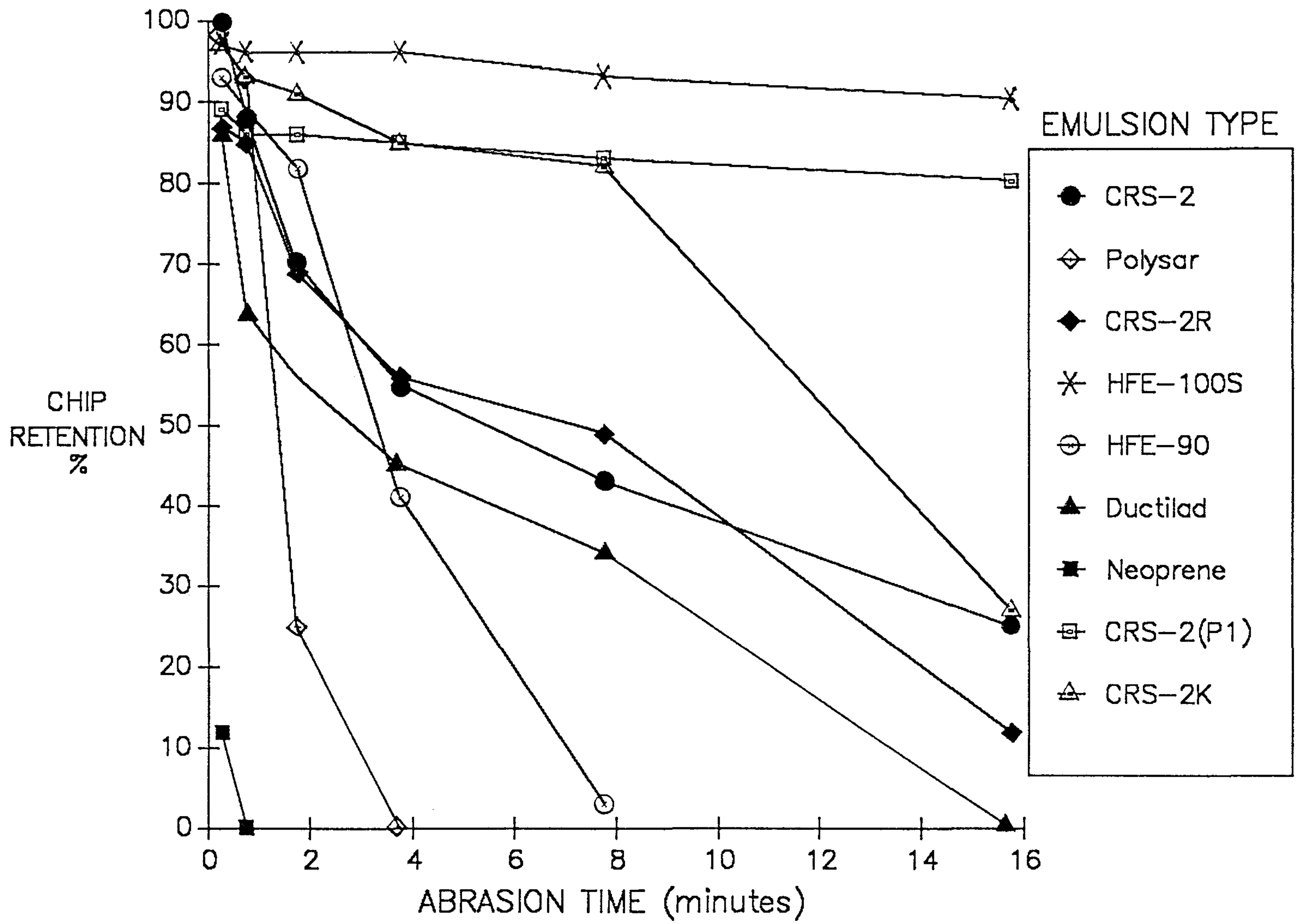


Figure 24. Chip retention durability--abrasion test.

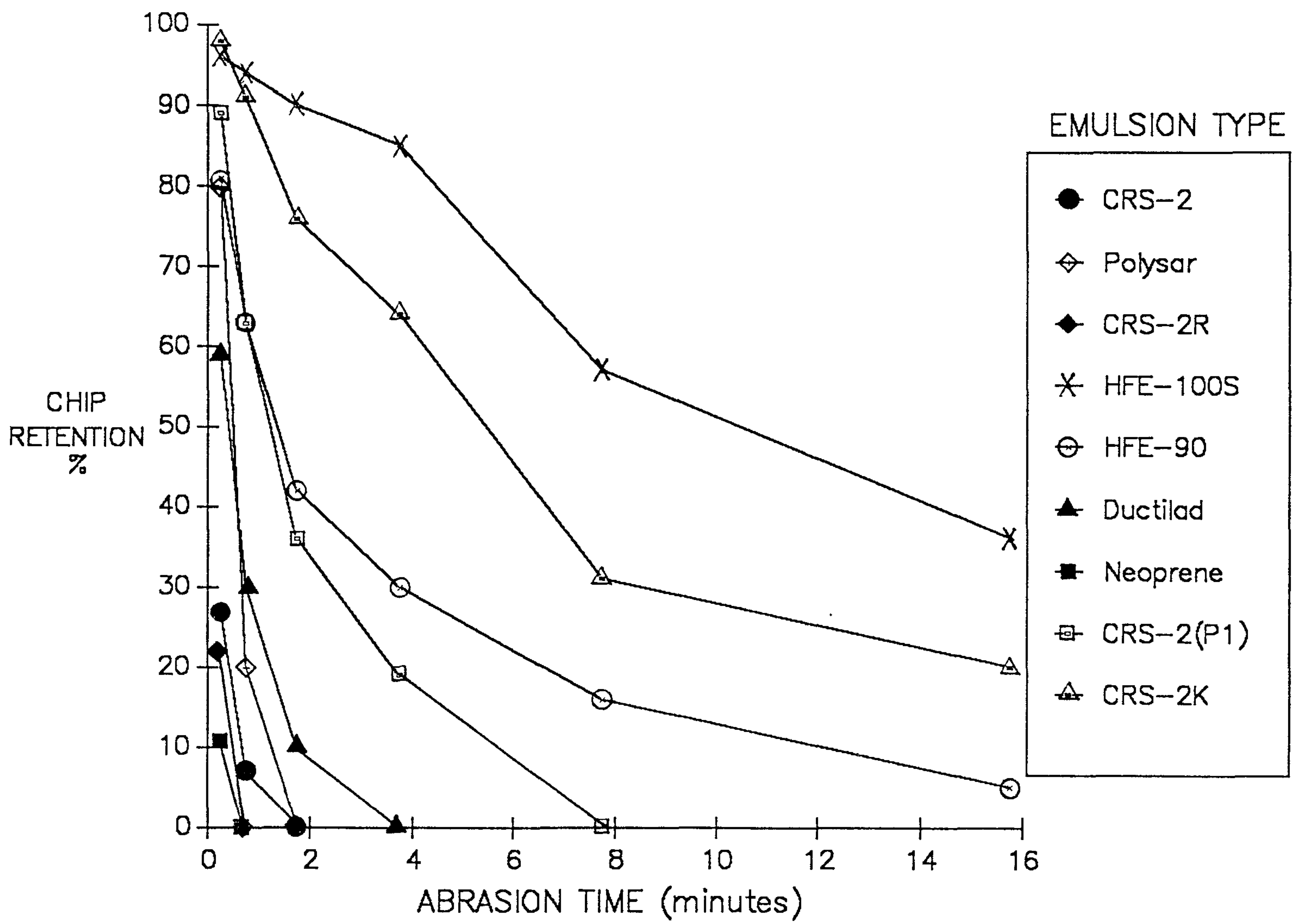


Figure 25. Effect of moisture on durability--abrasion test.

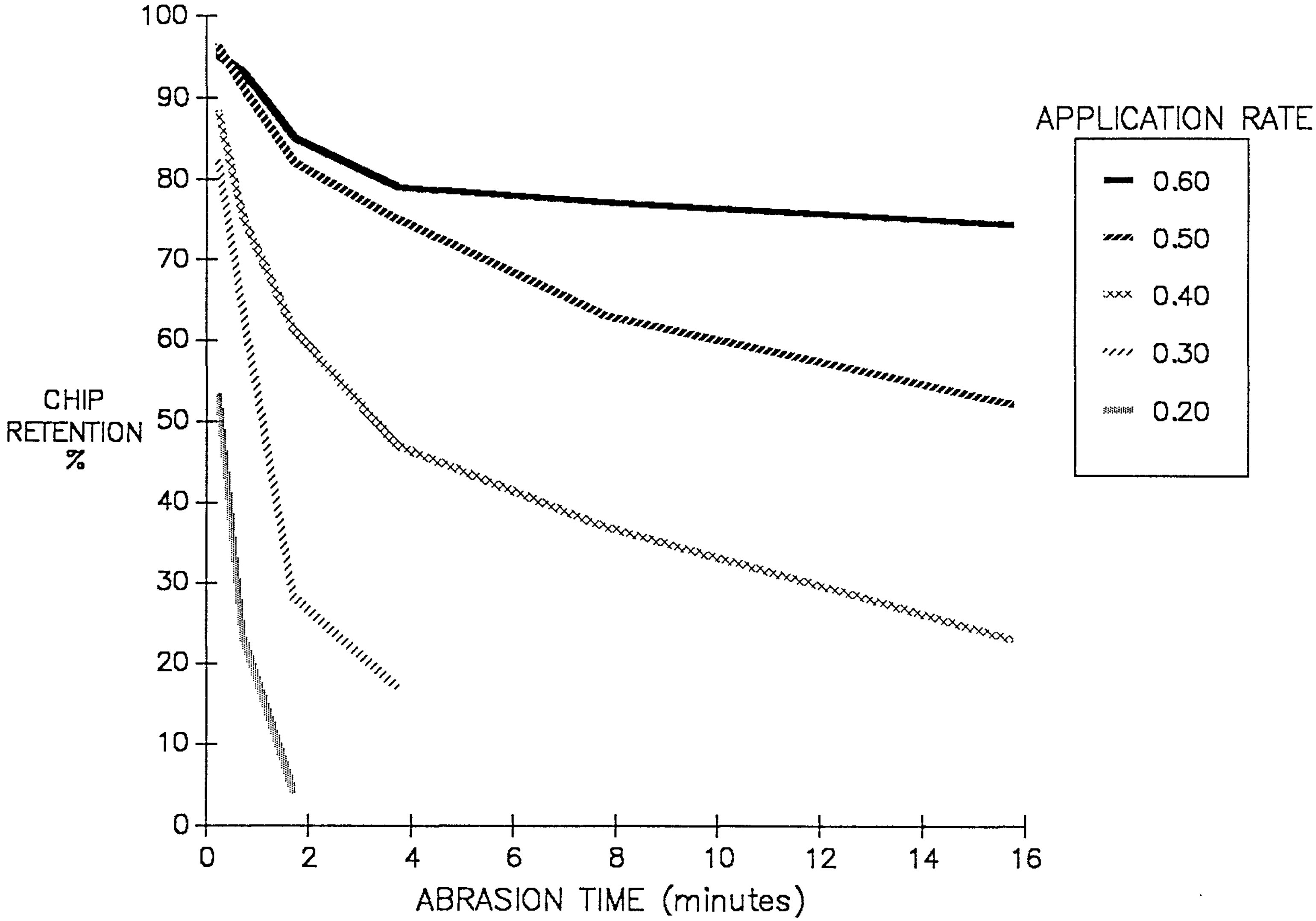


Figure 26. Effect of emulsion application rate (gal/yd^2) on durability--abrasion test.

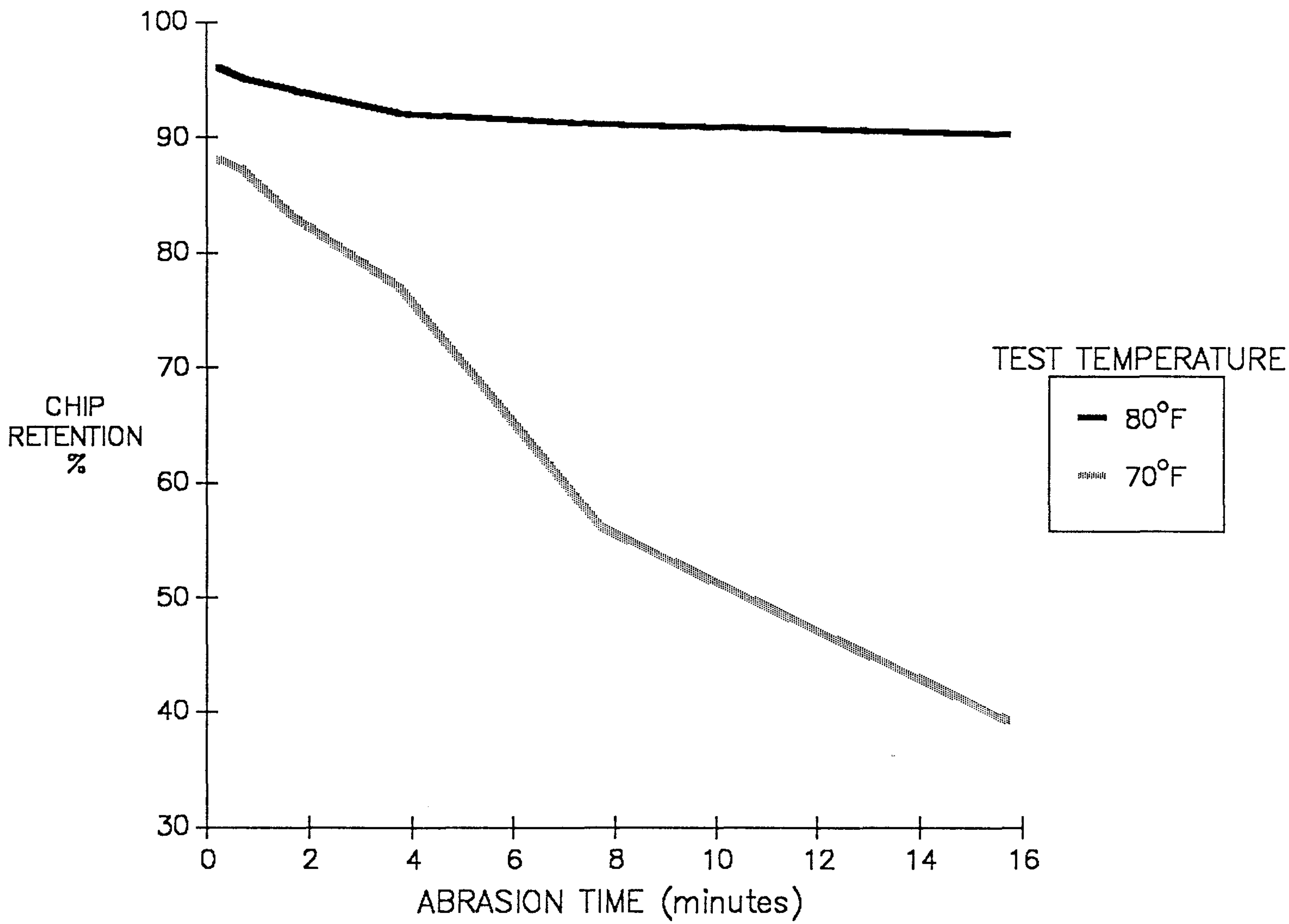


Figure 27. Effect of test temperature on durability--abrasion test.

The test method measured chip retention durability of the binder systems as well as the effects of moisture, emulsion application rate (aggregate embedment depth) and temperature. Figure 24 depicts chip retention durability of the various binder systems. Relatively, the HFE-100S, CRS-2 (P1) and CRS-2K emulsions performed well while CRS-2 and Neoprene emulsions performed poorly. Figure 25 illustrates the effect of moisture on chip retention durability. Here again, the HFE-100S and CRS-2K emulsions performed well while the CRS-2 and Neoprene emulsions performed poorly. Figure 26 shows the effect of binder application rate on chip retention durability. The results confirm expectations both from chip seal theory and the "binder fatigue failure mechanism" associated with this test; increased binder application rate causes greater embedment depth which both increase chip retention. Figure 27 displays the effects of temperature on chip retention durability. The higher temperature gave increased durability, perhaps by improving binder flexibility.

d. Postconstruction

Visual inspections of the project were conducted at various time intervals following construction by the authors, the consultant, and ODOT.

(1) Postconstruction evaluations were performed by the authors and the resulting condition scores based on aggregate loss are given in table 26. Evaluation notes for the 2-month and 2-year intervals are provided in appendix C.

(2) Evaluations were made by the consultant based on relative chip retention. The following rating format was used: 5 = excellent or best, 3 = fair or intermediate, 1 = unsatisfactory or worst. Relative chip retention performance after 1 month of service is listed in table 27.

Table 26. Condition rating of test sections by the authors.

Emulsion Section	Condition Score Time After Construction 1 Day	2 Months	2 Years
CRS-2 East	1.5=poor	N/A	1.5=poor
Polysar	3=poor/fair	4=fair	2.5=poor
CRS-2R	2=poor	3=poor/fair	3.5=fair
HFE-100S	6=fair	5.5=fair	6=fair
HFE-90	1=poor	2.5=poor	2=poor
Ductilad	6=fair	7=good	7=good
Neoprene	7=fair/good	7=fair/good	5.5=fair
CRS-2(P1)	8=good	7.5=good	8.5=good
CRS-2K	8=good	7.5=good	7.5=good
CRS-2 West		3.5=fair	1=poor

Table 27. Relative chip retention performance.[49]

Emulsion Section	1-Month Chip Retention Rating
CRS-2	1
CRS-2 (calibration section)	5
Polysar	1
CRS-2R	3
HFE-100S	5
HFE-90	1
Ductilad	3
Neoprene	5
CRS-2(P1)	5
CRS-2K	5

(3) ODOT personnel made performance evaluations after 1 1/2 and 2 years of test section service based on: excessive surface asphalt, aggregate embedment, resistance to raveling, and crack sealing ability. The rating criteria given in table 28 were used. It was not apparent whether the surface asphalt ratings were a function of excessive emulsion

quantities (i.e., bleeding) or the result of chip loss, or both. Table 29 summarizes the results of the performance evaluations after 1 1/2 years. In addition, an overall rating was averaged from the individual ratings. Table 30 displays the ratings assessed by ODOT after 2 years of service.

Table 28. ODOT chip seal performance rating criteria.

Numerical Score	Rating	Surface Asphalt %	Aggregate Embedment %	Resistance to Raveling	Crack Sealing
5	Excellent	0-10	50-60	*	**
4	Good	11-30	61-70	*	**
3	Fair	31-60	71-80	*	**
2	Poor	61-90	81-90	*	**
1	Unsatisfactory	91-100	91-100	*	**

Note: Percentages of excess surface asphalt and aggregate embedment are for pavement in the wheel tracks only.

* Subjective assessment of section ability to resist raveling both inside and outside of wheel tracks. Rating based on relative comparison of all sections at the time of inspection.

** Subjective judgments were made of the section ability to effectively seal pre-existing cracks both inside and outside of wheel tracks. Rating based on a relative comparison of all sections at the time of examination.

Table 29. Performance evaluation by ODOT of Oregon chip seal test sections after 1-1/2 years.[47]

Emulsion Section	Initial Chip Retention	Excess Surface Asphalt	Aggregate Embedment	Resistance to Raveling	Crack Sealing	Total/5 (rating)
CRS-2 East	1	3	2	3	2	2.2(poor)
Polysar	3	3	3	2	1	2.4(poor)
CRS-2R	3	3	3	2	3	2.8(fair)
HFE-100S	5	3	2	2	5	3.4(fair)
HFE-90	2	2	2	2	4	2.4(poor)
Ductilad	5	3	4	3	4	3.8(good)
Neoprene	4	3	4	3	4	3.6(good)
CRS-2(P1)	5	5	5	4	5	4.8(excel)
CRS-2K	5	3	2	4	5	3.8(good)
CRS-2 West	1	2	2	2	2	1.8(poor)
CRS-2 Cal.	5	4	3	3.5	3.5	3.8(good)

Table 30. Performance evaluation by ODOT of Oregon chip seal test sections after 2 years.[47]

Emulsion Section	Initial Chip Retention	Excess Surface Asphalt	Aggregate Embedment	Resistance to Raveling	Crack Sealing	Total/5 (rating)
CRS-2 East	1	2	2	2	2	1.8(poor)
Polysar	2	2	2	2	2	2.0(poor)
CRS-2R	3	3	3	3	3	3.0(fair)
HFE-100S	4	3	3	2	2	2.8(fair)
HFE-90	2	3	2	2	2	2.2(poor)
Ductilad	5	4	4	4	5	4.4(good)
Neoprene	4	4	4	3	2	3.4(good)
CRS-2(P1)	5	5	5	3	4	4.4(excel)
CRS-2K	5	3	2	5	5	4.0(good)
CRS-2 West	1	3	2	2	2	2.0(poor)
CRS-2 Cal.	5	4	3	4	4	4.0(good)

e. Findings

The data presented herein suggest the following conclusions:

- High volume traffic characterized the Oregon project.
- Both initially (1 day after construction) and after 2 years of service, half of the test sections had failed while half were performing satisfactorily.
- The primary mode of failure was chip loss followed by bleeding conditions.
- While it is noted that a conscious decision was made to adjust material quantities on each emulsion's initial test section (eastbound lane), material application rates, as well as measurement methods, varied unacceptably throughout the project. In addition, aggregate spread rates were observed to be excessive.
- The effectiveness of steel-wheeled rollers was questionable.
- Remedial choking and sweeping operations did not save failing sections.
- ODOT observed divergent emulsion viscosity values for the same product between data provided by suppliers and test results of materials sampled from the project, the latter being significantly lower.[47]
- ODOT analyzed various data to investigate possible correlations between test section performance versus material properties measured by laboratory and field test methods, material application rates, and construction procedures and conditions. The following conclusions were drawn:[47]
  - All laboratory binder tests correlated poorly to chip seal performance except for percent residue in the emulsion and the ODOT Vialit test which received a fair correlation rating (fair = a correlation coefficient of ±0.5 to ±0.75). Any correlations between binder test results (table 21) and chip seal performance are suspect because only single tests were conducted (i.e., replicate samples were not tested and inherent variations within the materials and testing procedures were not accounted for).
  - All chip seal test results correlated poorly to chip seal field performance with the exception of the consultant's modified surface abrasion test which received fair correlation ratings for 3- and 5-minute test durations under dry conditions. It was not surprising that the modified surface abrasion test correlated

better to field performance since it is intended to measure "durability" (i.e., long-term performance) of chip seal systems; Vialit test methods were intended to predict early (i.e., first few hours and days) performance of chip seals. The poor correlation of Vialit test results was confounded somewhat by the inconsistency between test method cure intervals and elapsed cure time before test sections were opened to traffic. The Vialit tests did screen the poor performance of the CRS-2R emulsion. Possibly, none of the Vialit test methods were severe enough (for project conditions) as evidenced by satisfactory Vialit test results but immediate failure of some field test sections.

- Pavement and air temperatures during construction and the maximum daily temperature produced correlation coefficients of 0.55, 0.75 and 0.78; providing fair, good and good correlations to field performance, respectively. These positively correlated factors indicate higher temperatures lead to better chip seal performance.

- Emulsion application rate was shown to correlate poorly and aggregate spread rate correlated well with test section performance. These correlations do not make sense and are likely confounded with the many other factors influencing performance. Upon further analysis, it was determined that the majority of test sections (5 of 6) which had received choke stone applications prior to traffic impact performed "above average." All "below average" performing test sections received choke stone applications after they were opened to traffic and had already begun to fail.

- While a certain amount of hedging has been incorporated into the preceding findings, the above comments should be considered with caution. The Oregon project was a complex undertaking and several uncontrolled factors combined to affect the ultimate performance of each test section. Unfortunately, it was difficult and may be impossible to determine, with confidence, the relative influence of each parameter.

- The main objective of the Oregon project was to evaluate the effectiveness of polymer-modified binder systems. Unfortunately, numerous factors influencing the Oregon project results obscured conclusions regarding the effectiveness of these modified emulsions. For instance, some modified test sections exhibited good performance whereas the two conventional CRS-2 control sections performed poorly. On the other hand, half of the modified test sections were rated as providing "below average" performance yet the conventional CRS-2 calibration section performed well; although the calibration section was constructed under different conditions, it was subject to the same levels of traffic. These conflicting results suggest the following:

- Modified binder systems should not be viewed as a panacea for unsound chip seal design and construction practices, and adverse project conditions.
- Continued research is required to investigate the benefits offered by modified binder systems with regards to chip seal performance and to determine the circumstances under which they are cost-effective and any associated limitations.

4. Nevada

Experimental chip seal sections were constructed in Nevada to investigate the effects of different types of emulsion, aggregate type and condition (i.e., moisture and precoating), and application rates thereof.

The project was constructed on a two-lane portion of U.S. 50 in Churchill and Lyon Counties of west central Nevada. This area is classified as a "Dry--Freeze" region. Average daily traffic over the length of the project varies between 1290 and 1720 vehicles per day.

UNR documented the results of the investigation.[46]

a. Preconstruction

Preconstruction notes were unavailable.

b. Construction

Standard construction data forms are not available in appendix C. However, notes were taken and the following observations were made during project construction:

- Weather was sunny and hot.
- Chip application occurred 10 to 15 seconds after emulsion spray.

- Rubber tire rollers completed rolling 10 minutes after aggregate application. Steel wheeled rollers were also used.
- Aggregate pick-up by rollers and chip loss from brooming were noted on one section; sweeping operations were delayed for 2 to 3 hours after aggregate application on subsequent sections.
- Sections damaged either during construction or by initial traffic required post treatments of sanding.
- Precoated aggregate sections were especially prone to aggregate pick-up by traffic due to the hot afternoon temperatures.
- Flush seals were used to mitigate chip loss in sections that exhibited low aggregate retention strength.
- Lightweight aggregate produced dusty conditions and crushed under steel rollers.
- High-float emulsion required delay of brooming operations due to slower rate of set.

c. Laboratory Testing

(1) Individual Material Properties. Two asphalt emulsion products were used on the project: a modified CRS-2 emulsion and a high-float anionic emulsion. Physical properties for the binders, as tested by the Nevada Department of Transportation (NDOT), are provided in table 31.

Table 31. Properties of asphalt emulsions from Nevada chip seal project.

Test	ASTM No.	LMCRS-2	HFE-100S
Residual Asphalt by Distillation,%	D244	69	68
Viscosity @ 122 °F, SFS	D244	132.8	92.7
Penetration of Residue @ 77 °F, 100g/5sec., dmm	D5	75	94

Three aggregate sources were used on the project: two different gradations of crushed river gravel from pits in Nevada and a Utah-source lightweight synthetic aggregate produced from expanded clay. One of the Nevada aggregates was blended to a Texas grading specification; thus it is labeled as "TX" in subsequent tables and figures. As an additional study variable, some of the two Nevada aggregates were precoated with 0.75 percent of AR4000 asphalt cement. Aggregate properties are listed in table 32.

(2) Chip Seal Properties by Vialit Testing. Modified Vialit test data are presented in appendix C of volume II. Samples were prepared using the same material quantities applied in the field. They were cured at a temperature of 77 ^{o}F ($\pm 5^{o}F$) and a relative humidity of less than 30 percent.

Table 32. Properties of aggregates from Nevada chip seal project.

Test	ASTM No.	NV	TX	Ute Lite
Bulk specific gravity	C127	2.655	2.552	----
Bulk specific gravity, SSD	C127	2.655	2.602	----
Absorption Capacity, %	C127	1.6	1.9	----
Sieve	C136	Gradation, % Passing		
1/2 in		100	100	98
3/8 in		65	73	79
No. 4		8	3	3
No. 8		1	2	1
No. 16		1	2	1
No. 40		1	2	1
No. 50		1	2	1
No. 100		1	2	1
No. 200		0	1	0

Figures 28 and 30 illustrate the relatively low chip retention provided by the HFE-100S emulsion at initial curing intervals as measured by the invert portion of the Vialit test. Both figures demonstrate the lack of surplus aggregate quantity (see results at the 24-hour cure interval). Figures 29 and 31 depict relatively low retention percentages for both emulsions at 10-minute and 30-minute cure intervals except with the precoated aggregate (NVP). Precoated aggregate chips formed earlier, stronger bonds with the emulsion. Figures 29 and 31 show the rate of set seemed to be dependent on aggregate sources and/or gradation. Unfortunately, the trends are confounded by the different emulsion application rates. Figures 29 and 31 also indicate the effect of emulsion quantity was inconsistent.

d. Postconstruction

Table 33 presents condition ratings of selected Nevada test sections one month following construction. The evaluations were somewhat subjective in nature. The overall rating was based on the overall "look" of each test section.

e. Findings

The data presented herein suggest the following conclusions:

- Precoated aggregate offered increased initial chip retention but exhibited aggregate pick-up problems under hot ambient temperature conditions.
- The modified Vialit test was sensitive to the increased chip retention provided by precoated aggregate during early cure intervals.
- The invert portion of the modified Vialit test exemplified the low chip retention strength provided by the HFE-100S emulsion in the field at early cure intervals.
- The effects of aggregate type, gradation and application rate, and emulsion application rate were confounded with one another; no one factor was shown to consistently and significantly affect the modified Vialit test results or field performance.

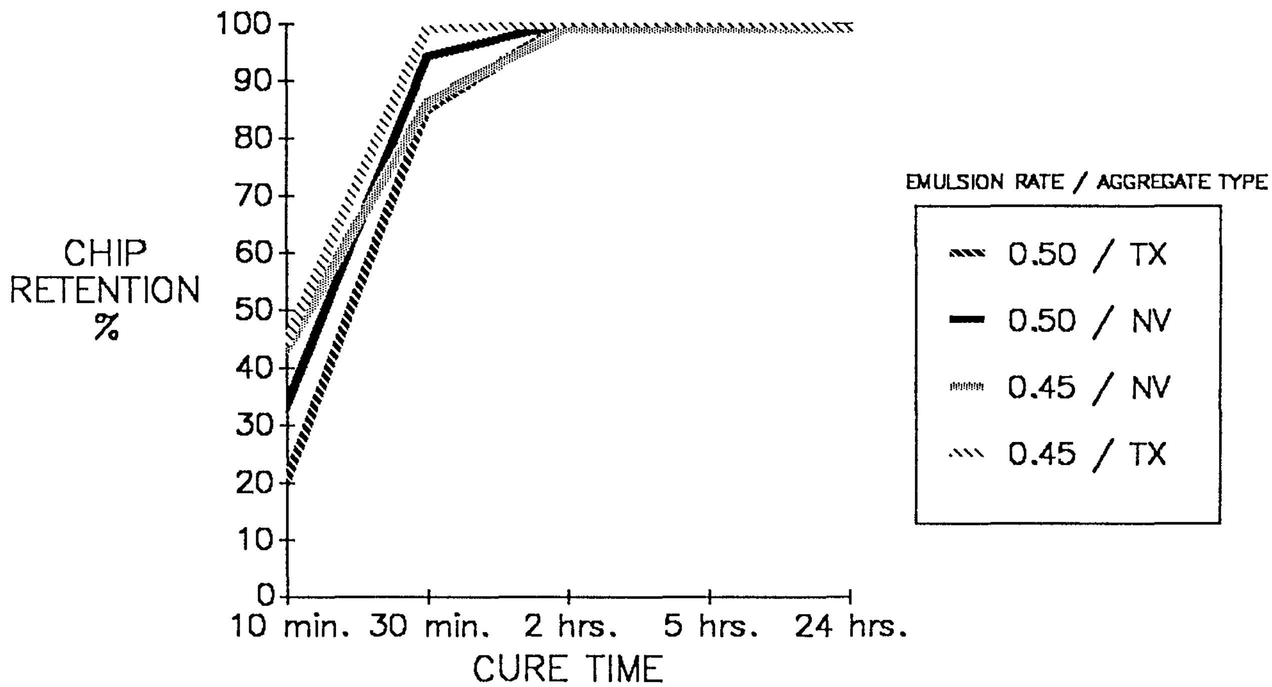


Figure 28. HFE-100S Vialit (invert) test results from Nevada project.

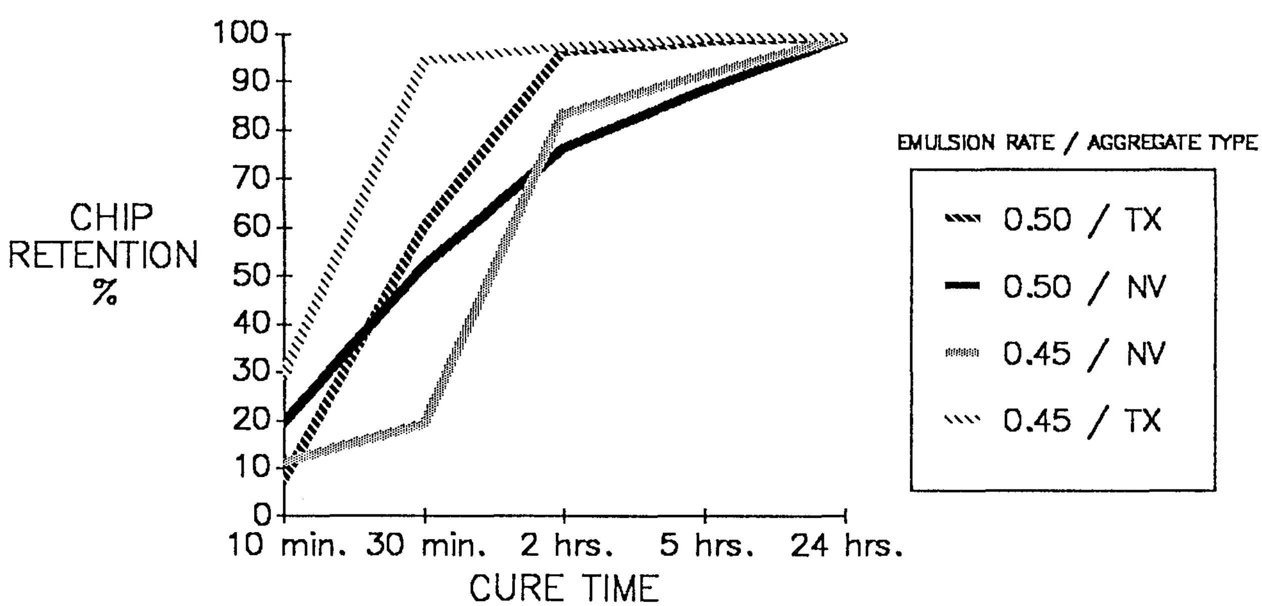


Figure 29. HFE-100S Vialit test results from Nevada project.

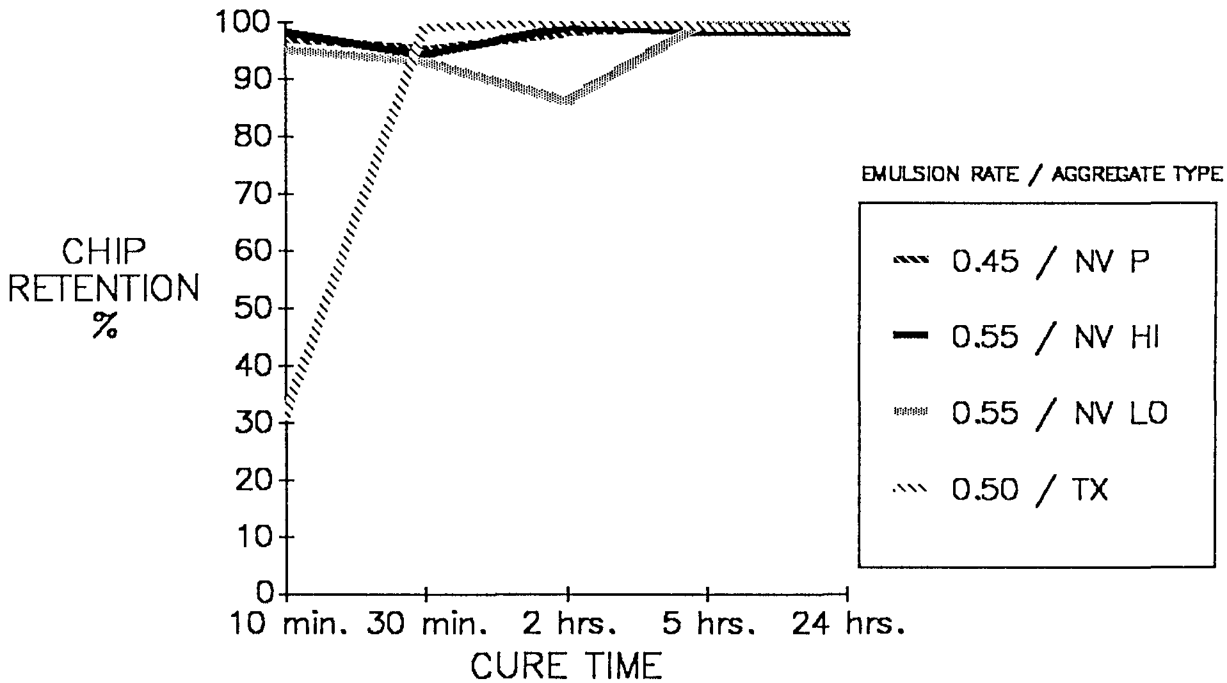


Figure 30. LMCRS Vialit (invert) test results from Nevada project. ("HI" and "LO" in legend refer to relative aggregate application rate.)

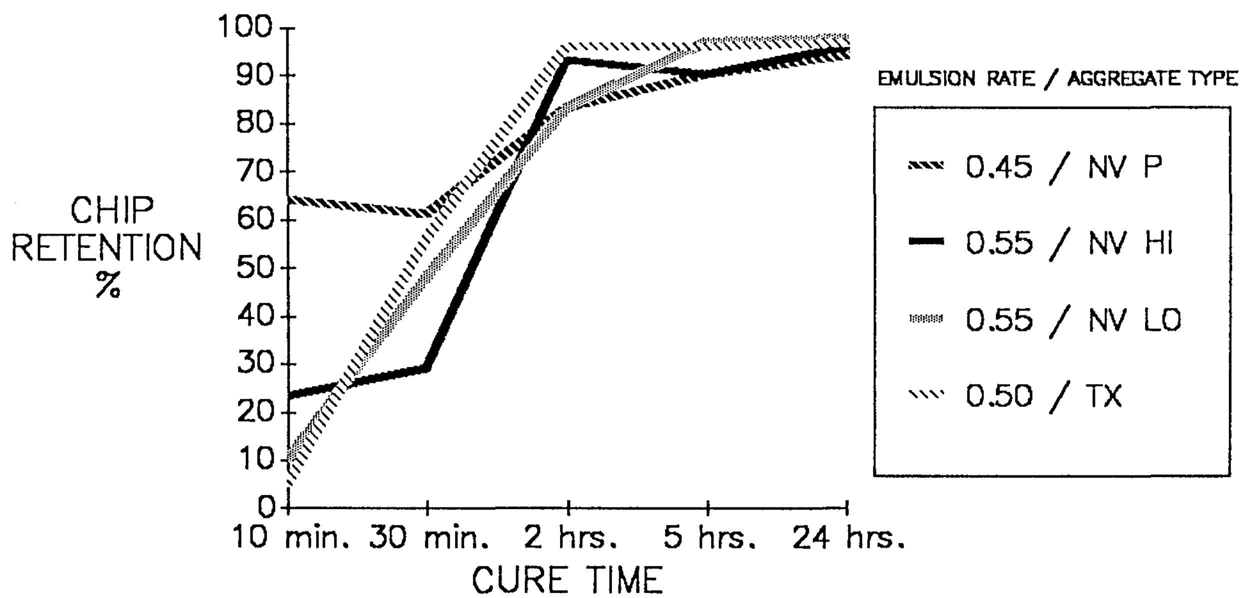


Figure 31. LMCRS Vialit test results from Nevada project. ("HI" and "LO" in legend refer to relative aggregate application rate.)

Table 33. Field evaluation of Nevada chip seal test sections 1 month following construction.

SECTION				WHEELPATHS			
Emulsion	Emulsion Quantity gal/yd^2	Aggregate	Aggregate Quantity lb/yd^2	Overall Rating	Material Retained (%)	Agg. Emb. (%)	Bleeding Rating
LMCRS	0.45	NVP	22	7	100	60	10
LMCRS	0.55	NV	22	5	100	40	10
LMCRS	0.55	NV	16	6	100	40	10
LMCRS	0.50	TX	22	2	100	55	10
HFE-100S	0.40	UT	16	7	100	40	10
HFE-100S	0.50	TX	22	8	100	40	10
HFE-100S	0.50	NV	22	8	100	35	10
HFE-100S	0.45	NV	22	7	100	35	10
HFE-100S	0.45	TX	22	5	100	35	10

- Based on observations made in the field and modified Vialit laboratory test results, the following minimum chip retention values relating to successful chip seal construction were suggested:
  - Pneumatic rolling should not start until a minimum 30 percent retention value is achieved.
  - Early brooming operations should be delayed until a minimum 65 percent retention value is realized.

5. Pennsylvania

A chip seal field study was conducted by the Pennsylvania Department of Transportation (PennDOT) to determine the extent of differences in Saybolt-Furol viscosity at 122 °F measured by emulsion suppliers at their facilities and those measured in the field a few hours after use on the construction site.[(50)]

The study was performed on five different contract chip seal projects located on State routes in York and Lancaster Counties of southeastern Pennsylvania. This location is classified as a "Wet--Freeze" region. Average daily traffic for the studied sections ranged from 209 to 600 per lane.

a. Preconstruction

Preconstruction evaluation forms documenting pavement site characteristics prior to construction are contained in appendix C of volume II. Particular conditions which might be expected to affect chip seal performance were not noted except, possibly, the coarse texture of the original pavement surface on sites 4 and 5.

b. Construction

Construction data for each site is also presented in appendix C. Salient items are summarized below:

Site 1

- Weather: clear, dry, relatively low air temperature (65 to 72 ^{o}F)

Site 2

- Weather: clear, dry, low air temperature (48 to 69 ^{o}F).

Site 3

- Weather: partly cloudy, heavy rain on portion of test site.
- Construction halted due to rain (5 to 8 in over 13 hours) and resumed next day.
- Long delays between delivery of aggregate; inadequate supply of haul trucks.

Site 4

- Weather: partly cloudy, light rain for 10 minutes during construction.
- Aggregate "turnover" observed in heavily shaded areas.

Site 5

- Weather: partly cloudy, dry.

c. Laboratory Testing

(1) Individual Material Properties. Emulsion viscosity was measured at different elapsed time intervals after construction and at different temperatures for each site emulsion. This information is summarized in table 34 while individual test values are included in appendix C. All emulsion viscosities sprayed on the job were substantially less than the values reported by the producer, and, except for site 3, near the low end of the PennDOT viscosity specification.

Aggregate properties from four of the test sites are given in table 35.

Table 34. Average emulsion viscosities of Pennsylvania chip seal test sites. (Time lapse between construction job shot and testing is indicated in parentheses.)

Site	Emulsion Type	Viscosity (SFS) @ 122 °F	Viscosity (SFS) @ 140 °F	Viscosity (SFS) @ 160 °F	Producer Data @ 122 °F	Producer Data @ 77 °F	Residual Asphalt %
1	anionic	130 (3 to 5 hrs)	98 (3 to 5 hrs)	48 (1 day)	251	121	63.5
2	anionic	132 (1 day)	92 (1 day)	43 (2 days)	251	121	63.5
3	cationic	248 (3 hrs to 1 day)	180 (3 hrs to 1 day)	108 (3 hrs to 1 day)	374	130	66.0
4	cationic	137 (4 hrs)	93 (4 hrs)	91 (4 hrs)	379	131	66.0
5	cationic	116 (4 hrs)	86 (4 hrs)	67 (4 hrs)	379	131	66.0

Table 35. Physical properties of aggregates from Pennsylvania chip seal test sites.

Test	ASTM No.	Limestone	Limestone Dolomite	Dolomite Sandstone Mixture	Serpentine
Aggregate Type					
Bulk specific gravity	C127	2.471	2.691	2.425	2.541
Bulk specific gravity, SSD	C127	2.765	2.707	2.444	2.585
Apparent specific gravity	C127	2.808	2.733	2.473	2.658
Absorption capacity, %	C127	1.00	0.60	1.00	1.73
Unit weight, pcf	C29	97.5	93.7	95.4	87.7
Sieve Analysis	C117,136	Cumulative Percent Passing, %			
1/2 in		100	100	100	100
3/8 in		83.8	84.4	86.8	90.2
No. 4		8.0	5.3	11.8	18.2
No. 8		0.9	1.0	1.6	0.7
No. 16		<1.0	<1.0	<1.0	<1.0
No. 30		<1.0	<1.0	<1.0	<1.0
No. 50		<1.0	<1.0	<1.0	<1.0
No. 100		<1.0	<1.0	<1.0	<1.0
No. 200		0.7	0.9	1.0	0.4
Median Size		1/4"	1/4"	1/4"	1/4"
Average Least Dimension (ALD) in.		0.20	0.20	0.20	0.20

(2) Design Quantities. Asphalt emulsion and aggregate quantities were calculated for the materials using the Asphalt Institute and Texas design methods. Actual quantities used on the test sites are listed in table 36. It is unknown whether these field quantities were determined from a design method or based on experience. All quantities are summarized in table 36.

(3) Chip Seal Properties by Vialit Testing. Modified Vialit tests were conducted on Pennsylvania materials to analyze cure rates. Samples were prepared duplicating field material quantities (table 36). Figures 32 and 33 depict modified Vialit test results. Appendix C contains all Pennsylvania modified Vialit test results.

Table 36. Comparison of asphalt emulsion and aggregate quantities: design versus field construction.

	QUANTITY					
	Asphalt Emulsion (gal/yd^2)			Aggregate (lb/yd^2)		
Site	Asphalt Institute	Texas	Field Construction	Asphalt Institute	Texas	Field Construction
1	0.32	0.22	0.30(A) 0.50(B)	19	14	20
2	0.37	0.30	0.35	21	14	20
3	0.34	0.25	0.33	19	14	21
4	0.40	0.35	0.46	20	13	18
5	--	--	0.43	--	--	19

(A) = Subsite 1-A
(B) = Subsite 1-B

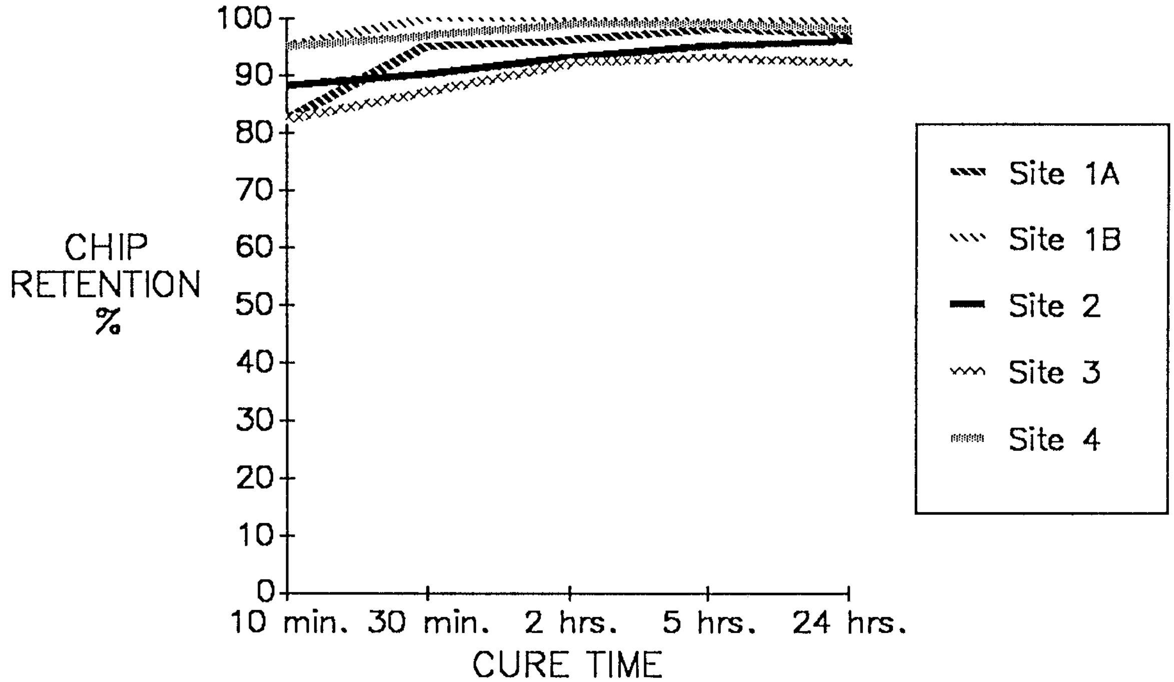


Figure 32. Pennsylvania Vialit (invert) test results.

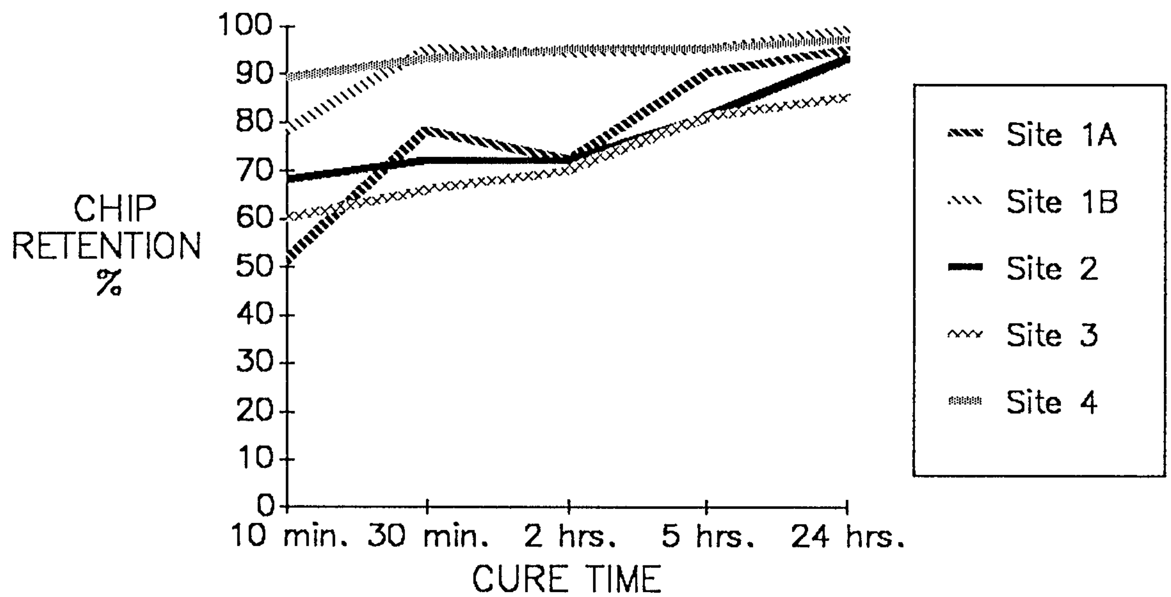


Figure 33. Pennsylvania Vialit test results.

Figure 32 indicates surplus aggregate quantities of 5 to 10 percent corresponding to normally accepted design practice. Samples simulating sites 1-A and 3 exhibited low retention strength at early cure periods (i.e., 10 minutes) as they lost chips which were coated with binder upon being inverted. Both of these samples were made with the lowest binder application rates. Figure 33 shows the relatively low retention capabilities of site samples 1-A, 2 and 3, through 2 hours of curing. Site sample 1-B was weak initially (after 10 minutes of cure) but recovered quickly (after 30 minutes of cure). Site sample 3 was still experiencing chip loss after 24 hours of time. Site sample 4 was strong throughout the curing process.

Figure 34 displays the cold temperature response of the residual asphalt cement in E-2 and E-3 emulsions when applied at different rates (gal/yd^2) and combined with particular aggregate types. The E-3 binder applied at a higher rate in combination with the site 4 aggregate provided more resistance to brittle failure response. It required a temperature of 20 ^{o}F before succumbing to brittle failure (indicated by the steep slope portion of the response curve); whereas, the E-2 sample experienced brittle failure at 40 ^{o}F.

d. Postconstruction

Postconstruction information concerning each site was recorded on forms which are included in appendix C of volume II. Evaluations are summarized in table 37 which indicates the performance characteristics of each site as a function of age. Sites 1-B, 2 and 4 were not successful chip seal projects. Sites 1-A and 5 were initially good projects but digressed rapidly after 1 year of service. Site 3 exhibited the best performance.

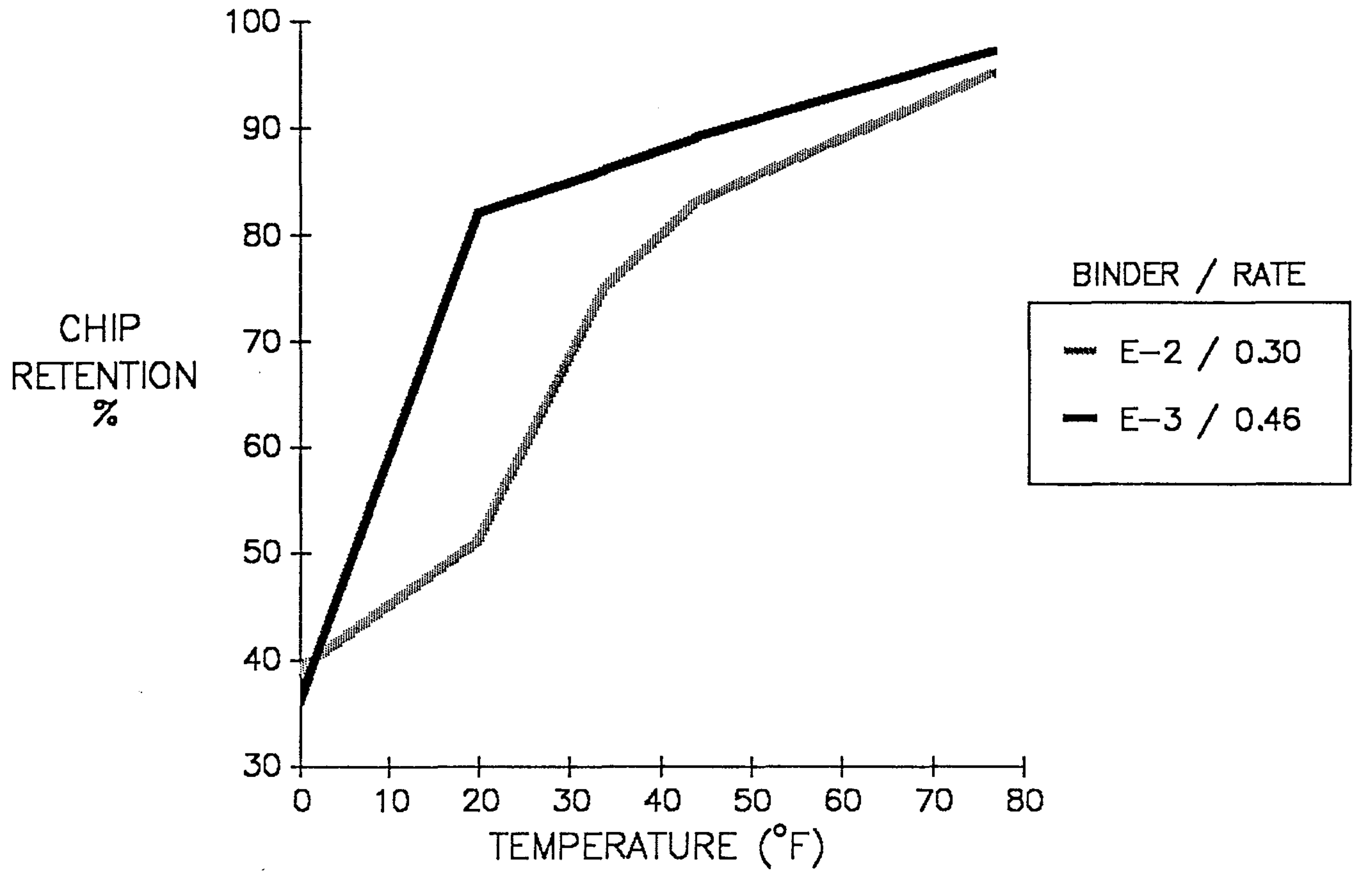


Figure 34. Effect of cold temperatures on Pennsylvania residual asphalts.

Table 37. Condition evaluation of Pennsylvania chip seal sites.

Size	Age (Month)	Overall Rating*	Aggregate Loss**	Bleeding**
1-A	1	9	L	L
	6	9	M	M
	12	7	H	M
	24***	5	M	L
1-B	1	6	H	L
	6	6	H	M
	12	N/A	N/A	N/A
	24	N/A	N/A	N/A
2	1	6	H	H
	6	6	H	H
	12	6	H	H
	24***	5	H	M
3	1	9	L	L
	6	9	M	L
	12	8	M	M
	24***	5	M	L
4	1	7	M	M
	6	7	H	M
	12	7	H	H
	24***	4	M	M,H
5	1	9	L	L
	6	8	M	L
	12	6	H	M
	24***	2	M	H

* 0 to 3 = poor; 3 to 7 = fair; 7 to 10 = good
** L = low = <5%; M = medium = 50 to 25%; H = high = >25%
*** Evaluation performed by different personnel
N/A Site failed and received another seal coat

e. Findings

The data presented herein suggest the following conclusions:

- Sites 1 and 2 were constructed during relatively low air temperatures, yet Site 1 exhibited good early chip seal performance. Site 2, which was constructed at the lowest temperatures, showed a decrease in performance. Sites 3, 4 and 5 were constructed during higher temperatures but did not result in significantly better performance than Site 1. Air temperature did not seem to have a significant impact on chip seal performance.

- Site 4 was the only section constructed during rainfall and it exhibited decreased performance in relation to other sites; Site 3 experienced rain but construction was stopped and then resumed the following day after adverse weather conditions had cleared. Site 2 was subjected to heavy rain 4 days after construction which may have contributed to its decrease in performance.

- The inadequate supply of aggregate haul trucks and the subsequent delay in aggregate delivery to the chip spreader did not adversely affect the performance of site 3.

- All emulsion viscosities sprayed on the projects were substantially less than the values reported by producers, and, except for site 3, near the low end of the PennDOT viscosity specification. However, no clear relationship between aggregate turnover (performance) and low emulsion viscosity could be made.

- Material quantities applied in the field were closer to quantities calculated by the Asphalt Institute design reference as opposed to the Texas reference.

- Although the modified Vialit test seemed to differentiate between early setting characteristics of the different chip seal systems, information relative to elapsed time before sites were opened to traffic was not available. Therefore, the relationship between chip seal setting behavior and field performance was impossible to analyze.

6. Texas

The investigators of this project did not conduct any specific laboratory or field evaluations in Texas; however, several studies have been performed with which project researchers were familiar. Because these studies have not received widespread distribution and they culminated in useful conclusions, it was deemed appropriate to briefly summarize their recommendations. For further information, consult references 4, 51, and 52.

The Texas studies recommended two changes to the modified Kearby chip seal design method currently used by Texas agencies:

- A different curve for determining binder application rate should be used for chip seals incorporating emulsified asphalt versus asphalt cement. Chip seals constructed with emulsified asphalt require approximately 15 percent less residual asphalt than those constructed with asphalt cement to provide the same aggregate embedment depth percentage.

- The current curve should be modified to decrease binder application rates for aggregate which produce an average mat thickness of 0.25 to 0.30 in and to increase binder application rates slightly for aggregates which produce an average mat thickness of about 0.40 in. Field experience has indicated that the existing design curve which was originally modified (increase asphalt) for lightweight synthetic aggregate, overestimates binder quantity for smaller, normal weight aggregate. Field performance also suggests that the present curve underestimates binder quantity for larger coverstone which often results in raveling and the subsequent requirement of a fog seal application.

CHAPTER 5. FINDINGS AND RECOMMENDATIONS

This section presents the significant findings and recommendations resulting from the literature search, brainstorming meeting, interviews of selected agencies, and laboratory and field evaluations. The findings are grouped into:

- General.
- Design.
- Materials.
- Construction.
- Performance measurement.

The recommendations are grouped into:

- Field projects.
- Performance monitoring.
- Design.
- Laboratory and field testing.
- Development of instructional materials.

1. Significant Findings

a. General

Based on this research study, the following appear to be the most significant general findings:

- There are a considerable number of guidelines available for the design and construction of seal coats. Despite their availability, there are still a number of "early" seal coat failures.
- The terminology related to seal coating appears to be more standard than was the case several years ago. However, there still seems to be some variation from agency to agency in some terms.

- Chip seals appear to be less forgiving than other types of construction since material proportioning and combining are done "on the go" and at the mercy of a variety of outside influences (e.g., weather, traffic.) Hence, successful construction is still considered somewhat of an art and the success depends on proper planning and to a large extent on the skill level of contractors, engineers and inspectors.

- In many circles, chip seals are still considered inexpensive and relatively simple to construct. Many times this results in lack of control or necessary supervision and subsequent poor performance.

- Monitoring of chip seal projects is spotty at best and different agencies concentrate on different aspects of the design, testing and construction depending on the needs of the particular situation.

b. Design

Based on this research study, the following appear to be the most significant findings related to design.

- While many design methods exist for determining the proper asphalt and aggregate application rates, the most popular in the U.S. appear to be McLeod's method and variations of Kearby's original method.[9,14] One agency in the survey used a variation of the California Method.[19]

- All design methods agree on the primary basic principles of chip seal design but the different design methods yield different application rates assuming identical material properties.

- Current design procedures lead to a range in spread rates for aggregates and emulsions. The detrimental effects of aggregates which are spread at rates greater than the optimum amount are felt to be the dislodging of other aggregates which are embedded in the binder layer and potential flying rock damage.

- Design methods typically do not discuss factors for selection of the type or grade of asphalt emulsion. Most guidelines for selection are based on previous experience.

- Void content of the aggregate in place is typically assumed or is assumed to be the same as the void content in a loose condition.

- For design methods that discuss embedment, there appears to be disagreement as to the optimum degree of embedment at the time of construction.

- There is disagreement as to what correction should be applied when calculating appropriate spray rates for emulsions. Opinions range from no correction to full correction for the water, emulsifier, etc., in the emulsion.

- There is disagreement as to whether the design methods give a better estimate of the initial application than rates based on experience. The latter rates usually only apply to a specific gradation and band of quality identified by the specifications.

- Of the chip seal projects monitored, actual field material quantities were closer to design quantities calculated from the Asphalt Institute design reference instead of the Texas design reference. Excessive aggregate quantities were noted. Performance of projects was dependent on many factors; therefore, conclusions regarding suitability of design methods were unavailable.[11,4]

- Extensive research studies in Texas have recommended the use of lower residual asphalt design quantities for projects using emulsified asphalt versus those incorporating asphalt cement.

c. Materials

Based on this research study, the following appear to be the most significant findings related to materials (asphalt emulsions and aggregates).

- The factors related to materials that appear to most affect chip seal performance include:

  1. Asphalt emulsion application rate.
  2. Aggregate cleanliness.
  3. Aggregate gradation.

- The literature and interviews suggest that asphalt emulsion application rate is probably the most important factor determining chip seal performance. However, field studies conducted within this investigation were unable to confirm that conclusion.

- Emulsion viscosity at the time of application is an important factor determining the rate and uniformity of application. Though specifications allow a range of viscosities at typical spraying temperatures, temperatures are specified rather than viscosity. One agency specifies viscosity then determines spray temperature based on temperature-viscosity relationships for the material. In addition, evidence was presented by two field projects (Oregon and Pennsylvania) which indicated a decrease in emulsion viscosity following production.

- Though aggregate cleanliness is important, some agencies do not test for the cleanliness or character of the fine material.

- Precoated chips offer increased initial chip retention; however, this benefit may be erased if used in hot weather as aggregate pick-up can occur.

- Standard quality control tests to ensure compliance with specifications are primarily used for determining suitability of aggregates and emulsions for seal coating.

- Current specifications for quality and durability of aggregates appear to be adequate, at least in the opinion of those using chip seals.

- Some foreign agencies have extremely tight controls to ensure that aggregates are essentially one size and cubical in shape. Other agencies allow a fairly wide band in gradation. Both approaches have been successful.

- Various modified versions of the Vialit test have demonstrated the ability to measure emulsion set rates under a multitude of environmental conditions.

d. Construction

In general, while selection of materials and adequate design are important, various aspects of the construction phase, when combined, probably make up the biggest single factor determining success or failure of the project. Many variables during construction influence the probabilities of success or failure, and some of them are completely out of the control of the designer, engineer, contractor, or inspector. Unfortunately, some of them, rain for example, can turn a splendid job into a disaster and can occur at any time. The main findings based on this work are the following:

- All of the following aspects of construction appear to be equally important.

    - Construction timing.
    - Field application amounts.
    - Application uniformity.

- Weather.
- Time of year.
- Traffic control.

- Common practice is to use design methods or historically determined rates as a starting point only for construction. Rates are modified in the field by knowledgeable personnel.

- Determining aggregate embedment seems to be the most common approach for agencies that try to use some "objective criteria" making changes to estimated initial rates.

- The change is typically made using a visual evaluation based on previous experience.

- While asphalt application rates are extremely important, agencies differ on their approach to determining field application rate. Equipment typically must be calibrated but methods of checking the calibration differ. Most agencies determine the total quantity applied over a fairly large area to determine average application rate. Some actually measure the rate using pads spread transversely across the roadway surface. Even under controlled conditions (Oregon field project), large variations in field quantities and among measurement methods can occur.

- Computer-controlled asphalt distributors are beginning to appear on the market. These may help control the asphalt application rate to a better degree.

- Only one agency attempts to maintain a systematic variation in application rate transversely across the roadway. This is performed using carefully designed and placed spray nozzles. The performance of chip seals constructed over rutted pavement may be enhanced by a modified application rate.

- Few specifications establish a "trial section" for controlled field adjustment of initial application rates based on design.

- Temperature and humidity play important roles in determining the severity of control over the traffic.

- The Oregon field project indicated high correlation between pavement and air temperatures during construction and subsequent seal coat performance. The Pennsylvania field project did not show any significant relationship between air temperature during construction and seal coat performance.

- Aggregate turnover and decreased service life may be encountered in portions of the roadway which are shaded during construction and the subsequent emulsion curing process.

- Rain during construction or in the early life of a seal coat can substantially reduce the treatment's performance.

- Under the high traffic volume conditions of the Oregon project, test sections receiving choke stone application prior to opening to traffic exhibited good performance. The poorly performing test sections did not receive choke stone applications until after they were opened to traffic and had already begun to fail. Remedial choking and sweeping operations did not save these sections from failure.

- Specified weather restrictions are fairly common between agencies. Most individuals agree that temperature well in excess of those specified are desirable. One agency applies very stringent construction guidelines.

- The level of knowledge and experience plus the concern or desire to obtain a successful job seem to be directly related to the probability of obtaining a successful seal coat job.

- Based on results of the Nevada field project, general guidelines were given relating modified Vialit chip retention values to timing of construction operations.

e. Performance Measurement

Based on this research study, the following appear to be the most significant findings related to performance measurement:

- The primary factors used to determine performance are aggregate loss, asphalt bleeding and flying rock damage.

- Skid resistance is also an important factor determining performance and is a potential quantitative measure of that performance.

- Definitions of failure are varied; however, all point to unacceptable aggregate loss or bleeding.

- More aggregate loss appears to be acceptable than asphalt bleeding. Aggregate loss in the wheel paths appears to be of more concern than outside the wheel paths.

- Aggregate loss on the order of 30 percent of the total area is probably a reasonable measure of "failure" for monitoring purposes.

- Asphalt bleeding on the order of 15 to 20 percent is probably a reasonable measure of "failure" for monitoring purposes.

- The modified surface abrasion test developed by the consultant was shown to correlate relatively well with seal coat performance.

2. Research Needs and Recommendations

The purpose of this section is to summarize the needs that seem apparent based on the work presented herein and indicate areas that need to be addressed in the development of future work plans for seal coat research.

a. Field Projects

Many of the unanswered questions concerning seal coat performance require reliable documented field performance to evaluate the significance of considered parameters. Unfortunately, most field projects (this study included) are so confounded by the interrelated effects of various study elements that conclusions and recommendations are either irresponsible or so diluted with qualifications they become worthless. This frequent outcome is usually the result of one or more of the following:

- Limited research funds.
- Too many factors studied for available research budget.
- Coordination difficulties and varied objectives between project players.
- The absence of a qualified statistician during planning stages of the project.

It is more desirable and efficient to present fewer limited findings with confidence, which can be applied to a specific set of conditions and may be extended to other circumstances, than to make recommendations of which the validity and applicability are questionable. If the state of seal coat practice is to be advanced in the future, a concerted effort in terms of resources, organization and commitment should be made with regard to field evaluation.

b. Performance Monitoring

Monitoring the field performance of road sections will be a key effort in future seal coat research. Based on the work so far, the method proposed by Epps should be used for gathering the data.(4) One improvement might be to include photographs depicting certain percentages of aggregate loss or bleeding.

c. Design

The five areas of design which have the greatest apparent research need are:

- Determining the void content of the aggregate in place.
- Estimating the demand of the existing surface.
- Estimating the traffic effect on asphalt application rates.
- Defining the optimum percentage of embedment and factors that would influence its selection.
- Determining the suitability and benefits, if any, associated with choke stone application and the excessive aggregate spread rates which are recommended by some designs and "experienced" individuals.

The South African NITRR has done considerable work in developing methods to determine the actual void content of material in place. Their procedures also contain methods for determining spread rates and equivalent layer depths. It should be noted, however, that their experience is limited primarily to "one-size" aggregates. Confirmation of their work would be helpful.

Rational estimation of the demand of the existing surface is a problem that has plagued designers for years. As was noted previously, this is one of the factors extremely difficult to account for during construction. The New Zealand agencies use the "sand patch" test to determine the demand resulting from the small cracks and the texture of the existing surface. As pavements age, it appears that their porosity increases. Measurement of the porosity has been attempted but the successful establishment of some relationship between porosity and the surface demand for asphalt has not been accomplished.

Defining the optimum percentage of embedment has a direct influence on the emulsion application rate and on the field evaluations of application rates during construction. The determination of this value is very important and is complicated by the fact that the void content and hence embedment will change with time and traffic. The use of emulsions further complicates this estimation because with emulsions, the asphalt volume itself decreases at the same time as the available voids decrease under the action of traffic. It is felt that this is a critical area of inquiry.

d. Laboratory and Field Testing

(1) General Discussion. Materials evaluation and construction control and their interrelation is a complex process. Many current test procedures are adequate for evaluating the asphalt binder or the aggregates alone. However, for seal coats it is difficult to predict how they will behave or perform when combined on the roadway.

Asphalt and aggregate are typically tested separately to screen them for potentially poor performance. The tests should be straightforward and with some logic as to how the test results indicate potential success or failure (i.e., adequate viscosity and temperature sensitivity for the asphalt binder and adequate abrasion resistance for the aggregate).

Probably the area that needs the most work includes the testing of asphalt and aggregate combinations in the laboratory prior to, and in the field during and immediately following construction. Temperature, moisture, dust, and other factors often combine to cause poor coating, slow curing and other problems that lead to premature failure. Guidelines on limitations of those factors that are important to construction are necessary and should be carefully evaluated. A means of alerting those involved with seal coat construction to potential problems related to material properties, construction timing and/or traffic control operations would be invaluable. New or less familiar tests such as the modified Vialit and surface abrasion test methods exhibit promise and may be desirable. A research study has investigated several chip seal test methods.(39) The modified Vialit test and another more analytical test method were considered useful and were recommended for further research.

Another area of improvement in performance is the early <u>recognition</u> of potential early failure and perhaps the correction of the deficiency <u>immediately</u>. Many projects with shortcomings may have been suspected by the foreman or supervisor as being deficient (wrong shot rate, for example), but existing policy or practice does not permit anything to be done. Rather, it might be monitored and eventually redone if it fails. It would make economic sense if the potential problem could be recognized, measured, and corrected, say within 24 to 48 hours.

Some agencies (Washington State DOT, for example) have explored corrective measures with some degree of success, and some of those ideas need to be evaluated. For example, within an hour or 2 after construction, the chip seal could be examined and compared to a standard for embedment and aggregate spread (i.e., percent exposed asphalt between chips). If either of these were found to be deficient, corrections should be made in the on-going operation <u>and</u> plans made to correct the deficient section already constructed in order to increase its chances for success. The idea here is that only a small effort may be necessary to correct it now while equipment, materials, traffic control, etc. are still available, rather than wait until next month or year. For insufficient embedment, an additional application of diluted asphalt emulsion may be all that is required. A decision could be made whether to spread additional fine aggregate or choke stone. If the large chips are too widespread, the choke could be added alone, but would probably not adhere unless additional binder was also applied. For extreme cases, it might be appropriate to simply construct a second chip seal on top of the first, i.e., a double seal, in order to preserve the roadway serviceability.

Longer term performance (during the first year and beyond) may need to be evaluated through some predictive procedure if possible. Included here might be aging characteristics of the asphalt, temperature sensitivity of the asphalt to prevent aggregate loss during cold weather and flushing during hot weather. Other factors such as polishing and skid resistance are important to the overall success of the surface treatment. The modified surface abrasion test has shown preliminary capabilities to predict chip seal durability (performance).[49]

(2) Testing. Any laboratory and/or field testing should be directed at improving emulsion seal coat effectiveness, specifications, procedures and guidelines by obtaining a better understanding of the basic behavior of the materials and answering questions related to the design and construction phases. Examples of the tests which might be performed include the following laboratory tests:

- Laboratory tests in conjunction with design procedures to determine asphalt and aggregate application rates.
- Determination of proper type of asphalt.
- Determination of the proper gradation of cover aggregate.
- Evaluation of temperature susceptibility of asphalt emulsion and residual asphalt.
- Extraction and recovered properties of asphalt binder.
- Evaluation of adhesion of aggregate to binder.
- Evaluation of chip retention capabilities of binder with respect to expected environmental and traffic conditions

Examples of field tests that might be performed:

- Aggregate embedment.
- Aggregate retention.
- Bleeding.
- Curing (shear resistance).
- Skid resistance.

Existing test procedures should be reviewed and suggestions as to appropriate revisions, if any, should be made. It is recognized that the longer term performance aspects will require diligent documentation; a commitment should be made to continuously monitor performance and incorporate information as it becomes available.

e. Specifications

Recommendations for specification changes will come about with enhanced monitoring and testing procedures. Based on the work to date, there are some immediate suggestions that could be made with respect to the specifications.

Field adjustment of application rates is quite common and seems to be accepted. If it is to be practiced, one suggestion is to establish a trial section in the specification to provide for adjustment of initial design rates (with the engineer's approval) according to field conditions. The contractor should be notified that field evaluation and adjustment will be practiced as part of contract performance.

Spraying temperatures are important to ensure that the correct viscosities for spraying are achieved. Texas' method of determining spray temperatures based on a desired viscosity and the temperature-viscosity relationship of the emulsion would appear to make sense. In addition, emulsion viscosities have been shown to change over time. It would seem prudent to think more in terms of viscosity rather than temperature, and specifications should be written such that emulsion viscosity desired for construction operations is achieved.

Rolling specifications typically identify a fixed number of rollers per job. If the specification for minimum numbers of rollers were based on the anticipated production rate of the spreading equipment, then a more rational approach for establishing this number would exist. The New Zealand requirement for a fixed ton-hr per volume of asphalt applied should definitely be considered.

Specifications for traffic control over new seal coat projects need to be developed quite carefully. Provisions should be made in the specifications to allow for flexibility in the traffic control requirements depending on the existing field situation, with primary emphasis on the weather conditions. A field test method which measures emulsion setting rate and tenacity of the binder would greatly aid in the task of traffic control. The modified Vialit and surface abrasion tests have shown promise in this area although continued research and likely modifications are required.

f. Development of Instructional Materials

As a result of this investigation, there is a strong feeling that increasing the level of awareness, knowledge and experience in constructing seal coats may, more than anything else, lead to fewer premature failures. The development of successful instructional materials is seen as a vital part in improving the state of practice.

The users manual (volume III) is the primary means presented for technology transfer. The objective of the users manual was to prepare a guide which summarizes the key factors necessary for successful chip seal performance. It basically summarizes the knowledge and findings gained from all facets of this research project. The approach was to present the material in a format that would be understandable and useful to both construction personnel and engineers. Detailed procedures related to materials testing, design, and construction were left to other excellent "how to" manuals and references. Rather, the manual focuses on key factors that should be considered when designing and constructing chip seals.

A slide presentation has been produced as a companion to the users manual. The collection of slides is intended to illustrate some of the design concepts and exemplify construction practice, both good and bad. A written, brief description of each slide accompanies the slide presentation.

Extensive video footage was recorded on selected chip seal projects, however project funds were not available to cover the considerable editing work needed to produce a finished project. If possible, this work should be completed as it is believed a video presentation would be very useful and effective in training and motivating those involved in chip seal construction.

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