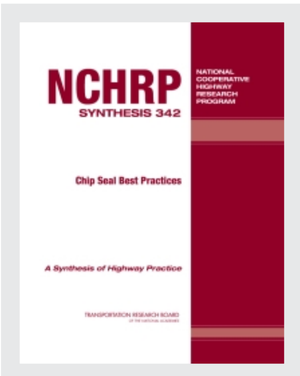

Chip Seal Best Practices

DETAILS

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AUTHORS

D Gransberg; DMB James; Transportation Research Board

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP SYNTHESIS 342

Chip Seal Best Practices

A Synthesis of Highway Practice

CONSULTANTS
DOUGLAS GRANSBERG
and
DAVID M.B. JAMES
University of Oklahoma

TOPIC PANEL

LITA DAVIS, *County of San Diego Department of Public Works*
BART DESAI, *California Department of Transportation*
LARRY GALEHOUSE, *Michigan State University*
JOE S. GRAFF, *Texas Department of Transportation*
MARK ISHEE, *Ergon Asphalt and Emulsions, Inc.*
FRANK LISLE, *Transportation Research Board*
BILL O'LEARY, *Prime Materials and Supply*
STEVE VARNEDOE, *North Carolina Department of Transportation*
DON WISE, *Pennsylvania Department of Transportation*
STEVE MUELLER, *Federal Highway Administration* (Liaison)

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- Dr. Brian Pidwerbeski from Fulton Hogan in New Zealand, who made both manuals and technical expertise available.
- Chris Summers from the U.K. Highway Agency who obtained photographs of the water retexturizing equipment and formed an ad hoc working group to develop the case study.
- Ian Cossens from VicRoads (Australia) for submitting hard copies of their chip seal manuals.
- Dr. Ron Ayers of the University of Southern Queensland, who found photographs and technical data on Australian chip seal practices.
- Tim Klassen and Robert Chartier of Manitoba for assisting in translating French Canadian chip seal manuals and specifications and furnishing photographs of Canadian practices.
- Gordon Hart of Transit New Zealand for submitting the complete New Zealand specifications.
- Tawan Songpiriyakij, a graduate student at the University of Oklahoma, who developed many of the graphics that are contained in this report.

It was gratifying to realize that this project created an international network of chip seal experts and laid the foundation for collaboration between the various nations in the years to come.

FOREWORD

By Staff
Transportation Research Board

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-5, "Synthesis of Information Related to Highway Problems," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, *Synthesis of Highway Practice.*

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

This synthesis report provides an overview of successful chip seal practices in the United States, Canada, and overseas. Although not meant to be an exhaustive study, it covers the spectrum of chip seal practice and presents, where possible, the state of the art, as reported in the literature and survey responses. The report presents ways to assist in the development and implementation of pavement preservation programs by identifying the benefits of using chip seal as part of a preventive maintenance program. Innovative and advanced chip seal programs from around the world were identified with respect to critical factors that can be incorporated by other transportation agencies. Approximately 40 best practices were identified in the areas of chip seal design methods, contract administration, equipment practices, construction practices, and performance measures. The increased use of chip seals for maintenance can be a successful, cost-effective way of using preventive maintenance to preserve both low-volume and higher-volume pavements.

For this synthesis report of the Transportation Research Board, 92 survey responses were received from state departments of transportation; U.S. cities and counties; Canadian provinces, cities, and territories; Australian and New Zealand provinces; and other public agencies. In addition, a comprehensive review of the literature covering nearly 80 years of research was undertaken, and more than 120 articles on chip seals and preventive maintenance identified. Case studies that illustrate trends found in best practices, taken from those respondents who routinely achieve good results from their chip seal programs, are also presented. In addition, two innovative and emerging technology cases that address areas of concern for the future implementation of chip seals are provided.

A panel of experts in the subject area guided the work of organizing and evaluating the collected data and reviewed the final synthesis report. A consultant was engaged to collect and synthesize the information and to write the report. Both the consultant and the members of the oversight panel are acknowledged on the title page. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

CONTENTS

SUMMARY

A chip seal consists of a layer of asphalt binder that is overlaid by a layer of embedded aggregate that furnishes, among other things, protection to the asphalt layer from tire damage and a macrotexture that creates a skid-resistant surface on which vehicles may safely pass. A chip seal's main purpose is to seal the fine cracks in a pavement's surface and prevent water intrusion into the base and subgrade. The use of chip seals and similar surface treatments began in the 1920s, and consisted primarily of providing one or more wearing courses in the construction of low-volume gravel roads. Since then, the use of chip seals as preventive maintenance (PM) treatments has been a successful surface treatment on both low- and high-volume pavements. Their popularity owes to their favorable cost in comparison with thin asphalt and other factors as a technique to extend the life of the underlying pavement structure.

A chip seal is a frequently used PM treatment on flexible pavements. It must be recognized that successful chip seals are a function of their application on underlying pavements that have not suffered structural failure. To achieve the pavement preservation benefits of a chip seal, an agency must apply it on roadway surfaces when the level of pavement distress is low. Thus, pavement selection becomes the first and perhaps the most critical factor in an agency's chip seal program.

Many agencies base their chip seal procedures on local anecdotal experience rather than on engineering principles and have limited knowledge of what other agencies may be doing to achieve success. Design and installation of chip seals involve a significant degree of "art." Also, much engineering information is available in the literature of transportation agencies, organizations, and academia. Technical information on good practice for materials, design, construction techniques, and effectiveness of chip seals is available and will be summarized in this synthesis. The project limits its focus to single- and double-course PM chip seal surface treatments.

This synthesis study was initiated with a comprehensive review of the literature on the subject to explore the theoretical foundations for chip seal practices and experiences as well as to set the stage for the identification of chip seal best practices. The review uncovered a large body of technical information. Nearly 80 years of research that included more than 120 published articles on chip seals and pavement PM were identified and reviewed to create the foundation for this synthesis.

Special consideration has been paid to the highly technical process used to design and build chip seals in Australia, New Zealand, South Africa, and the United Kingdom. These countries indicated that they consistently achieve chip sealing performance excellence on both low- and high-volume roads. Additionally, the chip seal design and construction manuals from Australia, New Zealand, South Africa, the United Kingdom, and a number of U.S. state departments of transportation (DOTs) were reviewed. The findings can be divided into seven basic categories:

1. Design methods,
2. Contract administration,
3. Material selection,
4. Equipment practices,

5. Construction practices,
6. Performance measures, and
7. Case studies in excellence and innovation.

A survey of U.S., Canadian, and other international public highway and road agencies that potentially used chip seals as a part of their roadway maintenance programs was developed and conducted. The survey was initially directed to the chief maintenance engineer in each state DOT, as well as to points of contact at federal, municipal, and county levels. It was also sent to international public highway agencies in Canada, Europe, Africa, and the Pacific. Appendix A contains a copy of the survey, and the summary of survey responses is shown in Appendix B. A total of 92 individual responses were received from 42 states, 12 U.S. cities and counties, 10 Canadian provinces, 1 Canadian territory, 2 Canadian cities, 4 Australian provinces, 2 New Zealand provinces, 2 public agencies in the United Kingdom, and 1 from South Africa.

Multiple responses were received from a number of agencies, and because each response represented the practices in that local area (which varied significantly in terms of climate and level of urbanization), no effort was made to consolidate them into a single statewide response. The survey responses indicated that the United States and Canada have very similar practices and that they are quite different from those employed internationally. The distribution of states and provinces that reported that they are achieving good results with their chip seal program is fairly evenly distributed across the continent. Also, there is not much difference in the average daily traffic levels at which U.S. and Canadian DOTs choose chip seal treatments. This supports the finding in the literature review that the experience of highway agency personnel appears to be the major factor for achieving chip seal success.

Because the literature review showed that climate has a large impact on chip seal performance, the survey responses were categorized by AASHTO climatic region and, surprisingly, no trend was evident. Agencies were able to achieve good results in all sorts of climates. The other surprising result was the almost total reliance on asphalt emulsion binders. Only three responding state DOTs indicated that they used hot asphalt cement binders in their maintenance chip seal program, and emulsions were used exclusively in Canada and overseas.

The study resulted in several significant findings. The first is that maintenance chip seals play an important part in the nation's pavement preservation program; therefore, they deserve the same level of technical engineering rigor that is reserved for the hot-mix asphalt pavements whose service life the chip seals extend. There was no trend in state population, urbanization, or climatic region as to whether or not maintenance chip seals were employed by a public highway agency. The survey showed that in some cases, local entities were successfully using chip seals when the state DOT indicated that it did not.

The view that a chip seal is an art, not a science, may be held by the agencies that do not use it in their pavement preservation programs. Another view is that maintenance chip seals can be successfully applied only to low-volume roads, despite evidence to the contrary. These views persist because the development of chip seal design methodology essentially ceased in 1970 in North America with the introduction of the McLeod method, subsequently adopted by the Asphalt Institute. This method relied on qualitative design input and field adjustment of the design rates of binder and aggregate. Although this approach has been successfully used since its introduction, it requires experienced personnel on both the agency and contractor teams, introducing another aspect of variability into an already highly variable technology. When one considers that the only really effective solution for an improperly installed chip seal is to mill and overlay the failed surface, one can understand why some agencies in this country have abandoned the technology. The international community, on the other hand, has been aggressively advancing the state of the practice in chip seals and has developed a number of highly engineered advancements that appear to hold great promise. Therefore, this report recommends that future research be directed at importing for North America the chip seal practices found in Australia, New Zealand, and South Africa.

The remaining findings dealt with construction and construction equipment. The report identifies the need to complete a definitive study of chip seal rolling requirements, because rolling is critical to chip seal performance, and to furnish specific guidelines for implementation in general specifications and chip seal quality control manuals. The report also recommends that special purpose equipment that is used overseas be investigated for use in North America. As can be seen, the findings relate to removing the art from the chip seal process and replacing it with solid engineering science.

Additionally, 13 respondents indicated that they routinely achieve excellent results from their chip seal programs. These responses were separated from the general survey population and analyzed as a group to identify trends associated with attaining excellence in chip seals. From that group, six case studies that illustrate the trends found in best practices from the chip seal excellence group are presented in chapter nine. Finally, there were two innovative and emerging technology cases provided by survey respondents that appeared to speak to areas of great concern for future implementation of chip seal techniques. Those cases are included and analyzed in Appendix D.

The combination of immediately implementable best practices and recommendations for the future research on chip seal technology in the United States and Canada make up the final results of this study. The research team was gratified by the strong and completely sincere response received to its “overly long and complicated” questionnaire and the willingness of engineers all over the world to share their experience and expertise. One unexpected by-product of the study was the establishment of an informal, international network of chip seal experts who can be called on in the future to assist in the revitalization of the pavement preservation technology in North America.

All of the best practices that were identified in the synthesis are organized in logical groups and cite only the best practice as identified. The definition of a best practice for this synthesis is a method or procedure that was found in the literature and confirmed as applicable through survey responses.

The literature review and survey responses identified 38 specific best practices in the several categories mentioned earlier. They ranged from packaging chip seal contracts in large enough volume to attract the most competent contractors to specific recommendations with regard to roller linger times. The best practices came from across the United State, as well as from international respondents. They are summarized in the following lists, and each is discussed in detail in the chapter indicated.

Best practices in pavement selection, design, and material selection are as follows:

1. View chip seals as a preventive maintenance tool to be applied on a regular cycle to reinforce the pavement preservation benefits of the technology (chapter nine).
2. Chip seals perform best on roads with low underlying surface distress that will benefit from this technology (chapter three).
3. Chip seals can be successfully used on high-volume roads if the agency’s policy is to install it on roads before pavement distress becomes severe or the structural integrity of the underlying pavement is breached (chapter nine).
4. Characterize the underlying road’s texture and surface hardness and use that as a basis for developing the subsequent chip seal design (chapter three).
5. Try using the “racked-in seal” as the corrective measure for bleeding instead of the North American practice of spreading fine aggregate (sometimes called “chat”) on the bleeding surface (chapter three).
6. Conduct electrostatic testing of the chip seal aggregate source before chip design to ensure that the binder(s) selected for the project is compatible with the potential sources of aggregate (chapter five).
7. Use life-cycle cost analysis to determine the benefit of importing either synthetic aggregate or high-quality natural aggregates to areas where the availability of high-quality aggregate is limited (chapter five).

8. Specify a uniformly graded, high-quality aggregate (chapter five).
9. Consider using lightweight synthetic aggregate in areas where post-construction vehicle damage is a major concern (chapter five).
10. Use polymer-modified binders to enhance chip seal performance (chapter five).
11. Recognize that both hot asphalt cement and emulsified asphalt binders can be used successfully on high-volume roads. The selection of binders modified by polymers or crumb rubber seems to reinforce success (chapter nine).

Best practices in contract administration, warranties, and performance measures are as follows:

1. Award chip seal contracts in time to permit early season construction (chapter four).
2. Time the letting of the contract to allow sufficient time for the curing requirements of preconstruction pavement preparation activities (chapter four).
3. Package chip seal contracts in jobs large enough to attract the most qualified contractors (chapter four).
4. In-house maintenance personnel are best used to install chips seals in areas where the greatest care must be taken to achieve a successful product (chapter nine).
5. Use warranties for chip seal projects only when the contractor is given the latitude to determine the final materials and methods used to achieve a successful chip seal (chapter four).
6. The sand patch method to measure chip seal macrotexture can serve as an objectively measured chip seal performance indicator (chapter eight).
7. The use of the chip seal deterioration model expressed in the New Zealand P17 specification can furnish an objective definition of chip seal performance based on engineering measurements (chapter eight).
8. The two previously described practices can be supplemented with continued visual distress rating based on the Ohio DOT chip seal performance criteria shown in the text in Table 13 (chapter eight).

Best practices in construction are as follows:

1. For optimum performance, apply all types of chip seals in the warmest, driest weather possible, for optimum performance (chapter seven).
2. Ambient air temperature at the time of application should be a minimum of 50°F (10°C) when using emulsions, and 70°F (21°C) when using asphalt cements, with a maximum of 110°F (43°C) (chapter seven).
3. When using emulsions, the temperature of the surface should be a minimum of 70°F (21°C) and no more than 140°F (54°C) (chapter seven).
4. Complete patches at least 6 months before and crack seals at least 3 months before the application of chip seals (chapter seven).
5. Variable nozzles permit the application of a reduced rate of binder in the wheelpaths and help combat flooding in the wheelpaths, a defect that makes chip seals prone to bleeding. Conversely, the Australian use of prespraying is another method for adjusting the transverse surface texture of a pavement surface before applying a chip seal (chapter seven).
6. A drag broom fitted on those rollers doing the initial roller pass corrects minor aggregate spread deficiencies such as corrugation, uneven spread, or missed areas (chapter seven).
7. Apply the aggregate as quickly as possible to both emulsified and hot asphalt binders (chapter seven).
8. The Montana field-sweeping test curtails the bias to spread excess aggregate created by a unit-price contract (chapter seven).
9. Have the most experienced inspector predrive each shot and paint binder rate adjustments on the pavement to facilitate field rate adjustments (chapter seven).
10. In areas where extensive stopping and turning movements take place, the application of a small amount of excess aggregate may reduce scuffing and rolling. The use of a racked-in seal may be a viable engineered solution for determining the precise amount of aggregate for these problematic areas (chapter seven).

11. Furnish and enforce rolling guidelines and specifications for roller coverage, rolling patterns, and minimum rolling time to achieve full lane coverage and a similar number of passes for all areas of the lane (chapter seven).
12. The required number of rollers is a function of desired distributor production and required rolling time for each shot width on the project (chapter seven).
13. Have rolling follow as closely as practical behind the chip spreader (chapter seven).
14. Maintain traffic control for as long as possible to give the fresh seal the maximum amount of curing time (chapter seven).

Best practices in chip seal equipment and quality assurance and quality control are as follows:

1. Require chip seal contractors to use state-of-the-art equipment and to control the rolling operation to enhance chip seal success (chapter six).
2. Use computerized distributors (chapter six).
3. Require preproject analysis of the ability of the chip seal equipment spread to keep up with the production rate of the distributor (chapter six).
4. Use variable nozzles to reduce the amount of binder that is sprayed in the wheelpaths (chapter six).
5. Plastic bristles for rotary brooms minimize aggregate dislodgment during brooming (chapter six).
6. An aggressive quality control testing program combined with close inspection generates chip seal success (chapter seven).
7. Assign experienced personnel who understand the dynamics of chip seal construction as field quality control and quality assurance persons (chapter seven).
8. Regularly calibrate both the distributor and the chip spreader (chapter seven).
9. Evaluate aggregate–binder compatibility tests shown in the text in Table 12 for local appropriateness and use in the field (chapter seven).
10. Field test both binders at the distributor and aggregate stockpiles to ensure that material has not degraded owing to handling during transportation (chapter seven).

CHAPTER ONE

INTRODUCTION

DEFINITION AND HISTORY

A chip seal (also called a "seal coat") is essentially a single layer of asphalt binder that is covered by embedded aggregate (one stone thick), with its primary purpose being to seal the fine cracks in the underlying pavement's surface and prevent water intrusion into the base and subgrade. The aggregate's purpose is to protect the asphalt layer from damage and to develop a macrotexture that results in a skid-resistant surface for vehicles. Chip seals and similar surface treatment use originated in the 1920s (Hinkle 1928). These early uses were predominantly as wearing courses in the construction of low-volume gravel roads. In the past 75 years, chip seals have evolved into maintenance treatments that can be successful on both low-volume and high-volume pavements. The popularity of chip seals is a direct result of their low initial costs in comparison with those of thin asphalt overlays and other factors influencing treatment selection where the structural capacity of the existing pavement is sufficient to sustain its existing loads.

Historically, most transportation agencies in North America would allow their pavements to deteriorate to fair or poor condition (Beatty et al. 2002). As a result of the national pavement preservation initiative, funding agencies are becoming familiar with the cost-effectiveness of using preventive maintenance (PM) to preserve the infrastructure, and they are finding that chip seal research is worth the investment. Figure 1 illustrates the concept of PM, whereby each dollar spent on maintenance before the age of rapid deterioration saves $6 to $10 in future rehabilitation costs (Hicks et al. 1999) and could conceivably save even more when user delay and traffic control costs are added to the bottom line.

The focus of this synthesis was on summarizing the research and practices that point toward consistently successful chip seal projects. For this synthesis, a "best practice" is defined as any superior planning, design, or construction method that was found in the literature review and confirmed by survey responses. The project's objective was to assist in the development and implementation of pavement preservation programs by identifying the benefits of using a technologically advanced chip seal as part of a PM program. A great deal of research on chip seals has been performed in Australia, Canada, New Zealand, South Africa, the United Kingdom, and the United States. Innovative and advanced chip seal programs have been identified with respect to critical factors that can be incorporated by other agencies.

A comprehensive review of the literature on this subject has been completed to provide a solid theoretical as well as anecdotal foundation for the review of chip seal construction practices. The literature review furnished a global perspective for identifying successful chip seal programs. Particular attention was paid to the sophisticated chip seals of Australia, New Zealand, South Africa, and the United Kingdom, as these nations consistently confirm chip sealing benefits and successful results on both low-volume and high-volume roads with routine service lives that are nearly double those assumed in North America, as shown in Figure 2. Additionally, the subjects of end-product and performance specifications, emerging construction methods and trends, and advanced design methodology have been covered to ensure that the latest developments in this field are considered as possible candidates for use in future research.

A comprehensive survey was developed and North American and international participation alike was encouraging. The survey emphasized identifying any critical and emerging best practices. The survey was developed to focus on the specifics of design, contracting procedures, construction methods, and performance measures. Figure 3 illustrates the amount of chip sealed surfaces that are under authority of the agencies that responded to the survey. Note that international responses were tailored to reflect actual lane miles sealed.

Survey analysis has been directed toward identifying practices that are likely to contribute to both successful and unsuccessful projects. After identification of such practices, a structured case study format was developed to clarify trends in the features of the best practices. The case study process illustrated lessons learned from highly successful practices. Considerable constructability improvements may be possible through emulating practices that have been identified as critical to project success.

CHIP SEALS AS A TOOL FOR PREVENTIVE MAINTENANCE

Definition

Pavement preservation is the long-term goal for most highway agencies. Such action must be taken to not only protect the capital investment made when a roadway is constructed but also to maximize its ultimate useful life. Pavement preservation has its own unique definition that must be

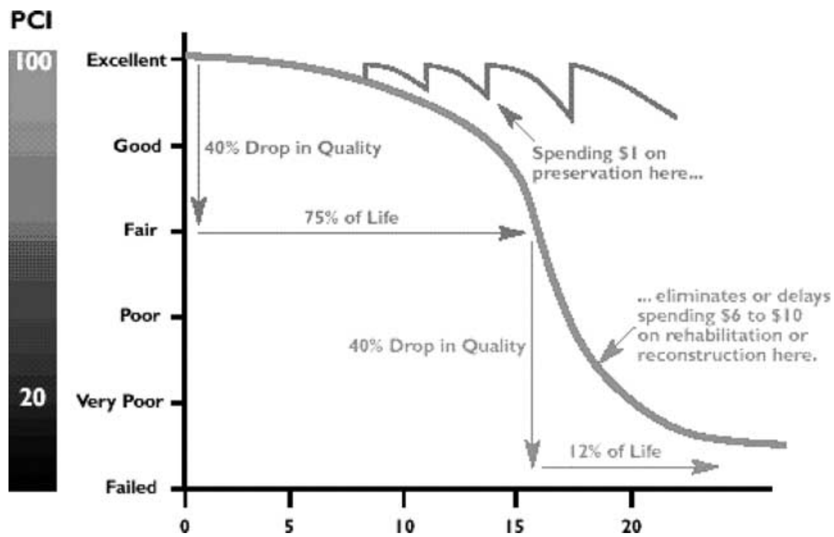


FIGURE 1 Preventive maintenance concept (*Source:* Galehouse et al. 2003). (PCI = pavement condition index.)

understood for one to put it in context with PM. The pavement preservation definition developed by the FHWA Pavement Preservation Expert Task Group states that

> Pavement preservation is a program employing a network level, long-term strategy that enhances function pavement performance by using an integrated, cost-effective set of practices that extend pavement life, improve safety, and meet motorist expectations (*Pavement Preservation* . . . 1999).

Furthermore, it is important that the reader understands that

> Pavement preservation is not a maintenance program, but an agency program. Almost every part of an agency should be involved. Success depends on support and input from staff in planning, finance, design, construction, materials, and maintenance. Two other essentials for an effective program are long-term commitment from agency leadership and a dedicated annual budget (Galehouse et al. 2003).

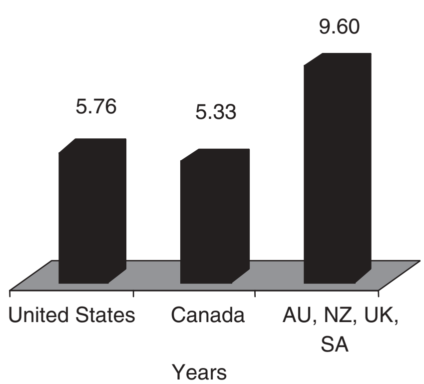


FIGURE 2 Survey respondents' chip seal service life (*Source:* Galehouse et al. 2003). (AU = Australia, NZ = New Zealand, UK = United Kingdom, SA = South Africa).

The AASHTO definition of PM is a "planned strategy of cost-effective treatments that preserves and maintains or improves a roadway system and its appurtenances and retards deterioration, but without substantially increasing structural capacity" (*Pavement Preservation* . . . 1999). Thus, one can see that planned PM actions are actually a part of a much broader pavement preservation program.

Benefits

Chip seals are most frequently used as PM treatments on flexible pavements. The ideal benefits of applying a chip seal are obtained if the chip seal is applied early in a pavement's life (i.e., before it exhibits a great degree of distress) and within the context of a PM program (Wade et al. 2001). A strict PM program whereby the roads are sealed at the end of every PM cycle may require several chip seals to be applied to the pavement's surface for that pavement to reach its ser-

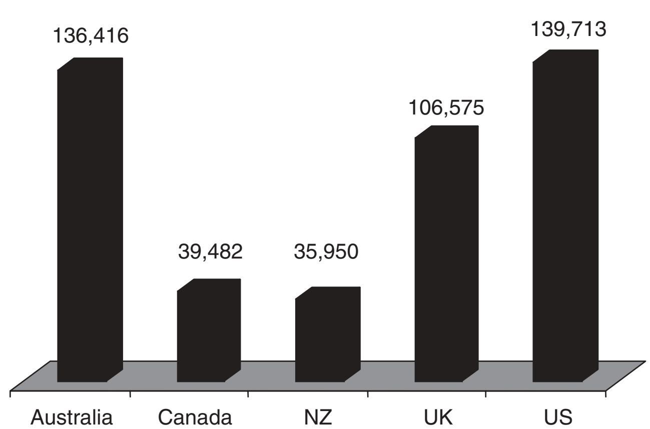


FIGURE 3 Lane miles of chip seal service life.

vice life. The main concept behind implementing a PM cycle is to maintain the desired quality of the pavement without the development of major distresses. In contrast with routine maintenance, which is a reactive approach to repair pavement distresses, PM is a proactive approach to preserve and extend a pavement's life (*Seal Coat and Surface Treatment Manual* 2003). In PM programs that use chip seals, practitioners believe that chip seals provide economically justifiable life extension benefits if applied at the correct time (Wade et al. 2001). Figure 4 shows the distribution of respondent agencies that strive to use chip seals as a PM practice.

Chip seals are expected to provide at least 5 years of service; therefore, three or four chip seals may be necessary for a pavement to reach its design life. When applied on an existing flexible pavement, a chip seal will provide a surface wearing course, seal the underlying pavement against water intrusion, enhance or restore skid resistance, and enrich the pavement surface to prevent the distresses caused by oxidation. Chip seals are generally effective in sealing fine cracks on the roadway surface, unless the cracks are indications of structural distresses.

Chip seals are not expected to provide additional structural capacity to the pavement, although it appears to be a common practice to apply chip seals to pavements that have structural distresses. Justification for chip sealing as a stopgap procedure is straightforward; it is believed that the chip seal will reduce the rate of further deterioration until funds are made available for a conventional overlay. However, as a PM treatment, chip sealing on pavements that are not in good condition is not recommended practice and will likely be more expensive in the long run. Therefore, chip seal applications should not be applied on badly cracked or weathered pavement surfaces where reconstruction, rehabilitation, or a conventional overlay is needed.

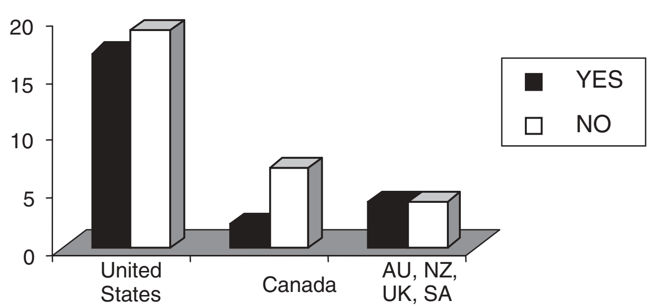


FIGURE 4 Preventive maintenance practice by survey respondents.

Process

The chip seal process begins in the planning stage when the pavement surface is analyzed to determine if a chip seal is an appropriate PM treatment. Surface characterization may consist of assessing the hardness, texture, and other measures of the structural condition of the pavement surface. If a chip seal is determined to be an appropriate treatment for the pavement, various surface preparation techniques are then performed on the surface. Crack repair, selected patching, leveling, presealing, and/or texturizing can be used to prepare the surface before chip sealing. These treatments should normally be performed 6 to 12 months before the chip seal to allow sufficient time for curing. The surface needs to be free of foreign materials before material application. The application of the chip seal involves essentially four pieces of equipment: the binder distributor, aggregate spreader, rollers, and brooms.

The binder distributor provides application of the binder to the pavement surface. A chip spreader immediately applies a uniform, predetermined rate of aggregate onto the binder. These two operations are at the heart of constructing a surface that is one stone thick and has enough binder to retain the aggregate, but not an excess amount of binder that causes the surface to bleed. Depending on the binder, aggregate, and actual type of chip seal being constructed, various rollers will be used to orient the aggregate to achieve appropriate embedment. Pneumatic rollers are typically found on all chip seal projects. The rollers are followed by the brooms that remove excess aggregate from the finished surface.

This report will cover the aforementioned process in detail. The results of the literature review have been correlated with the survey responses to identify best practices. These best practices will be discussed in detail. Specific best practice case studies will also be presented and their essence discussed.

CHAPTER TWO

SUMMARY OF INFORMATION COLLECTED

SCOPE OF RESEARCH

As mentioned earlier, a comprehensive review of the literature on chip seals provided a solid theoretical as well as anecdotal foundation for the review of chip seal practices and experiences. More than 120 published articles, representing 80 years of research on chip seals and PM, were reviewed for this synthesis. Technical information relating to emerging practices, problems solved, and lessons learned have been identified and investigated. The findings can be divided into the following seven basic categories:

1. Design methods,
2. Contract administration,
3. Material selection,
4. Equipment practices,
5. Construction practices,
6. Performance measures, and
7. Case studies in excellence and innovation.

CHIP SEAL SURVEY

A survey intended for those public highway and road agencies that were expected to use chip seals in their maintenance program was prepared and administered. In addition to the survey sent to the chief maintenance engineer in each state department of transportation (DOT), surveys were sent to points of contact at the federal, municipal, and county levels as well as to international highway authorities in Australia, Canada, New Zealand, South Africa, and the United Kingdom. A copy of the survey is contained in Appendix A, and the full results of the responses are contained in Appendix B. Ninety-two individual responses representing 42 states, 12 U.S. cities and counties, 10 Canadian provinces, 1 Canadian territory, 2 Canadian cities, 4 Australian provinces, 2 New Zealand provinces, 2 public agencies from the United Kingdom, and 1 from South Africa were received.

Analysis of the survey responses showed that the United States and Canada have very similar practices, and they are quite different from those employed overseas. Figure 5 summarizes the salient elements of the survey with regard to North America. One can observe that the distribution of states and provinces that reported good results with their chip seal program is fairly evenly distributed across the continent. Additionally, one can observe the similarity between the average daily traffic (ADT) levels at which U.S. and Canadian agencies use chip seals. Both of these statements support the finding in the literature review that the experience of the transit personnel appears to be a major factor for achieving chip seal success. Other success factors are discussed as they are encountered in the subsequent chapters.

The survey responses were also divided according to AASHTO climatic region. Surprisingly, trends were not observed. This finding will be discussed in detail later in this chapter. Another surprising result was the almost total reliance on asphalt emulsion binders. Only three responding U.S. state DOTs indicated that they regularly used hot asphalt cement binders in their maintenance chip seal programs.

REGIONAL CONTEXT

The importance of evaluating the findings of this synthesis within a regional context is critical. Chip seal practices generally vary by region as a result of three factors: local climatic conditions, binder availability, and local aggregate quality. Information from the literature review and survey has been grouped into logical sets based on regional characteristics. It is anticipated that agencies located in roughly the same climatic regions and using similar sources of aggregate will have similar chip seal programs.

The role that climate and weather play in chip seal operations cannot be overstated. It is accepted that ambient temperatures at the time of construction closely affect the quality of the chip seal (Benson and Gallaway 1953; Connor 1984). Emulsions are generally believed to be less sensitive, in comparison with hot applied asphalt cements, to failure during cool weather construction when ambient temperatures are low and aggregates are damp (*A Basic Emulsion Manual* 1997). Also, because emulsions require much lower application temperatures (130°F to 185°F) than do hot applied asphalt cements (300°F to 350°F), they are more suitable for chip seal work later in the season when average nighttime temperatures start to decline. On the other hand, high ambient air and surface temperatures can be a problem with emulsions, reducing the viscosity of binder to such a point that aggregate retention is adversely affected (*A Basic Emulsion Manual* 1997). The bottom line on the climatic context is underscored by the requirement to install all chip seals in the warmest, driest weather possible in the region.

FIGURE 5 Summary of survey responses.

Aggregate selection is largely a cost function of availability and transportation distance. Local geography largely determines the quality of the aggregate, and it is common for agencies to opt for a marginal quality (i.e., at the low end of the specifications) local aggregate owing to cost considerations. The quality of aggregate is important to the overall success of the chip seal program. As aggregate quality decreases, a number of constructability problems, such as dust and degradation of the aggregate during handling, may arise from using poor-quality aggregates located within proximity to the project. The Australians have been known to be willing to pay for high-quality aggregate imported from great distances to ensure the quality of their chip seals (*Austroads Provisional* . . . 2001). Finally, different types of aggregate are more suited to certain binders as a result of electrostatic compatibility, and this factor requires the chip seal designer to consider the electrostatic compatibility of local aggregate during binder selection.

CHIP SEAL—ART OR SCIENCE?

Traditional thought in the United States has portrayed chip seals as an art rather than a science (Wegman 1991). Beliefs that chip seal design is simply a "recipe" prevail to this day. The reasoning behind this is that the majority of North American chip seal practice is based on local empirical experience rather than on sound engineering principles. The main reason to approach chip seal as an art is derived from the uncertainties and variability that exist with all chip seal projects. Therefore, the experience of the construction crew, familiarity with the local materials, and suitable equipment usage are considered to be the critical factors for project success. Because the variability and uncertainties that affect the chip seals are independent of the design parameters, proponents of chip seal as an art argue that a formal design procedure is futile. One of the major difficulties involved in the design of material application rates is nonuniformity of the existing pavement surface. Such conditions necessitate binder rate adjustments in the field at the time of construction, a phenomenon that undermines formal design. This realm of thought contends that if chip seal projects require field adjustments to application rates, formal design is simply a tool for estimating quantities.

SOUND ENGINEERING PRINCIPLES

Australia, New Zealand, South Africa, and the United Kingdom have all developed their chips seal programs based on a greater set of engineering principles than those used by highway agencies in Canada and the United States. For example, all of the overseas agencies actually measure surface texture using a sand circle test to characterize the existing pavement surface. In addition, all of the overseas agencies find it necessary to carry out surface hardness tests by using specialty testing equipment such as a penetrometer or ball penetration device, to determine the nominal size of the aggregate to be used in their advanced design methodologies. The use of these sound engineering principles reduces the uncertainty and variability associated with chip sealing to the point where field adjustments of binder and aggregate application rates are minimized. Not only do these sound engineering principles seek to optimize material application rates, but they have furnished a platform on which to develop and enforce specifications to an extent where performance-driven contracts transfer the risk of the project to the contractor (*Sprayed Sealing Guide* 2004). As such, they have moved the chip seal project from the maintenance world and into the construction contract arena. Figure 6 shows the survey responses addressing the issue of using in-house maintenance personnel. It can be observed that the majority of the U.S. respondents are performing most, if not all, of their chip seal program internally. The situation is reversed in Australia, Canada, and New Zealand, where most of the work is contracted out.

CHIP SEAL TERMINOLOGY

One of the difficulties in communicating technical matters between highway agencies is the result of the different technical terms that are inherent to the chip seal process. This is further exacerbated because practitioners invariably believe that the terminology that they use is indeed technically correct. The Texas DOT (TxDOT) study found that definitions for common terms such as "flushing," "bleeding," "raveling," and "shelling" varied from district to district within that single state (Gransberg et al. 1998). As a result, an engineer in one district who defines the condition as one in which the chip seal is losing its aggregate as "raveling" may make a call for guidance to another engineer in a district where the condition is called "shelling" and the term "raveling" is applied only to hot-mix asphalt pavement distress. Because of the different local definitions, the first engineer may be given incorrect advice on how to rectify the problem.

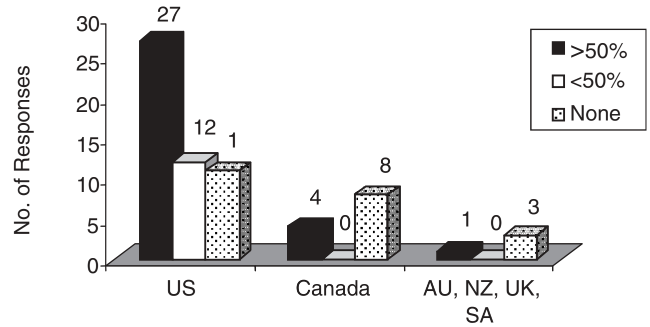


FIGURE 6 Use of in-house resources to complete chip seal program.

This synthesis study expanded its reach beyond the United States and found additional chip seal terminology in Canada, the United Kingdom, South Africa, Australia, and New Zealand. Thus, an effort was made to assemble a chip seal glossary, which is found following the References. For that glossary, chip seal terms were captured from both the literature search and the survey responses. Definitions were developed for each and an attempt was made to correlate those terms that have similar definitions in a manner that allows an easy reference for readers of this report.

This report uses the terminology found in the Strategic Highway Research Program's *Distress Identification Manual for the Long-Term Pavement Performance Project* (1993) to the greatest extent possible to maintain a consistent terminology. It is recommended that the reader frequently refer to the glossary to ensure that full understanding of the report's contents and that the reader is not assigning his or her own local meanings to the terms contained in the report.

The remaining chapters discuss both the literature review and survey responses in tandem. The objective is to report what was found in the literature and then allow the reader to use the survey results to either confirm or refute the statements in the literature. This method will then be used to distill the overall results of this synthesis into a list of best practices for each subject, by chapter.

CHAPTER THREE

CHIP SEAL DESIGN

INTRODUCTION

Before there is any consideration of design methodology, it must be understood that the selection of those roads that will benefit from the pavement preservation technology inherent with chip sealing is the first and most fundamental step in the design process. Chip seals are not meant to enhance the structural capacity of the pavement section and therefore should not be applied to roads that exhibit severe distress (Moulthrop 2003). The formula for chip seal success is eloquently framed by the following quotation: "Succinctly stated, the correct approach to preventive maintenance is to place the right treatment on the right road at the right time" (Galehouse et al. 2003).

There are basically only two types of materials used in chip seals: binder and aggregate. Aggregate selection is a function of geography, where availability and transportation distance essentially define the aggregate cost function. Aggregate selection is not only a function of seeking optimum gradation; it is also a function of selecting the most appropriate chip seal for the project (Moulthrop 2003). The Long-Term Pavement Program included the Specific Pavement Study 3 (SPS-3), which looked specifically at the timing of pavement maintenance actions. It found that roads that were in poor condition (i.e., exhibited high levels of distress) when a chip seal was applied had a probability of failure that was two to four times greater than those that were in good condition. It also found that "chip seals appear to outperform the other treatments . . . in delaying the reappearance of distress" (Eltahan et al. 1999).

The binder selection process is a function of the pavement's surface, size and gradation of aggregate, compatibility with local aggregate, and local climatic considerations (Gransberg et al. 1998). One of the major difficulties in the design of material application rates is the nonuniformity of the existing pavement surface. The engineer must remember that variation in the existing pavement occurs both in the transverse and longitudinal directions. The transverse variation is usually defined as the difference in the surface texture on the wheelpaths and outside and between the wheelpaths, including rutting. Longitudinal variation occurs as the surface condition varies along the road from areas where the underlying surface is oxidized to other areas where the surface may be smooth or bleeding. Particular attention should be given when determining binder application rates on pavements displaying varying surface textures. Such conditions necessitate alterations to the binder application rate as the underlying surface changes, making the specification of a single material application rate impossible. As a result, careful characterizing of the existing surface throughout the length of the chip seal project is vital to producing a successful end product.

CHIP SEAL PROGRAMMING

At the heart of a successful chip seal program is commitment to selecting the most appropriate PM treatment for the situation. PM programming that identifies the optimum timing of a chip seal cycle will maximize the economic benefits (Wegman 1991). Figure 7 is a flow chart showing the chip seal program cycle.

Chip seals will enhance pavement condition and extend pavement service life when applied on pavements showing minimal distress (Moulthrop 2003). Again, chip seals are not expected to improve structural capacity to the pavement. However, it appears to be common practice to apply chip seals to pavements that have structural distresses as a stopgap measure. Survey respondents indicated that determining when to use a chip seal could result from a combination of factors, ranging from formula-driven algorithms to birthday sealing or visual evaluation of the pavement surface. Some agencies rely on their internal pavement management system data as the trigger for deciding when to place a chip seal.

By identifying the triggers that initiate selection of a chip seal, the survey responses identified a difference of philosophies in chip seal use between the North American and the international respondents, as shown in Figure 8. In North America, the most common conditions that would trigger a chip seal are evidence of distress and prevention of water infiltration. The international respondents identified the loss of skid resistance and the need to provide a wearing surface as major reasons for chip sealing.

CHIP SEAL DESIGN METHODS

Chip seal design methods largely fall into two fundamental categories: empirical design based on past experience and design based on some form of engineering algorithm. A large body of research is available on formal chip seal design practices. A contemporary chip seal design process involves the determination of grade, type, and application rate for a bituminous binder when given the aggregate size and type,

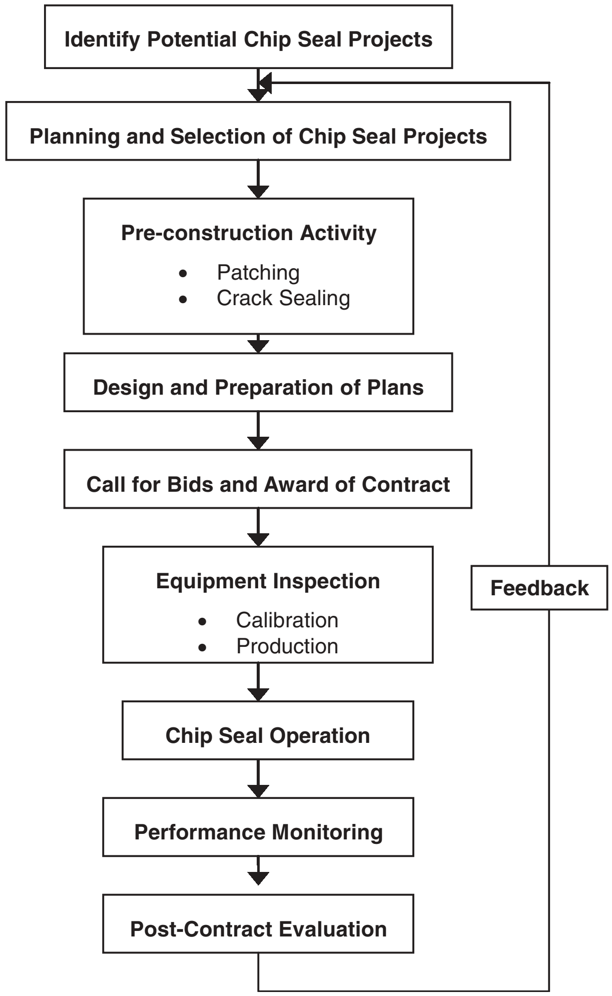


FIGURE 7 Chip seal program cycle [after Senadheera and Khan (2001)].

surface condition of existing pavement, traffic volume, and actual type of chip seal being used. Figure 9 illustrates the proportion of agencies that formally design their chip seal application rates before construction.

The earliest recorded effort at developing a design procedure for chip seals was made by Hanson (1934/35). Traces of Hanson's design can be found in all major chip seal design

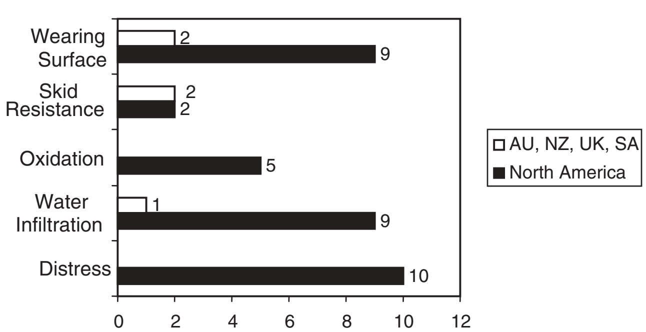


FIGURE 8 Reasons for chip sealing.

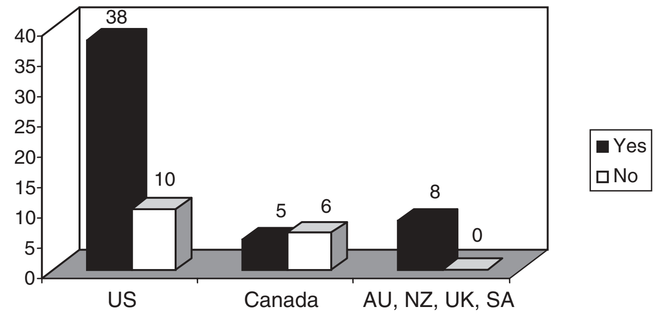


FIGURE 9 Proportion of agencies formally designing chip seal application rates.

methodologies in practice today. The literature review and survey results revealed the use of two generally accepted chip seal design methods in use in North America: the Kearby method and the McLeod method. Although a few North American agencies have also developed their own formal design procedures that are not based on either method, most use either an empirical design method or no formal method at all. Overseas, there are four additional chip seal design methods in use. The United Kingdom's Transport Research Laboratory (1996) has published several editions of a comprehensive design procedure for chip seals (called "surface dressing" in the United Kingdom). Commonly known as Road Note 39, this design method is based on a computer software program. A variation of Road Note 39, Road Note 3, has been developed for surface dressing design in tropical regions. Australia, New Zealand, and South Africa have also developed engineering-based chip seal design methods for use in their respective countries. Australia's is called *Austroads Provisional Sprayed Seal Design Method* (2001). New Zealand uses this method with its own regional variation, and South Africa's method is called TRH3 (i.e., Technical Recommendations for Highways, Surfacing Seals for Rural and Urban Roads). The primary formal design methodologies in practice today in North America and overseas are reviewed and analyzed in Appendix C. Table 1 shows the percentage of North American respondents using the various design methods.

Past Experience in Empirical Methods

The very early practitioners of surface treatments or seal coats appear to have used a purely empirical approach to

TABLE 1
CHIP SEAL DESIGN METHODS IN NORTH AMERICA

Chip Seal Design Method	United States (%)	Canada (%)
Kearby/Modified Kearby	7	0
McLeod/Asphalt Institute	11	45
Empirical/past experience	37	33
Own formal method	19	0
No formal method	26	22

their design. Chip sealing a pavement was considered then, as it is now in many circles, an art. Experience-based design is performed by starting with a base rate for the binder and aggregate determined after years of experience in the field. The main reason for this approach is the variable nature of existing surfaces. Factors such as transverse and longitudinal texture differences affect the ultimate performance of a given chip seal and are independent of the design parameters, thus creating a controversy as to whether a formal design procedure is really an exercise in pointless computation. Agencies that predominantly use empirical methods are basing their design on the assumption that the chip seal contract merely specifies a base rate for binder and aggregate. Therefore, the design is used primarily to estimate the quantities of each to be used during the bidding phase.

CHIP SEAL DESIGN PRACTICES

To accomplish the chip seal design in accordance with the formal methods, the engineer must first determine the input characteristics for project design. These characteristics basically involve the following stages of design:

- Evaluate surface texture;
- Evaluate traffic conditions: volume, speed, percentage of trucks, etc.;
- Evaluate climatic and seasonal characteristics;
- Evaluate and select type of chip seal;
- Evaluate aggregate selection;
- Determine binder application rate; and
- Determine how many hours per day are available for construction operations.

Evaluate Surface Texture

Surface texture refers to the surface properties of the pavement surface (*Sprayed Sealing Guide* 2004). It is a measurement that influences the nominal size of aggregate used for the chip seal and thus ultimately determines material application rates, skid resistance, and road noise. Figure 10 illustrates how the survey respondents typically characterize the surface conditions on the surfaces they are planning to chip seal. None of the North American agencies quantitatively characterize surface texture, whereas 75% of the international respondents characterized surface texture by using the sand patch method. Also of importance is that all of the non-North American respondents characterize surface hardness during the design of their chip seals. The significance of characterizing surface hardness is that the chip seal's aggregate can be selected based on its expected embedment depth into the underlying pavement.

Characterization of the pavement's surface texture is a critical step in the design process because nonuniform surface textures in both the transverse and longitudinal directions make it difficult to design a binder application rate. In Australia and New Zealand, it is a priority to perform corrective measures to restore the pavement's surface before a chip seal application. It is a common practice to treat flushing surfaces with a high-pressure water treatment to remove the excess binder and obtain a sufficient and uniform texture depth. Another technique for correcting surface texture, known as prespraying, involves the application of binder to select portions of the traffic lane and shoulders, while making sure not to apply any binder to the wheelpaths. A number of North American agencies indicated that they require the use of variable spray nozzles on the asphalt distributor to account for the transverse texture differential.

Sand Patch Method

A suitable test procedure for determining the texture depth is the sand patch method, also known as the sand circle test. This method is a procedure for determining pavement surface macrotexture through the spreading of a predetermined volume of sand or glass bead material on the pavement surface of a given area (ASTM E965). Ensuing calculations of the volume of material that fills the surface voids determine the surface texture. The principle of this method is fairly straightforward; the greater the texture depth, the greater the quantity of material lost in the surface voids.

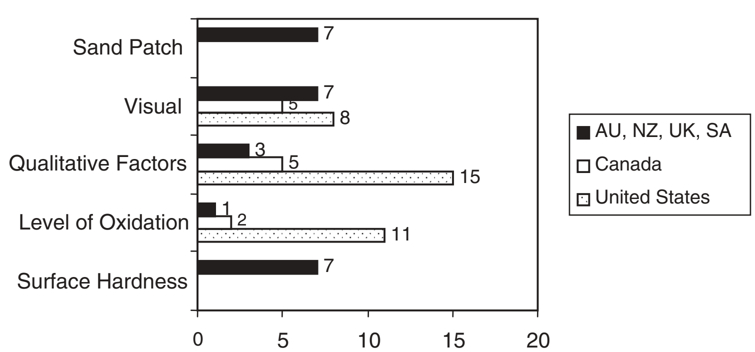


FIGURE 10 Typical surface characterization methods.

TABLE 2
CORRECTION FACTOR FOR EXISTING SURFACE CONDITION

Surface Texture	Asphalt Application Rate Correction [gal/yd^2 (L/m^2)]
Flushed asphalt surface	–0.06 (–0.27)
Smooth, nonporous surface	–0.03 (–0.14)
Slightly porous, slightly oxidized surface	0.00 (0.00)
Slightly pocked, porous, oxidized surface	+0.03 (+0.14)
Badly pocked, porous, oxidized surface	+0.06 (+0.27)

Source: Epps et al. 1980.

Visual Texture Analysis

Visual assessment of the existing pavement surface can also be used in determining binder application rates. Surface characterization using visual assessment is quite subjective, because surface characterization terminology is not consistent within agencies, let alone between them. Despite that issue, visual correction factors are essential correction factors for both the Kearby and McLeod design methods. Table 2 displays a range of correction factors developed for the Kearby method, the foundation of which has become known as the modified Kearby method. Table 3 provides a similar range of correction factors developed for the McLeod method.

Evaluate Traffic Conditions

The traffic volume on the pavement surface, in regard to ADT, plays a role in determining the amount of binder needed to sufficiently embed the chips. Having a fundamental knowledge of local traffic volumes and considerations is essential for determining the appropriate binder design rate. When traffic is used as a chip seal design criterion, the percentage of heavy vehicles should be considered. This may be done by calculating ADT and then using an adjustment factor for the heavy vehicles. Typically, higher traffic volumes reduce binder application rates (*Seal Coat and Surface Treatment Manual* 2003). This is because the heavy traffic will continue to embed that aggregate into the underlying surface after the road is opened to traffic. Additionally, areas where there are substantial starting, stopping, and turning movements also deserve special consideration. These movements all exert forces on the aggregate that cause it to roll, changing its position in the binder and often exposing the previously embedded surface that is covered in asphalt. This condition reduces the road's skid resistance and makes it prone to bleeding. Therefore, specifying a different type of chip seal such as the racked-in seal (discussed later in this chapter) may be in order.

Evaluate Climatic and Seasonal Characteristics

As previously stated, emulsions are thought to be more appropriate than asphalt cements during cool weather construction when ambient temperatures are low, and in areas where the aggregate may be damp (Griffith and Hunt 2000). Thus, the designer must select a binder whose inherent characteristics match the environment in which the chip seal will be placed. The existence of high pavement surface temperatures would indicate the use of a hot asphalt cement binder. The length of daily window in which traffic control can be employed could influence the designer to select a chip seal design that can allow the road to be opened to traffic as quickly as possible. Locations where there are a large number of turning movements could cause the designer to specify racked-in chip seals to protect the aggregate from rolling and bleeding. The designer must also specify the temperature ranges and weather conditions in which chip seal construction is permitted. Finally, the need to apply all types of chip seals in the warmest, driest weather possible using dry aggregates cannot be overemphasized.

Evaluate and Select Type of Seal

Essential to the design methodologies of Australia, South Africa, and the United Kingdom is a contention that different types of seals require different design methodologies. Critical differences based on the construction sequence, number of courses sealed, and variations in aggregate nominal size generally distinguish between the different types of chip seals. The basic divergence with double chip seal design is that the total design binder application rates are less than for a conventional single-course chip seal (McLeod 1969).

TABLE 3
CORRECTION FACTOR FOR EXISTING SURFACE CONDITION

Surface Texture	Asphalt Application Rate Correction [gal/yd^2 (L/m^2)]
Black, flushed asphalt	–0.01 to –0.06 (–0.04 to –0.27)
Smooth, nonporous	0.00 (0.00)
Absorbent—slightly porous, oxidized	+0.03 (+0.14)
Absorbent—slightly pocked, porous, oxidized	+0.06 (+0.27)
Absorbent—badly pocked, porous, oxidized	+0.09 (+0.40)

Source: *Asphalt Surface Treatments—Construction Techniques* 1988.

Single Chip Seal

A single-course chip seal is the most common type of chip seal. It is constructed from a single application of binder followed by a single application of uniformly graded aggregate, as shown in Figure 11. These seals are selected for normal situations where no special considerations would indicate that a special type of chip seal is warranted. It should be noted that the following figures are conceptual diagrams and that other variations on these designs are used in the field.

Double Chip Seal

A double chip seal is constructed with two consecutive applications of both the bituminous binder and the uniformly graded aggregate, as shown in Figure 12. The aggregate in the second application is typically about half the nominal size of the first application. Double chip seals have less noise from traffic, provide additional waterproofing, and are a more robust seal in comparison with a single chip seal (*Sprayed Sealing Guide* 2004). Therefore, double chip seals are used in high-stress situations, such as areas that have a high percentage of truck traffic or on steep grades.

Racked-in Seal

A racked-in seal is a special seal in which a single-course chip seal is temporarily protected from damage through the application of choke stone that becomes locked in the voids of the seal. The choke stone provides an interlock between the aggregate particles of the chip seal (see Figure 13). The choke stone is used to prevent aggregate particles from dislodging before the binder is fully cured. These chip seals are in order in areas where there are large numbers of turning movements to lock in the larger pieces of aggregate with the smaller aggregate and prevent the aggregate from being dislodged before the seal is fully cured.

Cape Seal

Cape seals, named after the area in South Africa where they were invented, are basically a single chip seal followed by a slurry seal (see Figure 14). The original South African technique was to use a larger than normal base stone (up to $\frac{3}{4}$ in.). However, their application in North America and other countries revolves around the use of a smaller nominal-sized aggregate. Cape seals are very robust and provide a shear resistance comparable to that of asphalt (*Sprayed Sealing Guide* 2004).

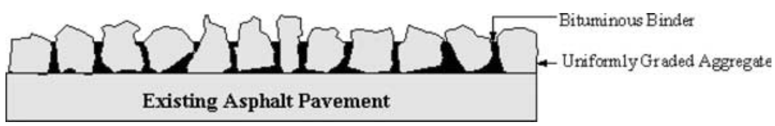


FIGURE 11 Single chip seal.

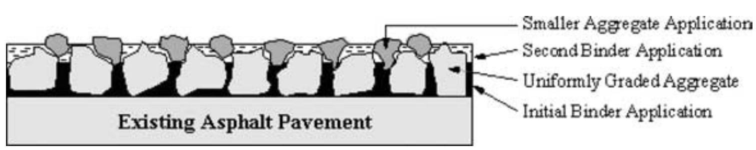


FIGURE 12 Double chip seal.

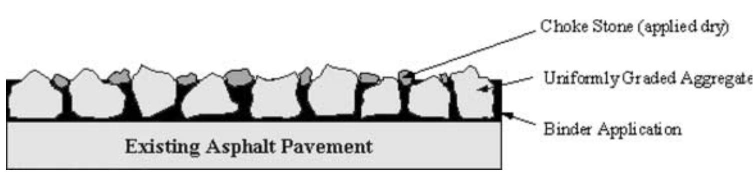


FIGURE 13 Racked-in seal.

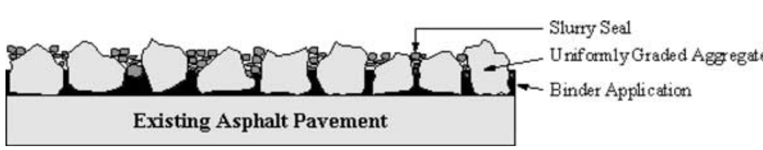


FIGURE 14 Cape seal.

Inverted Seal

Figure 15 shows how an inverted seal is constructed. It is called an inverted seal because the larger-sized aggregate goes on top of the smaller-sized aggregate and is therefore an inverted double seal. These seals are commonly used to repair or correct an existing surface that is bleeding. The Australians have successfully used these seals on bleeding surfaces with 30,000 ADT. Also, the seals are used for restoring uniformity to surfaces with variation in transverse surface texture (*Sprayed Sealing Guide* 2004).

Sandwich Seal

The sandwich seal, as shown in Figure 16, is a chip sealing technique that involves one binder application sandwiched between two separate aggregate applications. Sandwich seals are particularly useful for restoring surface texture on raveled surfaces.

Geotextile-Reinforced Seal

Reinforcing a chip seal with geotextile products can enhance the performance of a conventional chip seal over extremely oxidized or thermal cracked surfaces. The geotextile is carefully rolled over a tack coat, followed by a single chip seal being placed on top, as shown in Figure 17.

Evaluate Aggregate Selection

The selection of the specific aggregate essentially establishes the thickness of the chip seal, because this type of surface treatment is intended to be literally one stone thick. Most agencies use a nominal size that ranges from ⅜ in. (9.5 mm) to ½ in. (12.7 mm). As the nominal aggregate size increases, the surface texture becomes coarser, with a resultant increase in road noise and ride roughness. Additionally, the potential for windshield damage owing to dislodged and projected pieces of aggregate increases as the size of the aggregate increases. The Montana DOT (MDT) *Maintenance Chip Seal Manual* (2000) provides a comprehensive discussion on desirable aggregate characteristics. It states that the characteristics of a "good aggregate" are as follows:

- Maximum particle size—gradation shows ⅜ in. maximum;
- Overall gradation—one-size, uniformly graded;
- Particle shape—cubical or pyramidal and angular (one fractured face of 70%);
- Cleanliness—less than 2% passing the No. 200 sieve; and
- Toughness to abrasion—abrasion not to exceed 30%.

The final aggregate design consideration has to do with the type of stone that will be used to produce the chip seal aggregate. Both natural stone and synthetic aggregates are available and will be discussed in detail in chapter five. It suffices to say at this point that the cost of transporting acceptable aggregates often limits the chip seal designer's options. However, as the aggregate essentially protects the binder that is forming the barrier to water intrusion, the designer should use life-cycle cost analysis rather than simple comparative pricing to determine if a high-quality aggregate is economically viable (*Maintenance Chip Seal Manual* 2000). Once the aggregate is selected, the designer can move on to designing the binder.

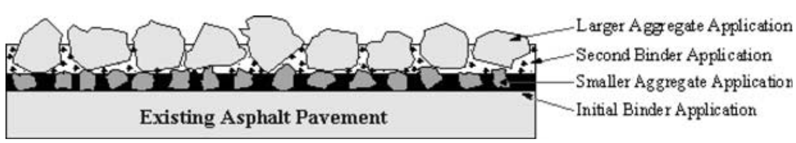


FIGURE 15 Inverted seal.

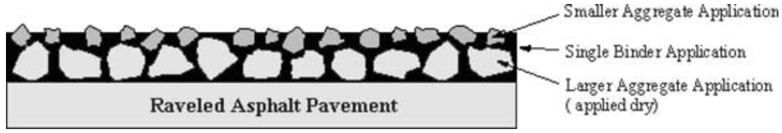


FIGURE 16 Sandwich seal (dry matting).

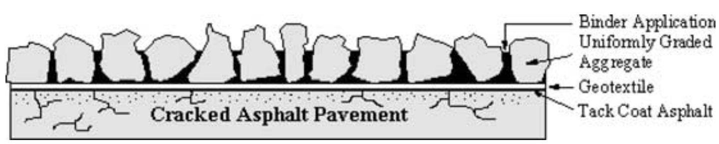


FIGURE 17 Geotextile-reinforced seal.

Determine Binder Application Rate

The previously outlined designed methodologies all determine a basic binder application rate that typically depends on the average least dimension (ALD) of the aggregate and type of chip seal being used. Intuitively, larger-sized aggregates require additional binder to achieve the optimum embedment. There are different schools of thought with regard to embedment. One approach is to seek to achieve approximately 50% embedment after rolling and thus leave room for traffic to finish the process by further embedding the aggregate after the newly chip sealed road is opened. This approach strives to avoid bleeding in the wheelpaths by leaving room for the additional embedment during the chip seal's service life. The major disadvantage of this approach is that it leaves the aggregate that is not on the wheelpaths prone to being dislodged by traffic movements across the lane's width. The other school of thought is to achieve an embedment of up to 70% during construction across the entire road width. This approach will adjust the binder application rate based on the measured or perceived surface hardness and account for hardness in the design. The latter school of thought means being on guard against aggregate loss, and it may mean leaving the road in a condition in which it is prone to bleeding if the design calculations do not exactly match the existing surface.

The design binder application rate is calculated after considering a number of correction features or allowances to the basic binder application rate. Typical adjustments are based on traffic characteristics, surface texture, aggregate absorption characteristics, and surface hardness. Typically, binder application rates are reduced where large traffic volumes are expected to considerably reorient and embed the aggregate after final rolling. The binder application rate may also be adjusted depending on the existing surface texture. It is necessary to increase the application rate on pocked, porous, or oxidized surfaces, because such textures will absorb more binder. In contrast, it is necessary to decrease the binder application rate on surfaces that exhibit susceptibility to bleeding. Surface hardness, as measured by the ball penetration test or a penetrometer, characterizes the likely depth of aggregate embedment into the underlying pavement.

CHIP SEAL DESIGN CONCLUSIONS AND BEST PRACTICES

Unquestionably, all of the design methods can effectively guide inexperienced personnel through the process of chip seal design. The following best practices can be drawn from a comparison of the chip seal design methodologies. To begin, the selection of the binder is a very important decision and should be made after considering all the factors under which the chip seal is expected to perform. After all, the primary purpose of a chip seal is to prevent water intrusion into the underlying pavement structure, and the asphalt layer formed by the binder is the mechanism that performs this vital function.

The previously explained design methods are all based on the assumption that single-course chip seal design requires the use of uniformly graded aggregate spread one stone thick in a uniform manner. The application rates of all methods appear to be based on residual binder, and each method has a procedure for dealing with adjustments owing to factoring the loss of binder to absorption by the underlying pavement surface and the aggregate being used. Contemporary design practices need to determine binder application rates based on surface characterization, absorption factors, traffic conditions, climate considerations, aggregate selection, and type of chip seal being constructed. Another important discovery is that all methods have a design objective for embedment to be between 50% and 70% of the seal's depth. A detailed discussion of formal design methods is contained in Appendix C.

Best practices for chip seal design are difficult to isolate, because there appears to be such a large variation in practices from agency to agency. However, the following can be identified as meeting this project's definition for best practices:

- Chip seals perform best only on roads with low underlying surface distress that will benefit from this technology.
- The international practice is to characterize the underlying road's texture and surface hardness and use that as a basis for developing the subsequent formal chip seal design. U.S. and Canadian agencies obviously recognize the need to factor in the underlying surface into the design, as shown in Figure 10, where the majority of North American responses indicated a routine use of qualitative characterization in the design process. Thus, the next logical enhancement would be to incorporate international methods to quantitatively characterize the underlying surface in the chip seal design process.
- One of those enhancements would be to try using the racked-in seal as the corrective measure for bleeding instead of the North American practice of spreading fine aggregate and sand on the bleeding surface.

CHAPTER FOUR

CONTRACT ADMINISTRATION

INTRODUCTION

The administration of a chip seal project has an immense impact on not only the cost of the project, but also its ultimate performance. The distribution of risk through the chip seal contract can create either an incentive to furnish the best possible quality or a bias to deliver the bare minimum. For example, the heavy use of method specifications that describe in detail the chip seal construction process essentially absolves contractors of long-term performance liability as long as they can prove that they followed the agency's method specifications to the letter. Therefore, it is important for owners to formulate the most appropriate contracts for their chip seal projects. This chapter offers direction on best practices for the administration of successful chip seal programs, from project development to post-completion. The types of contracts used, project planning and programming, and contract management procedures will be discussed.

CONTRACT TYPES

Transportation infrastructure contracts have traditionally been awarded using a low-bid process that is often required by legislation at the state and local level. The survey identified two primary types of low-bid contracts: unit price and lump sum. Lump-sum contracts are warranted in construction projects where the scope of work can be easily quantified. On the other hand, unit-price contracts are used in those situations where the aforementioned conditions do not exist (Clough and Sears 1994). The owner assumes the risk of quantity overruns by agreeing to pay for the actual units applied, rather than paying a premium for transferring the risk of quantity overruns to the contractor by means of a lump-sum price. Given that chip seal projects usually are limited to a defined area of pavement, quantity surveys should be fairly straightforward and not highly variable. Therefore, lump-sum contracts, including the total cost of the project plus mobilization and traffic control, could be used without the agency's incurring a substantial cost increase. The survey results revealed that Arkansas and Nevada are using lump-sum contracts for their chip seal projects. Arkansas also reported that it was getting excellent chip seal results.

Contracting procedures vary significantly between North American and international respondents. As can be seen in Figure 18, North America favors the use of unit-price contracts. As evident by the proportion of international responses totaling more than 100%, international agencies seem to prefer a mix of unit-price and lump-sum contracts, and they have also contracted with design–build, whereby the chip seal contractor is responsible for both the design and the construction.

The greater reliance on lump-sum contracts by international respondents is significant when one considers that all of those nations have developed their own chip seal design methodologies that are based on a much more detailed set of engineering measurements than those used in either the McLeod or the Kearby design methods. Perhaps their more scientific approaches to chip seal design allow those countries to feel more comfortable in transferring the construction material quantities risk to their respective construction industries. Under volumetric unit-price contracts, the contractor has an economic incentive to install as much asphalt and aggregate as possible and thus might construct the seal in a manner not beneficial to the life of the chip seal (Gransberg et al. 1998). Changing the measurement of the chip seal pay quantities to a surface area reverses this incentive. The significance of having an engineering-based design method that does allow for significant adjustments in the field is that quantity overruns may likely be reduced because the profit motive for the contractor disappears.

CONTRACT MANAGEMENT

Chip seal contract management practices in essence define the constraints within which chip seals are designed and constructed. There are a number of contract management issues that must be addressed to ensure that the ultimate performance of the chip seal is purely a function of the quality of the design and construction and not adversely influenced by external administrative constraints. The clarity of the contract documents is essential, because the agency can enforce only what is in the contract.

Construction Season

The literature review showed that chip seals applied early in the summer appeared to perform better than those applied at the end of the summer (McHattie 2001). It is not known what the temperature following chip seal placement will be, so the only way to address that concern is to limit the construction season. This is because these early season chip seals

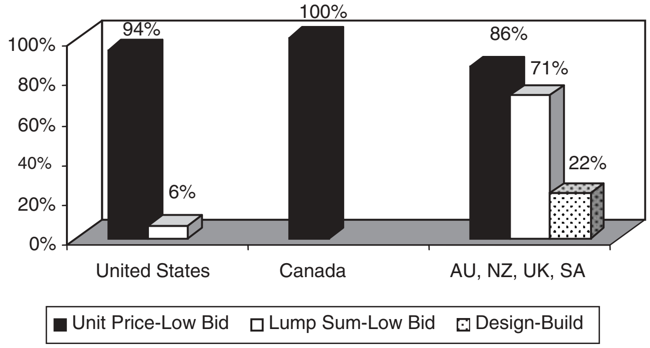


FIGURE 18 Types of chip seal contracts.

have more time to cure before being subjected to cold temperatures. Thus, it seems that a best practice is to award chip seal contracts accordingly to allow for early summer construction, which maximizes curing time before the first cold spell. The British have incorporated an element of risk management into their chip seal design process that relates to the season in which the chip seal will be placed. Figure 19 is taken from Road Note 39 and illustrates this approach to selecting the proper timing within the chip seal season for construction.

Survey respondents were asked to specify their allowable chip seal construction season. Analysis showed that the chip seal season is actually not nearly as variable for chip seal projects as for other highway construction projects such as hot mix paving. Most agencies, regardless of location, contract for a chip seal program of approximately 4 months in northern areas to roughly 5 months farther south. The season is constrained by daily temperature and weather requirements aimed at making sure that the chip seal is applied in the warmest, driest weather possible for the geography. This topic leads into a discussion of the timing in advertising and awarding the chip seal contract, which is commonly called bid letting.

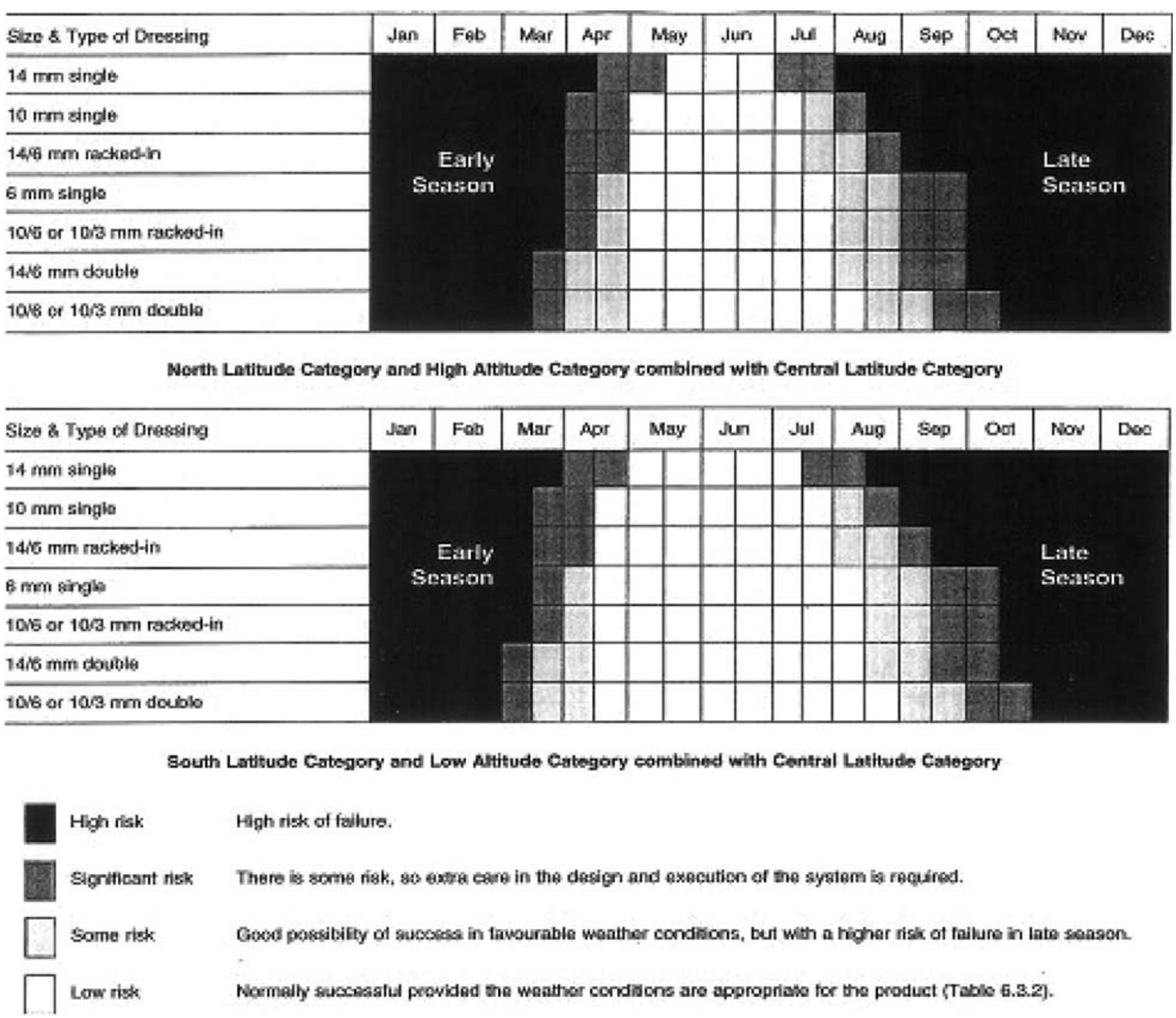


FIGURE 19 Road Note 39 construction season chart (*Source: Design Guide for Road Surface Dressing, Road Note 39* 1996).

Bid Letting

Project planning can provide critical input into the contract management aspects of highway maintenance. Typical project planning requires the letting of the chip seal project to follow, proceed, or coincide with other road works (patching, crack sealing, line painting, etc.). Patching and crack sealing should be completed as far in advance of the chip seal construction as possible to permit maximum curing time for those items (Wegman 1991).

The Washington State constructability study verified that patches and crack sealing are common causes of bleeding owing to localized increase of asphalt content over the sealed cracks and patches (Jackson et al. 1990). One study found that these activities should be completed a minimum of 6 months before the chip seal to allow time for the patches to cure and evaporate most of the volatiles (Gransberg et al. 1998). Early preparation efforts can be realized only with effective coordination between the agency's maintenance operations and contracting group. Therefore, planning maintenance activities should be performed with consideration of the construction schedule.

A contract management system with the ability to plan pavement preparation methods such as patching and crack sealing in the year before chip sealing would be ideal. Another best practice is for chip sealing projects to be contracted in a way that will maximize curing time. Thus, practices such as letting the contract late in the chip seal season should be avoided wherever possible. In line with the best practice of maximizing curing time, contract management should restrict late mobilization of the project, and agencies should enforce the contract's seasonal limitations in those cases in which the chip seal contractor has fallen behind schedule.

Contractor Competition and Competence

The number of contractors bidding for an agency's contracts is an important determinant of both quality and price. Research indicates that larger chip seal contracts produce a better quality of chip seals, because the better qualified contractors appeared to be more attracted to larger contracts, both in terms of quality control and fielding their best equipment and most experienced personnel (Gransberg at al. 1998). Survey respondents were asked to specify their typical project length. As shown in Figure 20, the typical overseas chip seal project is, to the extent possible, more than twice as long as its North American counterparts.

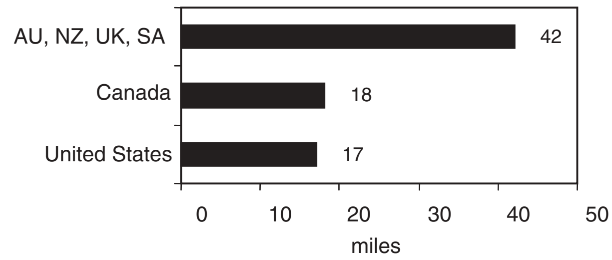


FIGURE 20 Typical length in miles of chip seal projects.

Although typical chip seal project lengths were generally not provided from the counties and cities that responded to the survey, the trend was for counties and cities to express that their organizations encounter problems attracting a satisfactory number of bidders as shown in Figure 21, where 88% of those respondents indicated that they did not have an adequate number of qualified chip seal contractors competing for their projects. The same phenomenon is found with state DOTs that do not routinely use chip seals as part of their PM program. The smaller dollar value of projects within these agencies may isolate them from attracting qualified contractors.

RISK AND WARRANTIES

Contracts are the legal instruments used to distribute risk between the owner and the contractor in the construction industry. The type of construction contract has a significant bearing on how the project's risk will ultimately be allocated. This extends beyond the risk differential between unit-price and lump-sum contracts and into the amount of design that is completed by the chip seal contractor. Some of the survey respondents indicated that they buy chip sealing services as a commodity purchase rather than a construction project, and they allow the chip seal contractor to determine the exact combination of materials and methods. Thus, the distribution of chip seal project performance risk, along with those contractual mechanisms to ensure that the contractor is held responsible for that risk, has been explored. The relationships between these mechanisms, specifically bonding and warranties, and their associated impact on chip seal performance

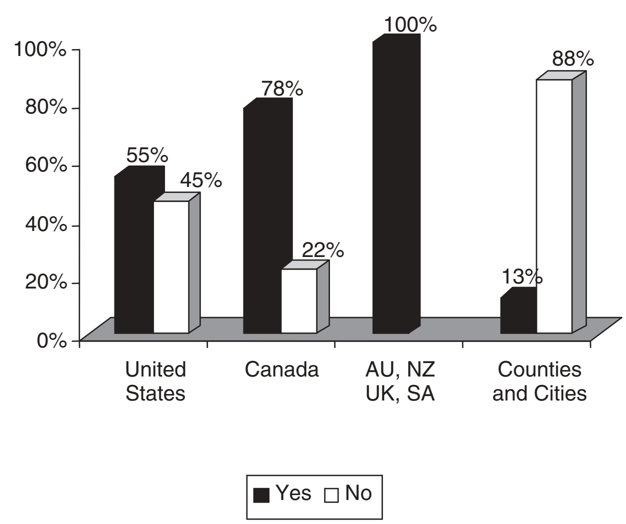


FIGURE 21 Response to adequate number of experienced chip seal contractors.

will be detailed. Because risks are interrelated with responsibility, an agency needs to carefully determine its role in the design and construction of the chip seal so as to most equitably allocate risk between the agency and the contractor.

CONTRACT RISK

Considering different contract types along a continuum of risk allocation allows one to distinguish risk based on project responsibilities. Essentially, there are four categories of contract information that must be evaluated to ascertain the risk allocation contained in a chip seal contract:

1. Design responsibility—Who does the design, the owner or the contractor?
2. Level of material specification prescription—Are end-product, performance, or method specifications used?
3. Level of construction methods prescription—Can the contractor choose the construction method and equipment?
4. Warranty content and period—What are the specific data?

Figure 22 illustrates the continuum of chip seal contract risk and relates the four categories to the type of contract risk that is inherent to each point on the continuum. It should be noted that the three examples shown in the figure are not the only possibilities that can be observed. However, they do represent the majority of this study's findings in both the literature review and the survey responses.

Input-Driven Contracts

As shown in Figure 22, input-driven contracts are differentiated by the agency's having the responsibility to prescriptively specify the chip seal's design and construction methods. Basically, the agency specifies where, when, and how (*Sprayed Sealing Guide* 2004). The contractor simply gets paid for any equipment and materials used on the project. Such contracts are likely to be found with agencies that perform their own field adjustments of application rates, for the contractor cannot be expected to be responsible for the decisions of the agency. Therefore, under input-driven contracts, the contractor is generally not held responsible for end-product performance; it is simply accountable for workmanship. Such contracts have the effect of making performance unwarrantable, because all project risk is allocated to the agency. Input-driven contracts are found in both Minnesota and Texas, two states with extensive and successful chip seal programs.

Output-Driven Contracts

For a contractor to guarantee performance, it needs to have input into the design of the project (Stephens et al. 2002). Output-driven contracts, exhibited in the center of the contract risk continuum, specify the where and when but allow the contractor's responsibilities to broaden into control over design and construction methods. As a result of the contractor's having some control over the end product, output-driven contracts are warrantable. The contractual arrangement in Ohio is an example of how end-product specifications allow the contractor to assume a greater level of project risk.

Performance-Driven Contracts

Overseas, chip seal contracts are increasingly moving toward performance-driven contracts (*Sprayed Sealing Guide* 2004). These contracts, as illustrated at the extreme right of the continuum, no longer have the agencies specifying where, when, or how. That network decision is now the responsibility of the contractor (*Sprayed Sealing Guide* 2004). All design and construction liabilities are assumed by the contractor, with the agency's only responsibility being to specify outcome. Examples of this type are found in New Zealand. The surface texture of the chip seal projects is measured by using the sand patch test after the end of 1 year, and the payment is adjusted according to whether the project's macrotexture has performed as designed. This is a country where hot-mix asphalt pavement is authorized only on roads carrying 20,000 ADT or more (B. Pidwerbeski, Fulton Hogan, Ltd., Christchurch, New Zealand, unpublished interview, Jan. 23, 2004). New Zealand also has many of the environmental challenges faced in the northern United States and Canada in its mountainous areas, where maintenance chip seals installed on top of two- or three-course surface treatments must be resistant to snowplowing (Owen 1999).

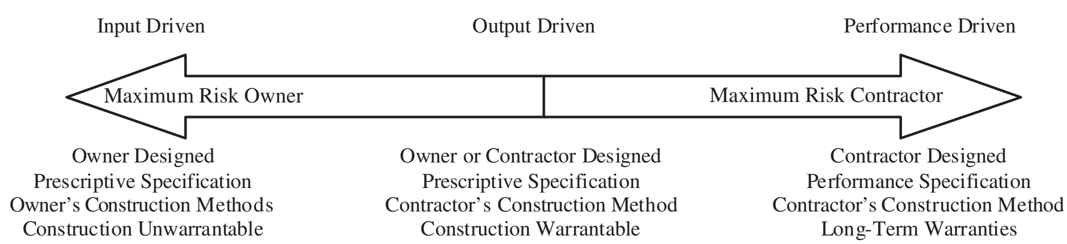


FIGURE 22 Contract risk continuum.

WARRANTIES

Warranties in highway construction are defined as "a guarantee of the integrity of a product and of the contractor's responsibility for repair or replacement of deficiencies" (Anderson and Russell 2001). The goal of a warranty in highway construction is to effectively transfer any risks controlled by the contractor to the contractor—basically distributing risk in a more equitable manner (*Notes for the Specification* . . . 2002). Warranties may also minimize the agency's risk by providing a method to require that the contractor correct failures that are the result of defective materials or workmanship. Most agencies generally require a warranty bond to transfer this risk; the bond provides the assurance that the materials and workmanship of the contractor will not fail soon after project completion and acceptance (Hancher 1999). For instance, Ohio's warranty requires the contractor to provide a 75% maintenance bond for a 2-year period (*Supplemental Specification 882* . . . 2002).

The key point is that the risk would be allocated to the party that has most control over the risk (Anderson and Russell 2001). Therefore, when it is believed that the risk is likely to be beyond the contractor's control, limitations should be placed on the warranty. For instance, in Ohio, the chip seal warranty is restricted to two-lane routes with less than 2,500 ADT and those projects, which do not qualify as PM, are not eligible for having warranty requirements (*Supplemental Specification 882* . . . 2002).

Warranty Requirements

The majority of information obtained on this topic was derived from the survey responses. For this discussion, the survey addressed the types of contracts used, inspection force responsibilities, and warranty requirements. Figure 23 illustrates the proportion of respondents with warranty requirements on their chip seals.

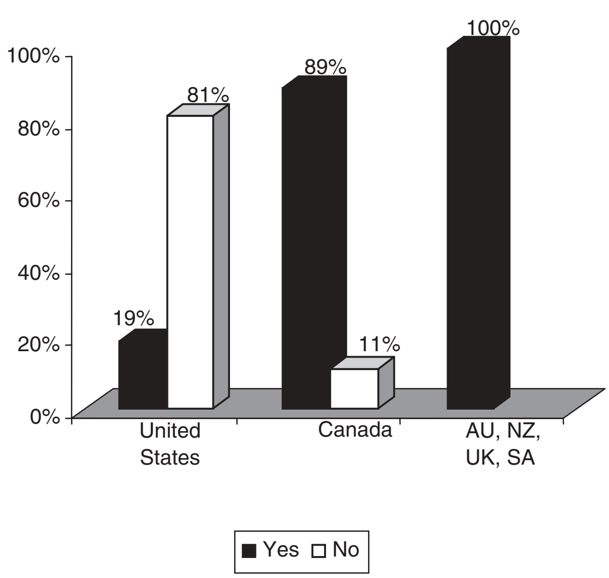


FIGURE 23 Proportion of respondents requiring warranties.

A major disparity between U.S. contracting practices and those of Canadian and overseas agencies lies in the use of warranties. International chip seal programs show a clear mandate toward the implementation of warranty requirements for their chip seal programs. The issue of warranties in the United States was addressed in a comprehensive study of the TxDOT chip seal program (Gransberg et al. 1998). In that state, the construction industry viewed the issue as one of not being able to control the risk that the traffic actually placed on a newly chip sealed road. Additionally, the industry believed that the longitudinal variation in the existing surface condition was so great that it virtually discounted the design calculations to a mere set of formulas to estimate the quantities for the unit-price contract, not a precise engineering design. Therefore, the prevailing notion among both the construction community and TxDOT personnel was that a chip seal was patently unwarrantable. Although warranties are an issue that needs to be addressed not only in Texas but throughout the United States, the situation shown by the international and Canadian responses appears to indicate that this risk can be adequately managed.

Warranty Duration

The length of the warranty period required to detect deficiencies is a concern. The survey responses noted that the most common warranty period for chip seals projects is 1 year. Of the 16 international agencies that have warranty requirements, all but the Yukon Territory of Canada responded that their warranty periods were 1 year in duration. Table 4 illustrates the warranty durations of the six states that have warranty requirements.

New Zealand's Experience with Performance-Driven Contracts

New Zealand's use of sound engineering principles seeks to minimize the uncertainty and variability associated with their chip seal program. The use of these sound engineering principles seeks to optimize material application rates to the point where the end-product specifications in their performance-

TABLE 4
U.S. STATES WITH CHIP SEAL WARRANTIES

State with Warranty	Warranty Duration
California	2 Years
Michigan	2 Years
Nevada	2 Years
New York	1 Year
Ohio	3 Years
Wyoming	4 Weeks

driven contracts transfer the risk of the project to the contractor. Research in New Zealand has shown that there has not been any significant increase in bid prices to reflect the shift in risk caused by their performance-driven contracts (Owen 1999). New Zealand's experience illustrates that when warranties are used in association with performance and end-product specifications, the contractor is provided with the incentive to pursue more innovative technologies and methods for highway projects, leading to economic benefits for all parties involved in the highway construction process (Owen 1999). Perhaps this is a fundamental reason why New Zealand and its Australian neighbors have taken the art out of chip sealing, and developed engineering-based chip seal programs. That the expected service life of a chip seal in these two nations is twice as long of that expected by North American agencies speaks for itself. It should be noted that Michigan had a similar experience when it experimented with chip seal warranties. Research on the Michigan experience noted that "The final results *gave contractors greater flexibility* [emphasis added] in selecting the materials and application methods used for warranted surface treatments" (Galehouse 1998).

CONTRACT ADMINISTRATION CONCLUSIONS AND BEST PRACTICES

This chapter has shown the need for an objective project selection and prioritization system that maximizes the economic benefits of a chip seal. The major conclusion from the warranty portion of the study relates the level of owner prescription to the ability of the owner to impose a warranty requirement on the chip seal contractor. Essentially, as the highway agency demands to retain more specific control over materials and methods, the balance of performance risk swings more toward the agency, and the chip seal contractor becomes merely an instrument to execute the agency's professional judgment, and the ability to effectively warrant the final product greatly diminishes. However, if the agency wants the contractor to assume the majority of the performance risk through a warranty, the agency must allow the chip seal contractor to make the salient detailed materials and methods decisions and to control the outcome of those decisions through promulgated performance specifications. The survey responses from the states indicated that they rate their resultant chip seal product as good to excellent no matter where the states are located on the risk continuum. Therefore, it is impossible to recommend one end of the spectrum over the other. The level of performance liability that a given agency wishes to assume must become a business and policy decision tempered by both the business and political climate in which the projects will be built and the past experience of the agency itself. Therefore, the following four contract administration best practices have been identified:

1. Letting chip seal contracts in time to permit early season construction;
2. Timing the letting of the contract to allow sufficient time for the curing requirements of preconstruction pavement preparation activities;
3. Packaging chip seal contracts in jobs large enough to attract the most qualified contractors; and
4. For warranty chip seal projects, giving the contractor latitude to determine the final materials and methods used to achieve a successful chip seal.

Because Transit New Zealand has been successfully using this warranty method argues strongly that it can be successfully implemented in the United States as well. The measuring of New Zealand chip seal project macrotexture after 1 year of service and then adjusting the maintenance contract payment as a function of actual performance versus design performance creates a strong financial incentive for chip seal contractors to both design and install the best possible chip seal.

CHAPTER FIVE

MATERIAL SELECTION

INTRODUCTION

Chip seal material selection is generally dependent on climatic conditions, binder and aggregate quality, product availability, and an organization's experience with particular practices. Bituminous binders and cover aggregate make up the finished product. The bituminous binder's functions are to seal the existing surface from water intrusion, provide an interfacial bond between the aggregate, and provide the adhesive that bonds the aggregate to the existing flexible pavement surface. The aggregates in a chip seal provide a number of functions. Cover aggregate should provide a good skid-resistant surface while being resistant to polishing, durable against abrasion effects, and resistant to the disintegration caused by weathering (*Seal Coat* . . . 1993). Material selection is becoming more complicated as technology enhancements are continually developing adhesion agents, polymer modifiers, and geotextiles marketed for chip seal use.

AGGREGATE SELECTION

Aggregate selection is critical to determining which type of chip seal to use, which type of binder to design for, and which type of construction procedures to specify. The quality of aggregate is important to the overall success of the chip seal program, and quality involves a number of constructability issues about using aggregates that are clean, durable, and abrasion resistant. The cover aggregate is expected to transfer the load to the underlying surface. It should provide adequate skid resistance and should be durable against climatic effects and traffic wear. In North America, aggregate selection is a function of geography where availability and transportation distance essentially define the aggregate selection process. Local availability often constrains the quality of the aggregate, causing agencies to select lower-quality local aggregates based on cost and availability. This situation conflicts with philosophies in New Zealand and Australia, where aggregate is transported up to 500 mi to ensure the performance and longevity of their treatments (Beatty et al. 2002). They justify the added expense of using higher-quality aggregate with the benefits accrued in extended service life. The cost implications of using the higher-grade aggregate in conjunction with the appropriate binder type should be carefully assessed using life-cycle cost analysis. Another consideration is the ionic compatibility of the aggregate with the selected binder to ensure that good adhesion is developed between the aggregate and the binder. This is especially critical when using emulsions, because they routinely come in either anionic or cationic forms.

Size and Gradation

The aggregate gradation plays a key role in the design, construction, and performance of chip seals. Aggregate size, typically referred to as nominal top size, is the smallest sieve through which all of the aggregate passes. The average of the smallest dimension of the aggregate is referred to as the ALD (Hanson 1934/35). The nominal size of aggregate is selected based on traffic, surface condition, and type of chip seal. Larger aggregate particle sizes are generally more durable and less sensitive to variations in binder application rate (Gransberg et al. 1998). Additionally, as the binder material is meant to seal the surface, a larger-sized aggregate will result in a thicker binder layer, enhancing the quality of the chip seal. However, if not properly embedded and swept, larger aggregate can cause more damage to vehicles immediately after application. Its coarser texture also results in a chip seal with higher noise emissions. The survey results shown in Figure 24 indicate that the most common size for a single-course chip seal is usually a ⅜-in. (10-mm) chip. In addition, survey respondents commonly indicated that double-course seals usually have a ½-in. (12.5-mm) initial aggregate application, followed by a second aggregate application of approximately one-half that nominal size.

The specified gradation should be such that the texture of the chip seal is consistent. Tight gradation bands, which ensure a uniformly graded aggregate, with minimal fines and dust, are necessary for a high-quality project. The literature review and survey responses show a consensus that single-sized aggregate with less than 2% passing the No. 200 sieve is considered ideal (Wegman 1991). The amount of fines in the gradation affects the binder's ability to adhere to the aggregate. Because the amount of fines increases every time the material is handled, Minnesota requires a tighter specification of less than 1% passing the No. 200 sieve to allow for degradation during material movement and installation (Janisch and Galliard 1998). The ideal grading for an aggregate used in chip seals is one in which all the particles of stone are very close to one size, which helps ensure that the chip seal is only one-stone thick. Single-sized aggregate produces a constant embedment depth, which is a critical factor for the success of a chip seal. A uniformly graded aggregate provides a more consis-

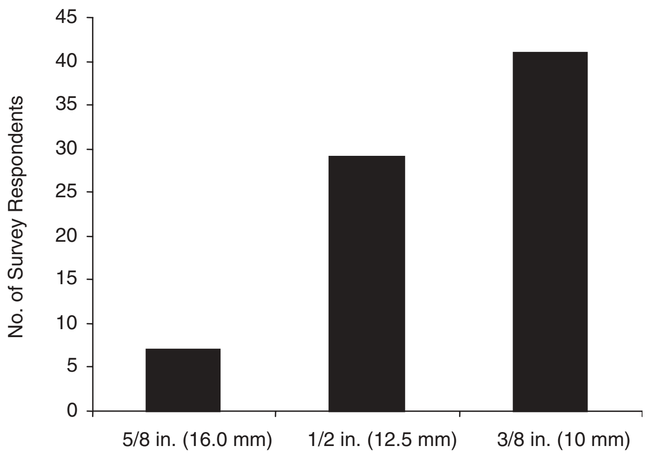


FIGURE 24 Single application chip seal size.

tent embedment that results in improved aggregate retention, surface friction, and drainage capabilities of the seal (McHattie 2001). Table 5 lists typical chip seal gradations taken from various state DOT manuals in the United States. The reader's attention is directed to the Minnesota gradation for choke stone. This was the only U.S. reference that furnished the specifications for this type of aggregate that would be used with the racked-in seals described in chapter three.

Aggregate Shape

The shape of cover aggregate is crucial to the successful performance of a chip seal. Aggregate shape is typically characterized by angularity. As the orientation of the embedded chip is important, cubical aggregate shapes are preferred because traffic does not have a significant effect on the final orientation of aggregate (Janisch and Galliard 1998). Cubical materials tend to lock together and provide better long-term retention and stability. The quantity of flat particles in the aggregate can be determined by the Flakiness Index test (*Seal Coat* . . . 2003). A low Flakiness Index indicates that all the particles are near to having a cubical shape. Under traffic, elongated and flat particles will lie on their flattest side and become covered within the binder. As a result, flatter aggregate is more susceptible to bleeding in the wheelpaths. Because the orientation of cubical aggregate is not as susceptible to displacement by traffic, the opportunity for bleeding is reduced.

The angularity of the aggregate, a characteristic that can be measured by testing for percent fracture, determines a chip seal's propensity to damage by stopping or turning traffic (Wade et al. 2001). Australian practice requires that 75% of the aggregate have at least two fractured faces (*Sprayed Sealing Guide* 2004). Rounded aggregates, as indicated by low percent fracture, are susceptible to displacement by traffic because they provide the least interfacial area between the aggregate and binder. The roundness of the aggregate will determine how resistant the chip seal will be to turning and stopping movements.

Aggregate Cleanliness

Dust on the aggregate surface is one of the major causes of aggregate retention problems. Dust is defined as the percentage of fine material that passes the No. 200 sieve. To improve the quality of the material, the percentage of fines passing the No. 200 sieve should be specified as a maximum of 1% at the time of manufacture (Janisch and Gaillard 1998). Dusty and dirty aggregate ultimately lead to problems with aggregate retention. Asphalt binders have difficulty bonding to dirty or dusty aggregate, causing the aggregate to be dislodged on opening to traffic (McLeod 1969).

It is recommended that the aggregate be sprayed with water several days before the start of the project (*Maintenance Chip Seal Manual* 2000). Washing chip seal aggregate with clean, potable water before application may assist in removing fine particles that will prevent adhesion with the binder. In addition, damp chips will assist the binder in wetting the rock, thus increasing embedment (*Maintenance Chip Seal Manual* 2000). In addition to washing with water, petroleum materials are sometimes used to clean the aggregate before application. Petroleum-based materials such as diesel fuel are commonly used to wash aggregate in Australia and New Zealand (*Sprayed*

TABLE 5
TYPICAL GRADATIONS FOR CHIP SEAL AGGREGATE (% passing)

	State and Gradations							
Sieve Size	Alaska E Chip	Arizona Low Traffic	Arizona High Traffic	Minnesota Aggregate	Minnesota Choke Stone	Montana Grade 4A	South Dakota Type 1A	South Dakota Type 1B
1/2 in.	100	100	100	100	100	—	100	100
3/8 in.	90–100	100	70–90	90–100	100	100	40–70	100
1/4 in.	—	70–90	0–10	40–70	100	—	—	—
No. 4	10–30	1–10	—	0–15	85–100	0–30	0–15	10–90
No. 8	0–8	0–5	0–5	0–5	10–40	0–15	0–5	0–30
No. 40	—	—	—	—	0–5	—	—	0–4
No. 200	0–1	0–1	0–1	0–1	0–1	0–2	0–1	—

Sealing Guide 2004). Such practice is not likely to be found in North America owing to environmental restrictions.

Aggregate Toughness and Soundness

Resistance to abrasion, degradation, and polishing will ensure that the selected aggregate remains functional for the expected life span of the chip seal. It is desirable to use aggregates with resistance to polishing, as indicated through tests such as the British Wheel test (AASHTO T279, ASTM D3319). The results of this test indicate the polished stone value of the aggregate, and the Australians recommend a polished stone value in the range of 44 to 48 (*Sprayed Sealing Guide* 2004). Resistance to degradation and abrasion is also an important characteristic of suitable aggregate. The survey results indicated that testing for those characteristics is quite common and usually measured by the Los Angeles abrasion test (AASHTO T96, ASTM C131). Resistance to weathering and freeze-thaw degradation is generally measured by either magnesium sulfate loss or sodium sulfate loss (AASHTO T104, ASTM C88).

Aggregate Type

The literature review and survey responses revealed that aggregate selection is usually based on the availability and cost of aggregates within proximity to the project. Igneous, metamorphic, sedimentary, and manufactured aggregates have all been successfully used for chip sealing (*Sprayed Sealing Guide* 2004). Table 6 illustrates the varieties of aggregate used for chip seal projects, both domestically and abroad. Limestone, granite, and natural gravels are most widely used in North America.

A comprehensive report studied the suitability of lightweight aggregate as cover stone for chip seals (Gallaway and Harper 1966b). That report indicated that lightweight aggregate proved to be a highly successful cover aggregate for chip seals. A more recent study showed that lightweight synthetic aggregate furnished a superior ability to retain its skid resistance (Gransberg and Zaman 2002). Such a phenomenon was highlighted by Australian and United Kingdom responses that stressed the use of calcined bauxite, a synthetic aggregate, in high-stress areas where chip polishing is an issue. Lightweight aggregates carry the additional benefit of a significant reduction in windshield breakage claims, because their specific gravity is approximately 25% of that of natural stone aggregate (Gallaway and Harper 1966b). However, lightweight aggregates are generally more expensive than natural aggregate and may have high water absorption. Figure 25 illustrates the proportion of respondents using synthetic aggregate. Canadian responses were excluded because none of the provinces responded that they regularly use synthetic aggregates.

Precoated Aggregates

Precoated aggregate can be used to increase the performance of the chip seal as well as to expedite the construction process (Harris 1955). The use of precoated aggregate improves aggregate binding properties, reduces dust in the aggregate, and results in better contrast between the pavement and its markings. Precoating generally involves applying either a film of paving grade asphalt or a specially formulated precoating bitumen to the aggregate. Precoated aggregates considerably shorten the required curing time by minimizing the problems associated with aggregate dust and moisture. Reduced dust enhances the bonding between the aggregate and binder and reduces vehicle damage resulting from loose chips.

Precoating the aggregate chips with asphalt before placement has been found to decrease the initial amount of chip loss (Kandhal and Motter 1991). In that same study, chips that were 90% precoated were found to have up to an 80% lower initial loss than uncoated aggregates. The amount of precoating asphalt is typically 0.8 to 2.4 gal/yd^3 (4 to 12 L/m^3) (*Sprayed Sealing Guide* 2004). The application rate depends on the size and absorptive properties of the aggregate, amount of moisture and dust present, and type of precoating material. Precoated aggregate is typically used with asphalt cement binders. When emulsion binders are used, the aggregate is usually not precoated because the precoating inhibits the breaking of the emulsion (*Seal Coat* . . . 2003). The rough surface of the aggregate provides the interface necessary for the emulsion to cure.

The survey indicated that most U.S. and Canadian agencies do not precoat chip seal aggregates. The states in which precoating aggregate was used with asphalt cement binders were

TABLE 6
NATURAL AGGREGATE USED FOR CHIP SEALS

Type	North America (%)	Australia, New Zealand, United Kingdom, South Africa (%)
Limestone	37	13
Quartzite	13	38
Granite	35	38
Trap Rock	13	25
Sandstone	10	25
Natural Gravels	58	25
Greywacke, Basalt	4	88

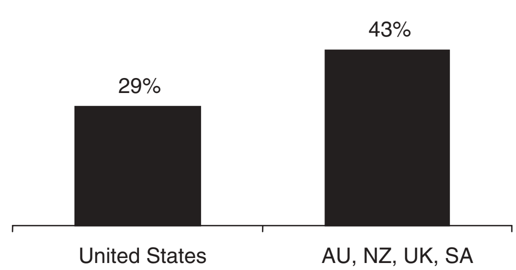


FIGURE 25 Proportion of agencies using synthetic aggregate.

Arizona, California, Colorado, Idaho, Louisiana, Rhode Island, Texas, and Wisconsin. All respondents from Australia, New Zealand, and South Africa indicated the use of precoated aggregate with asphalt cement binders. Alaska, Pennsylvania, Texas, and Wisconsin indicated that they also use precoated aggregate with emulsion binders.

BINDER SELECTION

The Asphalt Institute's *Asphalt Surface Treatments—Construction Techniques* (1988) outlines the following requirements for chip seal binders:

- The binder should not bleed when applied at the appropriate rate.
- At the time of application, the binder needs to be fluid enough to uniformly cover the surface, yet viscous enough to not puddle or run off the pavement.
- The binder should develop adhesion quickly and hold the aggregate tightly to the roadway surface.

There are two main binder types used for chip seal operations: asphalt cements and emulsified asphalts. Climate and weather play an extremely important role in chip seal binder selection. The selection of the binder should be influenced by surface temperature, aggregate, and climate of region during construction operations (McLeod 1969). One of the most important environmental factors to account for when using any bituminous binder is the ambient air temperature. It is accepted that ambient temperatures at the time of construction closely affect the quality of chip seal (Gransberg et al. 1998). In hot weather, bleeding can be prevented with binder selection directed toward the use of "harder" hot applied asphalts and emulsions. During construction with low ambient air temperatures, high humidity, or damp aggregate and pavement surfaces, emulsions are generally believed to be more successful than hot asphalts (*Sprayed Sealing Guide* 2004).

As a result of differences in nomenclature between North America and overseas, international responses to questions about binder were not effective. Figure 26 is a graphical representation of binder selection practices in Canada and the United States. One specific practice that is apparent is that high float emulsions are more widely used in Canada than in the United States.

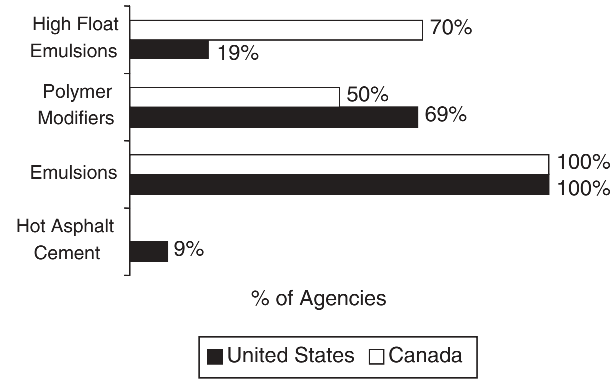


FIGURE 26 Distribution of North American chip seal binder selection.

Asphalt Cement Binders

Some agencies use hot-applied asphalt cement as the binder for chip seals. Soft asphalt cement grades are recommended for use in chip seal applications (*Asphalt Surface Treatments—Specifications* undated). Adhesion agents may be added to these asphalt cements to enhance chip retention. Asphalt cements are advantageous because the roadway can be opened for traffic early after chip seal application and brooming. However, the disadvantages include high application temperatures, sensitivity to moisture in rock particles, and a requirement for more rolling energy. High working temperatures can also create safety concerns that may limit the application season to hot summer months. Harder asphalt cements hold cover stone more tightly, but initial retention is more difficult to obtain (Benson and Gallaway 1966). Table 7 shows the typical hot asphalt binders being used in the United States, as found in the survey responses.

Emulsion Binders

Emulsified asphalts have three primary constituents: asphalt cement, emulsifying agent, and water (*A Basic Emulsion Manual* 1997). The asphalt cement is suspended in the water with the help of an emulsifier. At the time of the application of the binder, the water evaporates, leaving behind the residual asphalt that bonds with the aggregate. One of the major concerns with using emulsions is the spreading time of the aggregate after the emulsion is applied. The phenomenon that occurs when the water evaporates is called "breaking," evidenced when the binder's color changes from brown to black. The aggregate chips must be applied and rolled before the emulsion has broken (Jackson 1990). This emulsion-specific issue indicates that if there is too long a wait, the ability for the rollers to properly seat the aggregate is greatly reduced.

Emulsions can be either anionic or cationic depending on the chemistry created by the emulsifying agent. Generally,

TABLE 7
HOT ASPHALT CEMENT BINDER USE IN THE UNITED STATES

Binder Type	State DOT
AC-10	Georgia
AC15-P	Texas
AC15-5TR	Arizona, Texas
AC-20	Georgia

cationic emulsions outperform anionic emulsions on a chip seal project because they are less sensitive to weather, inherently have antistripping qualities, and are electrostatically compatible with more types of aggregate (McHattie 2001). Cationic emulsions have a positive charge, and because opposite charges attract, they are drawn toward most aggregate particles. Thus, a direct and very rapid bonding between the emulsion and an aggregate or pavement is possible. In addition, emulsions are not as sensitive as asphalt cements to the moisture in aggregate and in the atmosphere. Also, because excessive presence of water reduces the viscosity of the binder, emulsions require much lower material application temperatures than asphalt cements. Asphalt emulsions are graded based on setting speed and the relative viscosity of the emulsion. Table 8 lists emulsion use as found from the survey responses.

High Float Emulsions

High float emulsions are those emulsions that pass the float test (AASHTO T50, ASTM D139). High float emulsions allow for a thicker residual asphalt film on the aggregate, and this prevents runoff of the asphalt from the surface of the road (*Seal Coat* . . . 2003). The wetting agents used in this type of binder penetrate the dust coating and provide a good bond with the aggregate particles. Agencies that use high float emulsions commonly state that they used them in situations where local aggregate is excessively dirty or dusty and the cost to wash them to meet a specification of less than 1% passing the No. 200 sieve would be too expensive. This type of binder can be used with aggregates having as much as 5% passing the No. 200 sieve (Janisch and Gaillard 1998).

Modified Binders

The survey results show that modified binders are used by most agencies, with the only limit to their use being the additional cost. The most common type of modification is through the use of polymers. Research has shown that polymer modification reduces temperature susceptibility, provides increased adhesion to the existing surface, increases aggregate retention and flexibility, and allows the roadway to be opened to traffic earlier (Zaniewski and Mamlouk 1996). Polymers are considered to be beneficial in minimizing bleeding, aiding chip retention, and enhancing the durability of the chip seal, and they are recommended for high traffic volume roads and late season work (Shuler 1990; Wegman 1991).

Integrating crumb rubber into chip seal binders has proven successful at mitigating reflective cracking, improving aggregate retention, and reducing noise emissions. When blended with bitumen, the binder behaves as an elastomer (*Sprayed Sealing Guide* 2004). In Australia, crumb rubber is added at a rate of 16% to 20% by volume (Beatty et al. 2002).

Proprietary additives, known as adhesion agents, are used to improve the degree of wetting of the aggregate by the binder, thus enhancing the adhesion between the binder and aggregate. Adhesion agents are generally proprietary products. Therefore, their application rates are usually specified by their manufacturers. Also known as antistripping agents, these addi-

TABLE 8
ASPHALT EMULSION BINDER USE IN THE UNITED STATES

Binder Type	U.S. Locations	Non-U.S. Locations
CRS-1	Nevada	None
CRS-1H	Kansas, Nevada	None
CRS-2	Connecticut, Iowa, Maryland, Michigan, Montana, Nevada, New York, North Carolina, Oklahoma, Utah, Virginia, Washington, Wisconsin	Ontario
CRS-2H	Arizona, California, Texas	None
CRS-2P	Arizona, Arkansas, Alaska, Idaho, Iowa, Louisiana, Michigan, Minnesota, Mississippi, Montana, Nebraska, North Carolina, New York, North Dakota, Oklahoma, Texas, Washington, Wisconsin, Wyoming	New Zealand, Nova Scotia
HFRS	Alaska, Colorado, New York, Wisconsin	British Columbia, Manitoba, Ontario, Saskatchewan, Quebec, Yukon
HFRS-2P	Colorado, New York, North Dakota, Oregon, Texas, Wisconsin, Wyoming	Saskatchewan, Quebec

Note: Includes city and county responses in state/province designation.

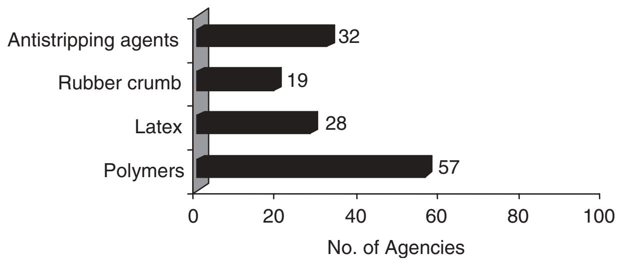


FIGURE 27 Use of binder modifiers.

tives may be added to either the binder or precoating asphalt (*Sprayed Sealing Guide* 2004). In addition, hydrated lime can also be used to enhance adhesion and improve a binder's resistance to oxidation (Dickinson 1984). Figure 27 shows the polymer modified binders to be the most popular among respondents, with 57 agencies reporting that they regularly use them.

AGGREGATE–BINDER COMPATIBILITY

Adhesion between the aggregate and binder is governed by a number of variables, but most important is the type of aggregate. The adhesion between aggregate and binder is a function of mechanical, chemical, and electrostatic properties (Yazgan and Senadheera 2003). Possible mechanical- and chemical-related factors include aggregate dust, moisture content, and binder temperature. Different types of aggregate are better suited to certain binders as a result of electrostatic charges (*Sprayed Sealing Guide* 2004). Basically, the binder and aggregate must have opposite charges. If this is not the case, the binder will not form a strong bond with the aggregate and it will ravel. Therefore, local aggregate is critical to determining which type of chip seal to use, which type of binder to design for, and which type of construction procedures to specify. In addition, porosity and the presence of water on the surface of the aggregate affect binder–aggregate compatibility. Aggregate, which is quite porous, will actually lead to excessive absorption of the binder. Loss of aggregate shortly after construction is indicative of poor adhesion between the binder and aggregate. Before construction, it is essential to conduct laboratory testing to determine the adhesion capability between the aggregate and the binder. An antistrip test, such as ASTM D1664 (AASHTO T182), will assist in determining the compatibility between the aggregate and binder. This test may also highlight the need for an antistrip additive (*Asphalt Seal Coats* 2003).

GEOTEXTILE- AND FIBER-REINFORCED SEALS

The use of geotextiles and sprayed fibers is common practice in Australia and New Zealand. A small number of geotextile-reinforced seals have been constructed in the United States with mixed success. Montana and Nevada responded that their trials were unsuccessful; however, Oklahoma and two counties in California reported that theirs were a success.

International respondents unanimously believe that geotextile-reinforced seals are effective for treating badly cracked, oxidized, or structurally distressed pavements. The construction process basically involves placing a tack coat on the distressed pavement, spreading the geotextile on the tack coat, spraying the geotextile with binder, and then applying the aggregate. Figure 28 shows the mixed success rate of geotextile chip seals in the United States, yet overwhelming success in countries overseas. None of the Canadian provinces responded that they had performed trials with geotextile-reinforced seals.

A fiber-reinforced seal usually involves blowing glass fibers onto an application of a polymer-modified binder, with the aggregate being spread quickly after this application. Fiber-reinforced chip seals require special purpose–built equipment to spray and apply the treatment. In general, these seals are not as effective as geotextile seals, but they are less costly (*Sprayed Sealing Guide* 2004).

MATERIAL SELECTION CONCLUSIONS AND BEST PRACTICES

The conclusions in this area are quite evident. First, the selection of chip seal materials is project dependent, and the engineer in charge of design must fully understand not only the pavement and traffic conditions in which the chip seal will operate but also the climatic conditions under which the chip seal will be applied. It appears that the widespread use of emulsion binder chip seals results from the notion that emulsions are less sensitive to environmental conditions during construction. Additionally, as emulsions are installed at a lower binder temperature, they are probably less hazardous to the construction crew. Binder performance can be improved through the use of modifiers such as polymers and crumb rubber.

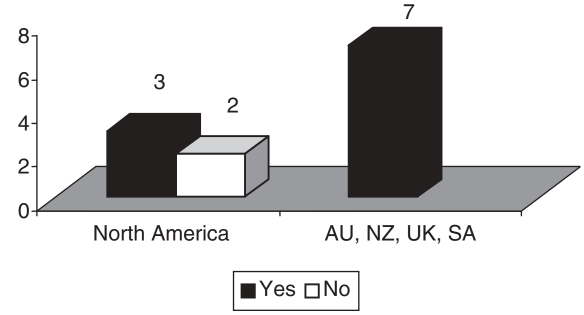


FIGURE 28 Success rate of geotextile-reinforced chip seals.

Next, the selection of the binder is dependent on the type of aggregate that is economically available for the chip seal project in the United States and Canada. That Australia and New Zealand are willing to bear additional aggregate costs to ensure the quality of their chip seals is something that should be seriously considered in North America.

The aggregate should be checked to ensure that electrostatic compatibility is met with the type of binder specified. Also, precoating of the aggregate appears to be required for use with hot asphalt cement binders to ensure good adhesion after application. Finally, it appears that the use of geotextile-reinforced chip seal is promising and should be considered for those roads that have more than normal surface distress and for which an overlay is not warranted. Therefore, several best practices can be extracted from the foregoing discussion:

1. Conduct electrostatic testing of chip seal aggregate source before chip design to ensure that the binder selected for the project is compatible with the potential sources of aggregate.
2. Specify a uniformly graded, high-quality aggregate.
3. Consider using lightweight synthetic aggregate in areas where post-construction vehicle damage is a major concern.
4. Use life-cycle cost analysis to determine the benefit of importing either synthetic aggregate or high-quality natural aggregates to areas where availability of high-quality aggregate is limited.
5. Use polymer-modified binders to enhance chip seal performance.

CHAPTER SIX

EQUIPMENT PRACTICES

INTRODUCTION

The quality of the equipment and the appropriate use of its capabilities undoubtedly play roles in successful chip seal projects. This chapter explores the state of the practice in chip seal equipment selection and use. For this synthesis study, particular attention was paid to the types and sizes of equipment typically specified. The survey responses and literature review identified a number of equipment technologies being widely used abroad, with which North Americans have little familiarity or expertise. They are discussed at the end of the chapter.

The following major types of equipment are typically used on all chip seal projects:

- Asphalt binder distributors,
- Aggregate (chip) spreaders,
- Rollers,
- Dump trucks, and
- Sweeping equipment.

BINDER DISTRIBUTOR

The binder distributor is essentially an asphalt tank with spraying equipment mounted on a truck chassis. Analysis of binder distributors has paid particular attention to binder distributor components, production characteristics, controls and calibration, and spraying operations. The binder distributor has gone through some significant technological advancements, with most manufacturers now offering binder distributors with parallel spray bars (also called wheelpath bars) that enable variable spray rates across the lane. In this discussion, particular attention is being paid to the binder distributor, with a special focus on the use of variable nozzles and multiple spray bars. The use of computerized distributors is becoming more common in North America, with 63% of agencies in Canada and the United States requiring computerized rate-controlled distributors in their specifications, as shown in Figure 29. International specifications requiring computerized distributors appear to be more stringent, with 88% of international respondents indicating that they mandate this technology.

Distributor Components

A straightforward way of understanding a distributor is to break it down into its four essential components:

1. Insulated asphalt tank,
2. Heating system and circulation pump,
3. Spray bar and nozzles, and
4. Distributor controls and gauges.

Insulated Asphalt Tank

The distributor's tank must be capable of efficiently storing the binder at temperatures that allow the heated binder to remain consistent with the appropriate viscosity for spraying operations and within the design specifications. Most of the asphalt distributor tanks used for chip seal work hold from 1,000 to 4,000 gal of liquefied asphalt. They should be equipped with baffles to prevent pressure surges resulting from the asphalt sloshing in the tank when starting and stopping.

Heating System and Circulation Pump

Depending on the make and size of the distributor, either one or two burners are used. These burners are supported at the rear of the tank and positioned with a configuration that directs the flames into the insulated tank's flues. A constant volume circulation pump maintains a pressurized system so that the binder can be uniformly heated. The circulation pump must also spray a constant volume for the entire length of the spray bar for each application. In addition, the pump enables the distributor operator to load the tank with binder from a storage tank.

Spray Bar and Nozzles

Figure 30 shows a typical distributor spray bar. There are many different bar widths available, with typical spray bars on North American distributors being 12 ft wide, whereas agencies that prespray as a method of surface preparation use spray bars as wide as 24 ft (*Sprayed Sealing Guide* 2004).

Spray bars connect a series of evenly spaced nozzles along its length. Nozzles are manufactured with different sizes of openings to permit different volumes to be pumped from the same pump pressure. The nozzles control the spray pattern of bituminous binder shot from the distributor. Appropriate selection of nozzles is critical to achieving a consistent and accurate spray pattern. Nozzles with larger openings need to be considered for viscous asphalts such as

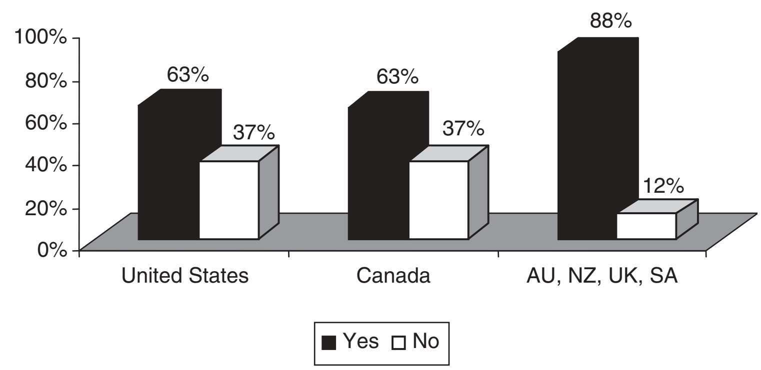


FIGURE 29 Respondents requiring computerized distributors.

crumb-rubber binders (*Sprayed Sealing Guide* 2004). One may be able to modify the spray bar on the asphalt distributor so that it has smaller nozzles in the wheelpaths, a practice that results in more binder in the nontraffic areas than in the traffic areas (Gransberg et al. 1998). The nozzles are installed in the spray bar so that the fan-shaped spray is at an angle to the axis of the spray bar. The angle varies from manufacturer to manufacturer. Figure 31 shows that this angle is usually between 15° and 30°, depending on the manufacturer. All nozzles must be set at the same angle to avoid distortion of the spray pattern.

The spray bar and nozzles are designed to provide an appropriate fan width to ensure uniform transverse distribution, without any corrugation or streaking. Chip seal projects require either double- or triple-lap coverage, as shown in Figure 32. The advantage of using double or triple lapping is that it ensures a uniform distribution of binder across the shot width and that no areas are missed. However, to do so, the spray bar must be adjusted to the correct height or the spray pattern will become distorted. A spray bar with a positive shutoff called a cut-off valve will avert problems with nozzle dribbling. This is particularly important on the end nozzles, which might also be equipped with a deflector to develop a sharp edge on each side of the shot or by changing the angle of the end nozzles.

FIGURE 30 Distributor spray bar.

Distributor Controls and Gauges

Typical controls and gauges include tachometers, volume measuring devices, pressure gauges, and a thermometer. In addition, most distributors manufactured today have computerized systems that not only regulate the pressure of the material to compensate for the speed of the vehicle, but also allow the operator to quickly make accurate rate adjustments, adjust the spray bar height and width, and even shut off individual spray bar sections from the cab. Before the development of computerized rate control systems, a distributor would require more than one operator. Figure 33 shows a contemporary computerized control panel for a binder distributor. Such a panel is capable of allowing the operator to control all distributor operations from the cab of the distributor.

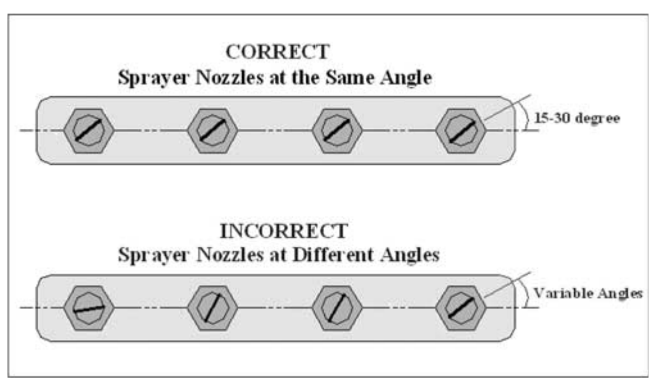


FIGURE 31 Spray bar nozzle alignment.

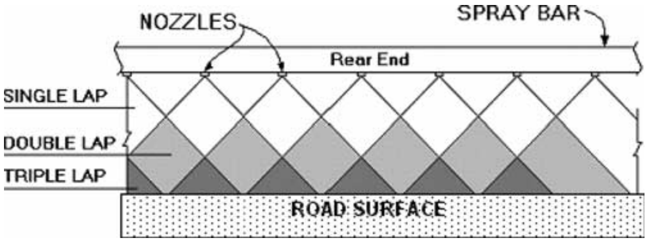


FIGURE 32 Spraying lap coverage.

AGGREGATE (CHIP) SPREADER

The aggregate (chip) spreader must apply a uniform, even layer of aggregate across the full width of the binder. Tailgate box spreaders are commonly used for spot (strip) sealing, whereas self-propelled chip spreaders are used on larger-scale projects. Truck-mounted box spreaders or self-propelled spreaders are equally capable of aggregate application, although the self-propelled spreaders are more controllable, providing more accurate and uniform rates of spread. The most obvious drawback of using a tailgate box spreader is that there are considerable interruptions between loads being spread; it is not a smooth and continuous process like that of the self-propelled spreader. Figure 34 shows a typical box spreader attached at the rear of a dump truck bed.

A self-propelled spreader, equipped with a receiving hopper in the rear, belt conveyors to carry the aggregate to the spreading hopper, and a spreading hopper with adjustable discharge gates, is generally specified for most chip seal projects in North America. A discharge roller that assists in ensuring uniform transverse application rates is located at the bottom of the discharge gate. These spreaders can be equipped with variable-width spreading hoppers that will hydraulically extend to adjust to changing spread widths, such as a shoulder widening. Most manufacturers offer chip spreaders equipped with computerized controls that allow the gates to open and close hydraulically, to compensate for the speed of the spreader. This ensures a constant application rate, regardless of travel speed. Some models also come equipped with a vibratory hopper that further improves the uniformity of the discharge. Figure 35 shows a typical self-propelled aggregate spreader.

FIGURE 33 Computer rate control panel for binder distributor.

FIGURE 34 Dump truck bed aggregate spreader.

A sufficient number of dump trucks should be available to circumvent any interruption in the supply of chips to the aggregate spreader. The dump trucks used on nearly all chip seal projects are tandem axles, because single-axle trucks require additional hookups and therefore increase the chance of spillage and damage to the constructed seal. The dump trucks used for transporting the aggregate need to be compatible with the aggregate spreader, meaning that their hitches must match and that the dump truck bed will not damage the aggregate spreader's receiving hopper. Compatibility of the dump truck's bed and spreader is essential to ensure that aggregate is not spilled onto the roadway. Dump trucks or aggregate spreaders are sometimes equipped with aprons to ensure that the aggregate is effectively dumped into the aggregate spreader's hopper.

FIGURE 35 Self-propelled aggregate spreader.

ROLLERS

The covering aggregate is rolled for the following reasons (*Maintenance Technical Advisory Guide* 2003):

- To orient the aggregate to their least dimension,
- To embed the aggregate into the binder, and
- To achieve mechanical interlock between the individual pieces of aggregate.

It must be pointed out that the roller's purpose is to achieve the desired aggregate embedment depth. It achieves this by redistributing the aggregate and seating it in the binder (Benson and Gallaway 1953). To realize proper embedment and orientation, particular attention must be paid to the time between the aggregate spread and initial rolling, selection of the most appropriate roller type, and determination of rolling requirements such as rolling patterns and number of rollers (Gransberg et al. 2004). Achievement of the full design life of a chip seal is not possible without the bonding that results from proper embedment and orientation of the chips. Figure 36 shows the types of rollers being typically used by the respondents. Respondents were permitted to identify more than one type of roller typically used on their projects.

Pneumatic Rollers

For all practical purposes, pneumatic (rubber-tired) rollers are being universally used. There are two primary functions for rolling chip seal: embed the aggregate into the binder and orient the chips so that maximum bonding can occur. Pneumatic rollers exploit the machine's weight per unit area of surface contact to provide the forces needed to embed the aggregate firmly in the binder. Pneumatic rollers are capable of ballast loading, with either water or sand, which allows the weight of the machine to be varied "from four to six tons" (*Maintenance Technical Advisory Guide* 2003) or "not less than eight tons" (*2003 Standard Specifications* . . . 2003) to be able to achieve the specified contact pressure, which typically is around 80 lb/in.^{2} (*Minnesota Seal Coat Handbook* 1998; *Maintenance Technical Advisory Guide* 2003). In addition to the machine's weight, the number of tires, tire size, and inflation pressure determine the machine's contact pressure (*Minnesota Seal Coat Handbook* 1998). The orientation of the aggregate is facilitated by the seating action of the rubber tires. Most pneumatic rollers are 60 to 80 in. wide and have two axles, with four tires on the front axle and five tires on the rear axle. The alignment of the axles is such that the rear axle tires, when inflated to proper pressure, can compact the voids untouched by the front-axle tire, as illustrated in Figure 37. It should be noted that if the tires are inflated to their maximum pressures on some models of rollers, there may not be 100% overlapping coverage between the front and back tires.

Static Steel-Wheeled Rollers

Static steel-wheeled rollers use a smooth-surfaced cylindrical steel drum to exert rolling forces. Use of steel-wheeled rollers should be carefully observed, because these types of rollers can crush and degrade the aggregate. Steel-wheeled rollers used for surface treatments typically weigh between 3 and 6 tons, and thus are comparatively lighter than those used in asphalt paving (*Seal Coat* . . . 2003). Steel-wheeled rollers may be used on the surfacing

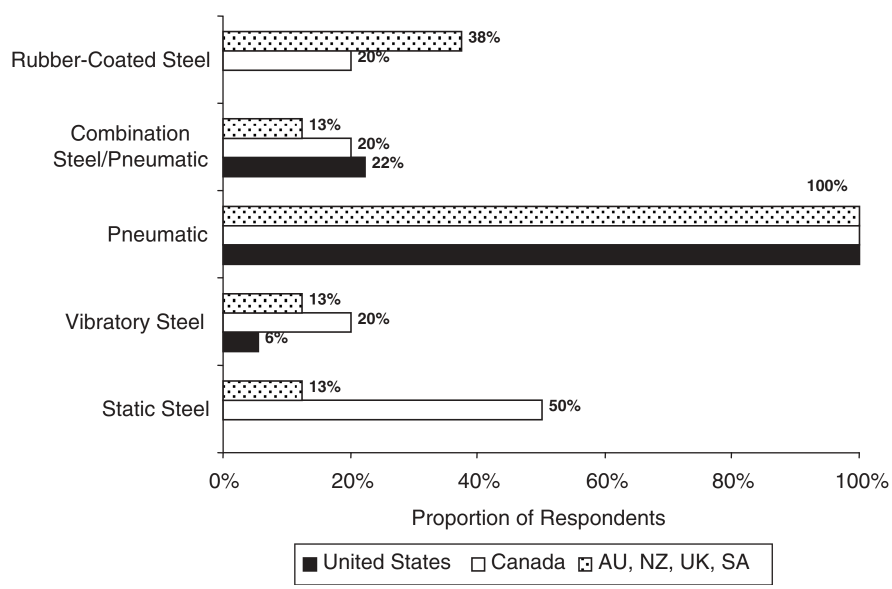


FIGURE 36 Typical types of rollers used.

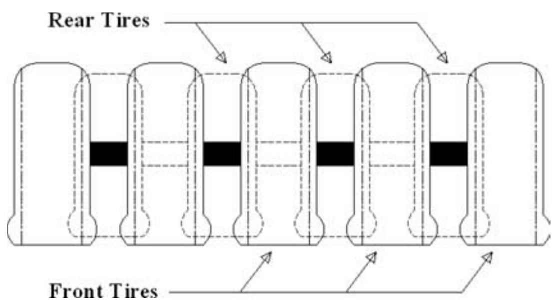


FIGURE 37 Pneumatic roller tire configuration.

to "tighten it up" and create a uniformly prepared surface (McLeod 1969). Steel-wheeled rollers will have difficulties when the underlying pavement is rutted, because they will bridge over the ruts and fail to properly seat the aggregate in the wheelpaths.

Other Roller Types

The other types of rollers are variations on either the pneumatic or steel-wheeled roller. The rubber-coated, steel-wheeled roller has a layer of rubber attached to the drum and causes less damage or degradation to the aggregate while retaining the high contact pressure inherent to the static steel-wheeled roller. With the vibratory steel-wheeled roller, the machine vibrates as it rolls and is thought to better seat the aggregate owing to the vibration's effect. Finally, the combination pneumatic and steel-wheeled roller has a set of pneumatic tires on one end and a steel drum on the other. This piece of equipment attempts to combine the advantages of both roller types in a single machine.

SWEEPING EQUIPMENT

There are two main tasks for sweeping on a chip seal project: cleaning the existing road surface of dust and foreign materials before placing the chip seal and removing excess aggregate from constructed chip seals. There are three different types of sweeping equipment typically used in chip seal construction: rotary brooms, pickup sweepers, and vacuum sweepers.

Rotary Brooms

Rotary brooms, such as the one shown in Figure 38, are employed to remove the excess aggregate from the surface of the chip seal without dislodging the embedded particles. The downward pressure must be kept to a minimum as the broom's bristles will remove the aggregate with a flicking action. The main concern with rotary brooms pertains to bristle selection. Steel bristles are unquestionably more successful than other types in removing foreign materials from the surface of the existing pavement surface before placing the chip seal, but they are more likely to dislodge embedded aggregate after construction. Plastic bristles require earlier replacement; however, they are not as likely to damage the new chip seal.

FIGURE 38 Typical rotary broom.

Rotary brooms generate dust, which can affect visibility for traffic. Additionally, they move the excess aggregate to the side of the road, where it can eventually be swept back onto the traveled way by either rain or vehicles using the shoulder for parking.

Pickup and Vacuum Sweepers

Pickup sweepers are generally used wherever dust must be minimized and it is desirable to remove all excess aggregate from the project limits. A pickup sweeper features a broom that sweeps the aggregate to a suction head that deposits the material in a storage tank. Pickup sweepers are particularly useful in urban areas where aggregate accumulation in gutters or along the edge of the roadway is undesirable. Vacuum sweepers represent purpose-built equipment that removes the excess aggregate through suction only. The lack of contact with the chip seal's surface minimizes damage and is the preferred method of loose aggregate removal in Australia (*Sprayed Sealing Guide* 2004), as well as in some parts of the United States.

UNIQUE EQUIPMENT

An effort has been made to associate construction methods with unique pieces of construction equipment. Thus, a number of pieces of equipment that are not found in North America have been identified and are described here to furnish information to agencies that may be looking for new solutions to their chip seal equipment concerns.

Aggregate Precoating Loader

Precoating of aggregate with a purpose-built aggregate loader is a common practice in Australia and New Zealand (*Sprayed Sealing Guide* 2004). The loader is a unique piece of equipment that takes windrowed aggregate in one end and screens out the dust. It then precoats the aggregate through a trommel screen and loads the precoated aggregate directly into the dump trucks. VicRoads, an Australian road agency equivalent to an American state DOT, contends that using front-end loaders is not acceptable for loading chip seal aggregate owing to the increased fines associated with aggregate degradation during handling (*Bituminous Sprayed Surfacing Manual* 2003). Figure 39 shows this special piece of equipment in operation.

Low-Drop Aggregate Spreader

Low-drop aggregate spreaders are used in Australia. This machine was developed to minimize the bouncing and turning of aggregate as it hits the freshly shot surface. It is believed that this machine increases the uniformity of the aggregate's spread by placing it as close to the surface as possible. From Figure 40, one can see that the operator is facing forward, which also contributes to better control of the aggregate spreading operation.

Rubber-Coated Drum Rollers

Rubber-coated drum rollers are purpose built for chip seal operations. The rubber coating supposedly reduces the crushing of the aggregate inherent with steel-wheeled rollers, while achieving the embedment and mosaic characteristics not capable with a pneumatic roller. The survey responses indicated that rubber-coated drums are commonly used on chip seals (known as surface dressings in British terminology) in the United Kingdom, and they are also used when required on sprayed seals in Australia. British Columbia was the only North American agency that prescribes the use of rubber-coated drum rollers.

FIGURE 39 Aggregate precoating loader.

FIGURE 40 Low-drop aggregate spreader.

Water-Retexturizing Machine

A water-retexturizing machine can eliminate the effects of bleeding by using carefully directed high-pressure water to remove any binder that is submerging the aggregate on the existing surface. These machines have been used in Australia and the United Kingdom to treat bleeding surfaces. Such equipment is especially valuable for preparing the surface of the road before receiving a chip seal. Figure 41 illustrates a water-retexturizing machine in use in the United Kingdom.

Combination Vibratory Pneumatic Rollers

Finally, none of the respondents indicated that they used combination vibratory pneumatic rollers, probably owing to the recent development of the rollers. Trials of vibratory pneumatic rollers are suggested, because they are specifically designed for achieving both the benefits of aggregate particle orientation and embedment compaction. They appear to offer some significant advantages to standard pneumatic

FIGURE 41 Water-retexturizing machine.

rollers in seating the aggregate as quickly as possible in the roller operation.

EQUIPMENT CONCLUSIONS AND BEST PRACTICES

Superior equipment does not prevent all failures. However, the findings of this portion of the study do result in several best practices with respect to chip seal equipment.

1. Use computerized distributors.
2. Preproject analysis of the ability of the chip seal equipment fleet to keep up with the production rate of the distributor is important.
3. The use of variable nozzles reduces the amount of binder that is sprayed in the wheelpaths.
4. Plastic bristles for rotary brooms will minimize aggregate dislodgment during brooming.

Although not a best practice pertaining to this synthesis, the equipment and procedures used overseas show great promise for application in North America. The use of water-retexturizing machines to prepare the road's surface texture and therefore allow a constant rate of binder to be shot should be investigated for North American projects. Doing so would be particularly useful on any roads whose surface is bleeding. Equipment best practices cannot be isolated from the presence of experienced equipment operators and the use of regimented construction practices. The following chapter describes how the construction phase ultimately determines which projects are successes.

CHAPTER SEVEN

CONSTRUCTION PRACTICES

INTRODUCTION

To a great extent, the construction phase drives the quality and performance of chip seals during their service life. Therefore, it is critical that the construction system be well defined, controlling the construction means and methods critical to the performance of the chip seal. Construction practices and procedures vary from region to region and are generally associated with local equipment availability and empirical knowledge of its use. This chapter draws information from both the survey responses and the standard chip seal specifications from several highway agencies to identify those construction practices that are associated with successful chip seal projects. Special attention has been paid to method specifications that prescribe specific construction equipment or that serve to enhance equipment operation.

WEATHER

It is widely recognized that weather-related factors are often responsible for the failure of a newly constructed chip seal (*Asphalt Surface Treatments—Construction Techniques* 1988; *Asphalt Seal Coats* 2003). Because the performance of emulsions depends on evaporation for developing their adhesion characteristics, ambient and pavement temperatures, relative humidity, wind velocity, and precipitation all have an impact on the constructability of emulsion chip seals. Ideal chip seal weather conditions are those with low humidity, without wind, and with sustained high temperatures (*Maintenance Chip Seal Manual* 2000). Chip seals constructed with hot asphalt cements have been shown to experience serious adhesion problems when there is high humidity or moisture present during construction (Wegman 1991). High humidity is a detriment to any chip seal operation mainly because of the resulting poor adhesion between the binder and the aggregate. The MDT recommends that binder be shot only if the humidity is 50% or lower (*Maintenance Chip Seal Manual* 2000). The Minnesota DOT (Mn/DOT) allows chip seal placement with a relative humidity of up to 75% (*Minnesota Seal Coat Handbook* 1998). Additionally, when using emulsions, break times are significantly increased with high humidity (*Asphalt Surface Treatments—Construction Techniques* 1988).

Ambient Temperature

It is accepted that ambient temperatures at the time of construction closely affect the quality of chip seals (*Asphalt Surface Treatments—Construction Techniques*). Because the adhesion process is closely related to the viscosity of the binder, warmer ambient air temperatures result in better adhesion obtained between not only the aggregate and binder, but also between the chip seal and pavement surface. It is also accepted that roadway surface temperature at the time of construction closely affects the quality of chip seals. General consensus among the majority of respondents is that ambient air temperature should be a minimum of 50°F (10°C) when using emulsions, and 70°F (21°C) when using asphalt cements. Responses from Caltrans and a number of counties in California specify a maximum ambient air temperature of 110°F (43°C) for their chip seal construction projects. The Indiana DOT allows placement in air temperatures from 40°F to 60°F only if the aggregate has been heated to a temperature of 120°F to 150°F (*Seal Coat Placement* 2004).

Roadway Surface Temperature

The surface temperature of the existing roadway is also a critical factor, because energy transfer between the binder and the pavement surface greatly affects the resultant viscosity of the binder and the speed at which it will break. In regard to surface temperature, the survey responses showed that significant variation in requirements between agencies and trends on a regional basis were difficult to develop. This is a concern, because low surface temperatures can lead to poor adhesion of the chip seal to the existing pavement surface (*Asphalt Surface Treatments—Specifications* undated). The Asphalt Institute recommends that the temperature of the surface be a minimum of 70°F (21°C) when constructing a chip seal (*Asphalt Surface Treatments—Specifications* undated). If the surface temperature were low as, for example, during the morning, asphalt would be more viscous than desired to attain appropriate adhesion between aggregate and binder. On the other hand, excessive pavement temperatures can also be a problem, particularly with the emulsions. In such a case, viscosity would be so low that binder could not secure the aggregate in place. The survey results indicate that Michigan limits construction to a pavement surface temperature of less than 130°F (54°C), whereas Ohio specifies a maximum surface temperature of 140°F (60°C).

Rain

Chip seals should never be constructed when rain is likely. A rainfall, during or shortly after the construction of a chip seal, can cause a chip seal project to fail. If an unexpected rainstorm ensues, sufficient aggregate should be spread to cover all of the applied binder. If possible, the road should be closed to traffic and, if not, traffic must be kept to a minimum speed during this period, because adhesion between the binder and aggregate is at risk (*Asphalt Seal Coats* 2003). The amount of rolling should be reduced, if not completely ceased, while the aggregate is wet, because the binder may emerge from the voids and be picked up on the wheels of the roller (*Bituminous Sprayed Surfacing Manual* 2003).

Wind

Chip sealing during windy conditions raises a number of issues. Wind can be either beneficial or detrimental to a chip seal during construction. The benefits of wind are directed toward the curing process for emulsions, because wind may speed up this process and thus allow for earlier sweeping and opening to traffic (Gransberg et al. 1998). The destructive nature of wind is noted during the application of the binder. Wind can distort spray patterns, which may lead to a non-uniform application (*Asphalt Seal Coats* 2003). A shield may be installed on the distributor to prevent any disturbance to the spray pattern from wind (*Seal Coat* . . . 2003).

ROAD PREPARATION

Preparation activities before the chip seal work are essential to produce a uniform surface, because most chip seal activities are applied on pavements that show various distresses. A pavement that is well prepared for chip sealing should have a uniformly textured surface and a smooth ride, and it should contain only those minor defects that can be corrected by the chip seal. Figure 42 shows the results of the survey responses for this area. The following are requirements for preparation of a pavement surface for chip sealing (*Asphalt Surface Treatments—Specifications* undated):

- Repair all holes and depressions and replace with a tight surface conforming patch;
- Fill and seal all cracks;
- Level all bumps, waves, and corrugations that will impair riding qualities;
- Remove all excess asphalt on patches and joints; and
- Clean full width of the surface to be treated.

Repairs

Significant deficiencies in the pavement surface must be repaired before applying a chip seal to the roadway. Potholes must be filled, and ruts of significant depths must be leveled. The survey analysis revealed that the most common repair activities to be completed before a chip seal are hot-mix and cold-mix patching and crack sealing. In addition to preventing water from entering the base, crack seals prevent loss of chip seal binder through existing cracks, and patches are intended primarily to level up the pavement surface as well as address isolated pavement distresses. The type of material used for the various repairs is important and can affect the quality and overall longevity of the finished chip seal surface. Patching materials and crack sealant need time to cure before placing a chip seal. This work, when possible, needs to be programmed and scheduled to take place several months in advance of the chip seal construction to allow for crack sealant and paving materials to cure (*Sprayed Sealing Guide* 2004). As a rule of thumb, patching should be completed at least 6 months before construction and crack sealing should be applied at least 3 months before the application of chip seals (Gransberg et al. 1998). Road Note 39, the United Kingdom's chip seal design and construction policy manual,

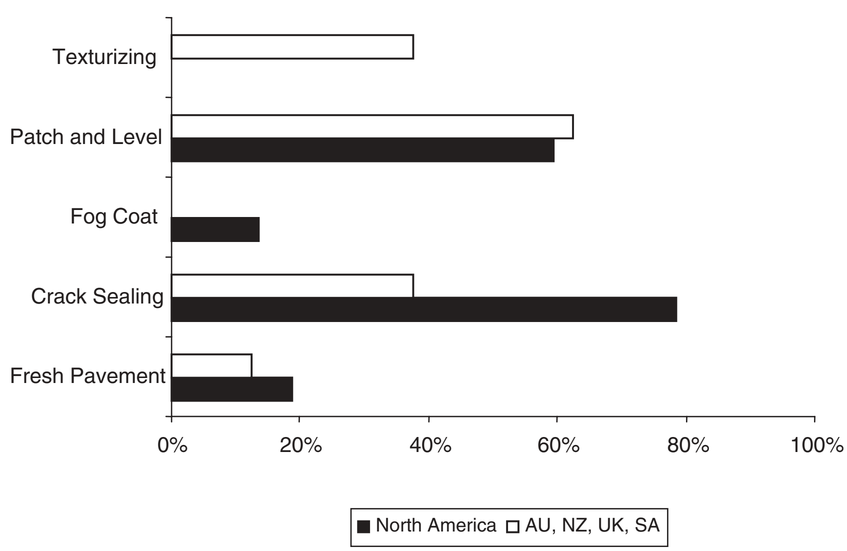


FIGURE 42 Typical road preparation methods.

indicates that surface preparation activities such as patching and crack sealing be completed "the previous autumn" before the year the chip seal will be applied (*Design Guide* . . . 1996). In contrast, the Indiana DOT states that patches must be completed not less than 10 days before a chip seal (*Seal Coat Placement* 2003).

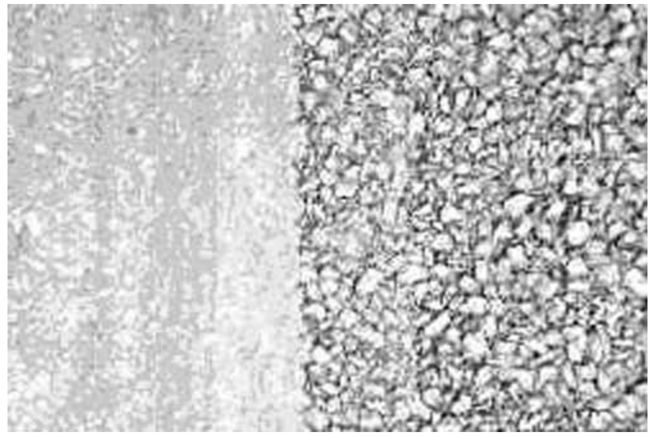
Preconstruction Sweeping

Preconstruction sweeping with rotary broom sweepers often creates considerable dust. If dust poses a danger to the traveling public, a flush truck may be employed to keep dust to a safe level. Preconstruction sweeping is performed to remove any dirt, dust, or debris from the existing pavement surface. Adequate sweeping will provide the necessary clean surface that permits good adhesion with the bituminous binder. It is important that the full width of the existing surface be swept to remove all foreign material to ensure a clean surface before application of a chip seal (*Asphalt Surface Treatments—Specifications* undated). If the surface is swept too far in advance, it may need to be swept again on the day of construction. Figure 43 shows a typical rotary broom sweeper engaged in this task.

Water Retexturizing

The restoration of texture to a road surface that is slick with excess binder can be performed by the use of the water-retexturizing machine as shown in Figure 40. Its results are shown in Figure 44*a* and *b*. In addition to restoring road surface texture before chip sealing is done, water retexturizing could be used as a repair technique for a bleeding surface with poor skid resistance. Logically, care needs to be taken when water retexturizing to prevent nonexcess binder from being removed or stripped from the aggregate, because such a situation could invariably create a greater problem (*Sprayed Sealing Guide* 2004). An AASHTO scan tour report recommended that this and other Australian chip seal techniques be investigated for use in the United States (Beatty et al. 2002).

FIGURE 43 Rotary broom sweeper preparing surface for sealing.



(a) **(b)**

FIGURE 44 (*a*) Before and (*b*) after image of water retexturizing.

Transit New Zealand's belief in the value of water retexturing to prepare existing bleeding surfaces is exemplified by the following statement from the agency's chip seal manual:

> Texturing seal coats . . . can be expected to provide a service life of up to 75% of the normal reseal [chip seal] life, ensuring a satisfactory surface for resealing [chip sealing] at the end of that period (*Notes* . . . 2002).

Prespraying

Australia and New Zealand have identified prespraying as a method for adjusting the transverse surface texture of a pavement surface before construction of a chip seal. Surfaces that have significant disparity in binder content between wheelpaths and non-wheelpaths can be corrected with this technique. The areas outside of the wheelpaths are sprayed with an application of binder sufficient to increase binder content so that it is consistent with the texture of the wheelpaths. The spray run must be carefully planned to circumvent spraying the already binder-rich wheelpaths with additional binder (*Sprayed Sealing Guide* 2004). As is shown in Figure 45, the Australians prespray two lanes of traffic in one pass. Binder-deficient areas such as the centerline joint, the area between wheelpaths, and shoulders are typically sprayed. This technique and water retexturing are done to allow a constant rate of binder to be shot when applying the chip seal, thus eliminating the need to adjust binder and aggregate rates in the field.

SPRAYING OPERATIONS

Before spraying the binder, a number of procedures should be followed to ensure an accurate application:

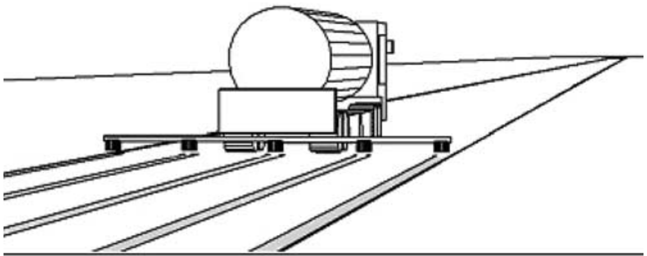


FIGURE 45 Prespraying of areas outside wheelpaths.

- Determine distributor velocity and pump speed;
- Delineate the distributor shot (limits);
- Construct paper joints;
- Blow out nozzles to make sure that none are plugged;
- Ensure proper transverse alignment of distributor; and
- Ensure that binder temperature is within specification limits.

The distributor cannot begin spraying the binder until all other required equipment has been prepared. The aggregate spreader, dump trucks, and rollers must be in position to begin their functions. A paper joint needs to be placed at the beginning of the shot so that the distributor not only attains the proper application speed on crossing the paper joint, but also to provide a neat line and avoid a double application of binder at the construction joint. At confirmation that the distributor's transverse alignment is perpendicular to the centerline, the binder application can commence (Figure 46). The binder application should appear as a uniform sheet of binder across the entire width of the shot.

One of the most important factors in any spraying operation is to visually inspect each shot to ensure that all nozzles are spraying correctly. Scrutinizing the binder distribution will ensure that any spraying problems, such as a clogged nozzle, nonparallel nozzles, or improper application temperature are mitigated immediately.

Distributor Production Characteristics

The chip seal system production rate is constrained by the asphalt distributor's ability to apply the binder. Therefore, every other component in the chip seal equipment train must at least be able to equal the distributor's sustained production to maximize the system's sustained production (Peurifoy et al. 2001). Observations in the field confirm that the distributor sets the production rate for the rest of the equipment fleet (Gransberg et al. 1998). As a result, the types and numbers of each category of equipment must be carefully determined to ensure maximum production, minimum disruption to the traveling public, and desired quality in the finished product. If there are not enough dump trucks, the aggregate spreader will lag behind the distributor, allowing the binder to cool before application of aggregate. This can create the potential for raveling owing to lack of sufficient adhesion between the aggregate and the binder.

If a project uses two distributors at the same time, the distributors' production rate may be greater than that of the aggregate spreader. It is essential that this not become a problem, and in concurrence with the practice illustrated in Figure 47, that the distributor not advance far in front of the aggregate spreader. The Asphalt Institute recommends not applying more binder than can be covered with aggregate within 1 min (*Asphalt Surface Treatments—Construction Techniques* 1988). The operator should always strive to keep a minimal distance between the distributor and chip spreader (*Maintenance Chip Seal Manual* 2000).

FIGURE 46 Spray bar applying bituminous binder.

FIGURE 47 Aggregate spreader within proximity of distributor.

Variable Application Spraying

Variable binder application rates are particularly useful for maintaining a consistent texture across the entire lane width. Because aggregate in the wheelpaths will be embedded more deeply, the amount of binder required will be less than in the other areas of the lane. The use of variable nozzles permits the application of a reduced rate of binder in the wheelpaths, while still achieving the design binder rate outside of the wheelpaths. The justification for using variable nozzles is to combat bleeding in the wheelpaths. The modified Kearby design method recommends that the binder application rate outside the wheelpaths be 20% greater than the design rate calculated for the wheelpaths. (See Appendix C for a detailed case study on a New Zealand contractor's method for designing variable transverse application rates.)

Construction Joints

An area of both aesthetic and service life concern is found with transverse construction joints. Special attention must be paid to the transverse construction joints at the start and end of each shot. Seamless transverse joints can be obtained through placing starting and finishing tar paper at the joint. This should ensure that the correct rate of application is achieved for the full length of the shot and avoid double applications of binder. The binder application shall commence with a running start on a strip of tar paper. The spray bar needs to be stopped on the tar paper at the end of each shot to ensure a straight transverse construction joint (Figure 48).

Longitudinal joints should not be in the center of the lane width, as this leaves an undesirable appearance and can lead to raveling. The number of longitudinal joints should be kept to a minimum and be located so that they will coincide with painted lines between traffic lanes to the greatest degree possible (*Seal Coat* . . . 2003). Careful attention should be given to the skill and workmanship of the distributor operator in regard to the longitudinal joints between adjacent sprays. When the outside nozzle is parallel with the other nozzles, overlapping is essential to ensure that binder application rates are achieved. The distributor operator should make a longitudinal overlap of 2 to 4 in. (50 to 100 mm) to ensure that the texture of the finished surface is uniform (*Supplemental Specification 882* . . . 2002).

AGGREGATE SPREADING

As with the binder distributor, the aggregate spreader needs to have correct transverse alignment before commencing the spread. To allow for timely aggregate coverage of the sprayed binder, it is essential to have two or three loaded trucks in queue behind the aggregate spreader and before the rollers. It is critical that the trucks stagger their wheelpaths, to assist the rolling operations when backing into the spreader (*Maintenance Chip Seal Manual* 2000). A self-propelled spreader pulls the dump trucks through the aggregate spread area, known as a "rock land." As each dump truck is emptied, the aggregate spreader operator releases that truck, and the next truck in queue is attached to the aggregate spreader (Figure 49).

Achievement of design application rates will generally mean that the aggregate uniformly covers the binder without excess aggregate. Overspreading can increase the risk of windshield damage as a result of dislodged aggregate, is not cost-effective, and requires additional post-construction sweeping efforts. Underspreading, as evidenced by visible areas of uncovered binder, will result in aggregate loss, because the excess voids in the aggregate will result in the binder not rising high enough to securely hold the aggregate particles in place. The material needs to be applied thick enough so that the tires of the dump trucks, aggregate spreader, and rollers are not picking up the binder. If the aggregate is being applied at the calculated rate and tires are still picking up

FIGURE 48 Paper used to ensure seamless transverse joint.

FIGURE 49 Aggregate applied with self-propelled spreader.

binder, then the binder application rate is either too high and the aggregate is rolling over on contact with the binder or the aggregate is too wet. When the aggregate spreader is proceeding too fast or alternatively when the binder is too viscous, the aggregate may roll over.

Minor aggregate spread deficiencies such as corrugation or missed areas can be corrected with the use of a drag broom or hand rake. Drag brooms are typically fitted on the roller doing the initial roller pass and will assist in redistributing minor spread inequalities. If the aggregate is uneven, nonuniform, or irregular for any reason, it should be drag-broomed or hand-raked immediately after spreading and before initial rolling.

Excess Aggregate

Loose aggregate, the application of excess chips, is a serious concern for all chip seal projects. There is also a tendency to apply more aggregate than is required when it is paid for by the ton, which ultimately just gets swept off the road and wasted (*Asphalt Surface Treatments—Specifications* undated). Application of chip quantities in excess of 10% of the designed rate makes sweeping challenging, and as the likelihood of unswept excess aggregate increases, so does the likelihood of vehicle damage from flying stones. Excess aggregate can also dislodge embedded chips under traffic, leading to the failure of the chip seal (Shuler 1990). A leading cause of excess aggregate is an improperly calibrated aggregate spreader. In an attempt to curtail excess aggregate spread, Montana performs a sweeping test in the field (*Maintenance Chip Seal Manual* 2000). Excess aggregate spread will be difficult for the sweeping equipment to remove and therefore weighing the quantity of unswept chips is an indication of whether or not the design rate was exceeded. Montana requires that the amount of excess chips be less than 10% of the design rate. The only possible exception to regulations about minimizing excess aggregate are when dealing with areas where extensive stopping and turning movements take place (Janisch and Gaillard 1998). In these locations, application of a controlled amount of excess aggregate may reduce the dislodging of the aggregate in the same fashion as with the racked-in seal method.

ROLLING OPERATIONS

The roller is the tool used to seat the aggregate and create embedment in the hot asphalt or emulsion binder. Rolling operations need to be preplanned and carefully spelled out for field personnel to follow. Verification of the rolling pattern should be done with a visual analysis of lane coverage, aggregate orientation, and embedment (*Minnesota Seal Coat Handbook* 1998; *Seal Coat . . .* 2003). Careful roller operation will ensure that the roller itself does not cause damage to the freshly constructed chip seal, especially by displacing aggregate.

The number of rollers should be determined by the width of the area to be covered, as well as the nominal aggregate size and traffic volume. As nominal aggregate size increases, the area that can be effectively covered by each roller decreases (*Sprayed Sealing Guide* 2004). Development of rolling guidelines such as patterns and minimum rolling time should be directed toward achieving full lane coverage and a similar number of passes for all areas of the lane. The survey responses indicated that most highway agencies use an average of only two rollers, with some agencies "requiring" only one. Such a phenomenon is in agreement with a Texas study, which found that rolling requirements are often ignored in the field because QC testing associated with chip seal rolling operations is not common (Gransberg et al. 1998).

Achievement of the service life of a chip seal is not possible without the bonding that results from proper embedment and orientation of the chips. A recent paper offered a straightforward mathematical equation to compute the required number of rollers based on maximizing distributor production rate (Gransberg et al. 2004). Distributor speed for the desired asphalt rate can be calculated from Eq. 1 (Epps et al. 1981). Spray bar output is dependent on the type of the binder sprayer used.

$$S_f = \frac{9G_t}{WR} \qquad (1)$$

where

S_f = distributor speed (ft/min),
G_t = spray bar output (gal/min),
W = sprayed width (ft),
R = rate of binder application (gal/yd^2), and
9 = conversion factor (from yd^2 to ft^2).

Distributor speed, S_f, can be modeled as the distributor production rate (P) by converting speed from feet per minute to lineal miles per hour. Next, assuming that the production rate of the rollers must be greater than or equal to the planned production of the distributor to ensure that the maximum system production is achieved (Peurifoy et al. 2001), the required number of rollers can be calculated by using Eq. 2 if a specified rolling time (also called linger time) is known.

$$N = \frac{1760PX}{A} \qquad (2)$$

where

N = required number of rollers,
P = distributor production (lineal mph) obtained by converting distributor speed (from ft/min to lineal mph),
X = shot width (yd),
A = roller linger time (yd^2/h), and
1760 = conversion factor (from yd to mi).

Similar computations can be made for each of the different shot widths that will be encountered during a chip seal project. The inspector can then be given a list of how many rollers are required with which to enforce the rolling time provisions in the contract. Figure 50 is taken from the aforementioned paper (Peurifoy et al. 2001) and illustrates the need to plan rolling patterns and roller coverage. It can be seen that the use of three rollers in this example results in an uneven roller coverage—and the least amount of rolling in the areas outside of the wheelpaths where possible loss of aggregate is the greatest potential. It should be noted that this roller has an effective rolling width of only 69.3 in. (176 cm), although it is widely accepted as being a 72-in. (183-cm) roller.

Additional rollers will be required when the viscosity of the binder is increased, "such as with the use of polymer-modified binders or during cool weather construction" (*Notes* . . . 2002). It may seem counterintuitive, but the Minnesota study found that the greatest rolling attention needs to be paid to roads that have light traffic volumes. The reason being that traffic assists in the orientation and embedment of aggregate, actually providing a level of rolling not obtainable with pneumatic rollers (Janisch and Gaillard 1998).

The Mn/DOT constructability study (Janisch and Gaillard 1998) also found that aggregate loss typically occurs outside and between the wheelpaths where the roller coverage is minimum with use of three rollers on a 12-ft (3.7-m) shot width (see number of passes in roller coverage graphs in Figure 50). The use of four rollers provides a uniform coverage and twice as much rolling between the wheelpaths as three rollers for the case study discussed earlier.

Prompt rolling is critical to achieve adequate aggregate embedment. It is important that the aggregate is rolled before the binder becomes cold or too viscous to achieve proper embedment. The justification behind prompt rolling is that as the binder cools, its viscosity may increase, which in turn increases the amount of rolling energy required to achieve the same embedment. Therefore, rolling must follow as closely as practical behind the spreader.

Allowing emulsions to break before applying aggregate contributes to aggregate loss (Jackson et al. 1990). This emulsion-specific issue indicates that by waiting too long, the ability of the rollers to properly seat the aggregate is greatly reduced. The binder will be brown in color at application and will turn black as it breaks. On a hot, low-humidity day, the binder will break in 3 to 5 min (Janisch and Gaillard 1998). A rule of thumb is that the first pass should roll the aggregate just before the binder breaking (*Asphalt Surface Treatments—Specifications* undated).

Rolling Requirements

Effective rolling specifications should detail the roller types permitted, number of rollers required, time between aggregate spread and initial rolling, maximum speed limit, and minimum rolling time or number of passes. Figure 51 shows the typical rolling requirements used by survey respondents.

It is interesting to note that none of the North American respondents specify a rolling time. This does not mean that there are none followed in North America. Some agencies have specified roller linger times in the range of 1,000 to 5,000 yd^2/h (Gransberg et al. 1998). Times in Australia range from 3,000 to 7,000 yd^2/h depending on traffic volume, as shown in Table 9 (*Bituminous* . . . 2003).

New Zealand uses the following equation (Eq. 3) to calculate the required rolling time (T) based on volume of binder to be shot (V_t), the rolling speed (S), and the number of rollers (N) (*Notes* . . . 2002):

$$T = \frac{V_t}{450(S)(N)} \quad (3)$$

where

T = rolling time (h),
V_t = volume of binder (L),
S = roller speed (km/h),
N = number of rollers, and
450 = conversion factor.

A consensus from the survey responses is that a maximum speed of approximately 5 mph (8 km/h) for pneumatic rollers should be mandated, to prevent the roller's tires from displacing the aggregate. Special attention should be given to ensure that the tire pressures of the rollers are set to obtain optimum embedment of the material without undue crushing of the aggregate. Pneumatic-tired rollers should have a total coverage width of not less than 60 in. (1.82 m), while also providing a minimum contact pressure of 40 lb/in.^{2} (2.81 kg/cm^2) to the surface (*Asphalt Surface Treatments—Specifications* undated). Texas specifications require that all tires on pneumatic rollers be inflated so that there is no more than 5 lb/in.^{2} variation within all tires (*Seal Coat* . . . 2003).

Typically, additional rolling is beneficial to the success of the chip seal, unless aggregate degradation is occurring. Australian agencies have recognized that the failure to achieve design embedment depth is primarily a function of achieving QC requirements for rolling time. Thus, minimum rolling times are specified, and the importance of adequate rolling has led to practices in Australia whereby extra equipment operators relieve the roller operators during breaks and even extend rolling operations into the evening after the construction has ceased (*Bituminous* . . . 2003). Table 9 highlights the necessity to pay particular attention to monitoring rolling times on roads with low traffic volume.

Steel-Wheeled Rollers

Steel-wheeled rollers are primarily used on multiple-course chip seals to rapidly achieve levels of embedment not possible

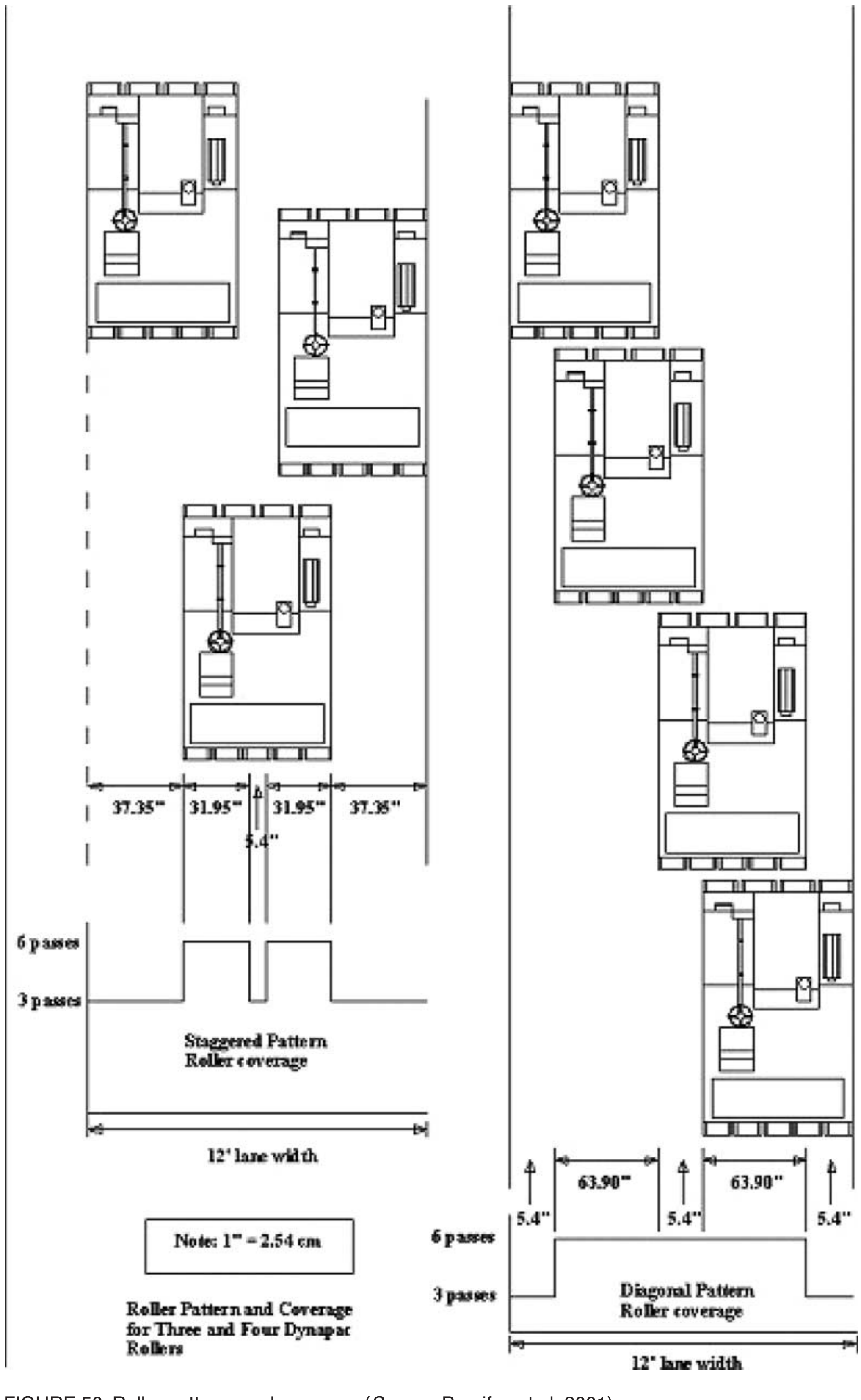


FIGURE 50 Roller patterns and coverage (*Source*: Peurifoy et al. 2001).

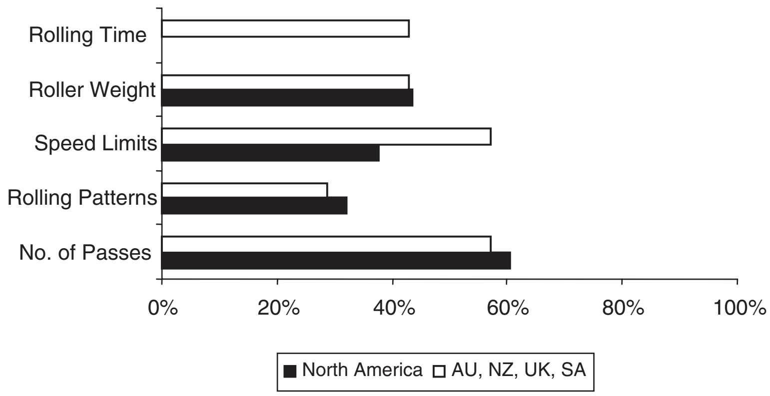


FIGURE 51 Typical rolling requirements.

with pneumatic rollers (McLeod 1969). A survey respondent from the United Kingdom indicated that steel-wheeled rollers had been used primarily to assist with the rideability of the chip seal, that this had been discontinued in favor of using rubber-clad steel rollers. When steel-wheeled rollers are being used, they should be lightweight models of 6 to 8 tons, as heavier rollers will likely break down the aggregate (*Asphalt Surface Treatments—Specifications* undated). Because degradation of aggregate is a serious concern with steel-wheeled rollers, those rollers should be operated only in static mode. If any fracturing or crushing of the aggregate becomes evident, the operation should immediately stop the use of such rollers. As mentioned earlier, steel-wheeled rollers will have difficulties when the underlying pavement is rutted, for they will bridge over the ruts and fail to properly seal the aggregate in the ruts. Steel-wheeled rollers should never be used alone (1) because they will not orient the particles into their least dimension and (2) because of contour bridging (riding on the high spots while spanning over the low spots), they will not contact the entire width. When achieving embedment becomes a concern, and the aggregate is not hard enough to sustain rolling with a steel-wheeled roller, larger pneumatics such as 10-ton, 11-wheeled pneumatic rollers may be an option to consider (Wegman 1991).

SWEEPING AND BROOMING

Sweeping is performed to remove the excess chips from the roadway. With adhesion of the aggregate to the binder, sweeping commences. Adequate sweeping is crucial to remove the excess chips that can dislodge and strike windshields causing damage. Sweeping operations need to be properly executed because the sweeping process itself can dislodge embedded chips (Shuler 1990). However, sweeping the loose aggregate from the roadway immediately following rolling is a critical mistake, for the residual binder has not yet cured enough to bond to the aggregate and underlying road surface.

The time frame for sweeping depends on how long it takes the binder to cure to a point sufficient to retain the aggregate. As the temperature declines into the evening, aggregate retention will be higher if sweeping is done at this time. The WSDOT recommends that final brooming occur "during the cool period of the day (early morning)" and that "if rock is dislodged (by the broom), that brooming be delayed until the asphalt has cured further or the weather is cooler" (*Asphalt Seal Coats* 2003). Typically three passes are required to adequately sweep each driving lane (*Seal Coats* . . . 2003). Figure 52 illustrates the typical number of sweeping passes as identified by the survey respondents. Of note is that in spite of the number of sweeping passes required, the objective should be to remove all excess aggregate from the surface of the chip seal. Logically, the sweeping operation should direct dust away from the traveling public. In areas where loose aggregate cannot be swept off the side of the road, a pickup sweeper should be used.

Sweeping should be started in the center of the pavement and progress to the edges (*Seal Coat* . . . 2003). Post-construction sweeping may occur for several days after the

TABLE 9
MINIMUM ROLLING TIME

	Traffic Volume (vehicles/lane/day)		
Aggregate Size	<300	300–1,200	>1,200
		[yd^2/h (m^2/h)]	
1/4 in. (5–7 mm)	4,780 (4,000)	5,975 (5,000)	7,170 (6,000)
3/8 in. (10 mm)	3,585 (3,000)	4,180 (3,500)	5,380 (4,500)
9/16 in. (14 mm)	2,990 (2,500)	3,585 (3,000)	4,180 (3,500)

Source: *Bituminous* . . . 2003.

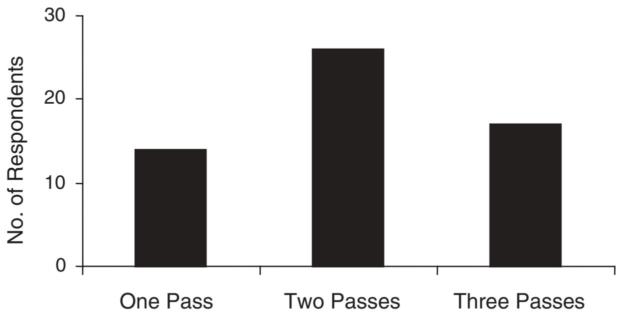


FIGURE 52 Typical brooming requirements.

placement of the chip seal. Australian agencies follow the sweeping operations with a roller to ensure that any disturbed aggregate is rolled back into place (*Sprayed Sealing Guide* 2004). If embedment is visibly low after sweeping, a fog seal, which is a second application of binder sprayed on top of the aggregate to enhance adhesion, should be applied to the chip seal. The MDOT recommends that if the embedment is more than 80%, no fog seal be applied even if one is required by contract (*Maintenance Chip Seal Manual* 2000).

TRAFFIC CONTROL

Traffic control designed in accordance with the *Manual on Uniform Traffic Control Devices* is not only vital to the safety of the traveling public and construction workers, it is also an indispensable tool for achieving levels of orientation and embedment beyond conventional rolling. Vehicle damage can also be prevented through adequate traffic control. Ample traffic control should be in full force for every chip seal project. Generally, loose gravel signs complement signage that indicates the reduced speed limits.

Traffic control is generally accomplished using signage, pilot vehicles, and flaggers during construction operations. The consensus among survey respondents was that the maximum speed limit should be 25 mph (40 km/h). A pilot vehicle is recommended to not only provide safe passage to the traveling public at reduced speeds, but also to assist in reducing windshield damage and increasing aggregate embedment. Besides restricting the speed of traffic through the work zone, a pilot vehicle can stagger traffic movement on the new chip seal to prevent vehicles from traveling in the same wheelpaths and helping to embed stone retention outside of them (*Asphalt Seal Coats* 2003).

It is good practice to delay the opening to normal traffic speeds until the midday road surface temperature drops, such as in the evening (McLeod 1969). The construction operation should avoid opening the chip seal to uncontrolled traffic in hot conditions when the ability of the binder to hold the aggregate is reduced (McLeod 1969). Opening a freshly constructed chip seal to traffic during midday is not recommended, because the binder is less viscous and there is an increased chance of the loss of aggregate. Asphalt cements are advantageous during hot weather because the roadway can be quickly reopened to traffic.

CONSTRUCTION PRACTICES FOR HIGH-VOLUME TRAFFIC

Survey results indicated that chip seals may be highly effective on high-volume traffic roads. California, Colorado, and Montana regularly construct chip seals on roads with greater than 20,000 ADT and reported that the performance of their chip seals was either good or excellent. The belief that chip seals are not suitable for high-volume traffic roads is rooted in perceptions that chip seal projects on those roadways are predestined to failure because of the liability and claims associated with damage to vehicles from loose aggregate (Shuler 1990).

Several factors should be considered to prevent vehicle damage for high-volume traffic applications. Common causes of vehicle damage from chip seals include the application of excess aggregate, inadequate low-speed traffic control, and poor sweeping (Shuler 1990). Shuler's recommendations for construction practices when constructing high-volume chip seals are shown in Table 10. Sweeping is essential to high-volume traffic chip seal applications. Vehicle damage can be avoided if the excess chips placed to minimize chip pickup on

TABLE 10
BEST PRACTICES FOR CONSTRUCTING HIGH-VOLUME CHIP SEALS

Practice	Reason
Reduce excess aggregate	Sweeping proficiency increased
Reduce aggregate size	Larger aggregate causes more damage
Use of double chip seals	Smaller aggregate in contact with tires
Use of lightweight aggregate	Lower specific gravity causes less damage
Use of choke stone	Locks in larger aggregate
Fog coat	Improved embedment
Precoat aggregate	Improved adhesion
Use of polymer modifiers	Improved adhesion
Allow traffic on chip seal	Vehicles provide additional embedment
Control traffic speed on chip seal	Reduced whip-off

equipment tires are swept from the pavement surface before opening to traffic. In cases where chip seals fail after a period of months owing either to loss of aggregate or flushing, the problems may be caused by materials, design, or construction (Shuler 1991).

Figures 53 and 54 summarize chip seal construction practices. Their intent is to present this information in a comparative manner where it can be easily understood and applied.

QUALITY ASSURANCE AND QUALITY CONTROL

The success of a chip seal is highly associated with the control implemented over the quality of materials and construction. Constructability reviews during planning, design, and construction phases improve the quality of only the final product. The QC measures widely implemented intended for chip seal projects are provided by material testing and inspection forces.

This synthesis subscribes to the definitions of QC and quality assurance (QA) recommended by TRB (1999). As such, QA is the "planned and systematic actions necessary to provide confidence that a product or facility will perform satisfactorily in service." Additionally, QC is defined as the "quality assurance actions and considerations necessary to assess production and construction processes so as to control the level of quality being produced in the end product." Both terms are inherent in all of the best practices identified in this synthesis.

Special attention was directed toward identifying laboratory and field tests that can be correlated with successful chip sealing practice. The QC section of the survey emphasized the requirements that respondents use for ensuring conformance of the materials and the construction operation to the contract specifications. Table 11 is an indication of some specific chip seal testing methodologies that were verified in the literature review.

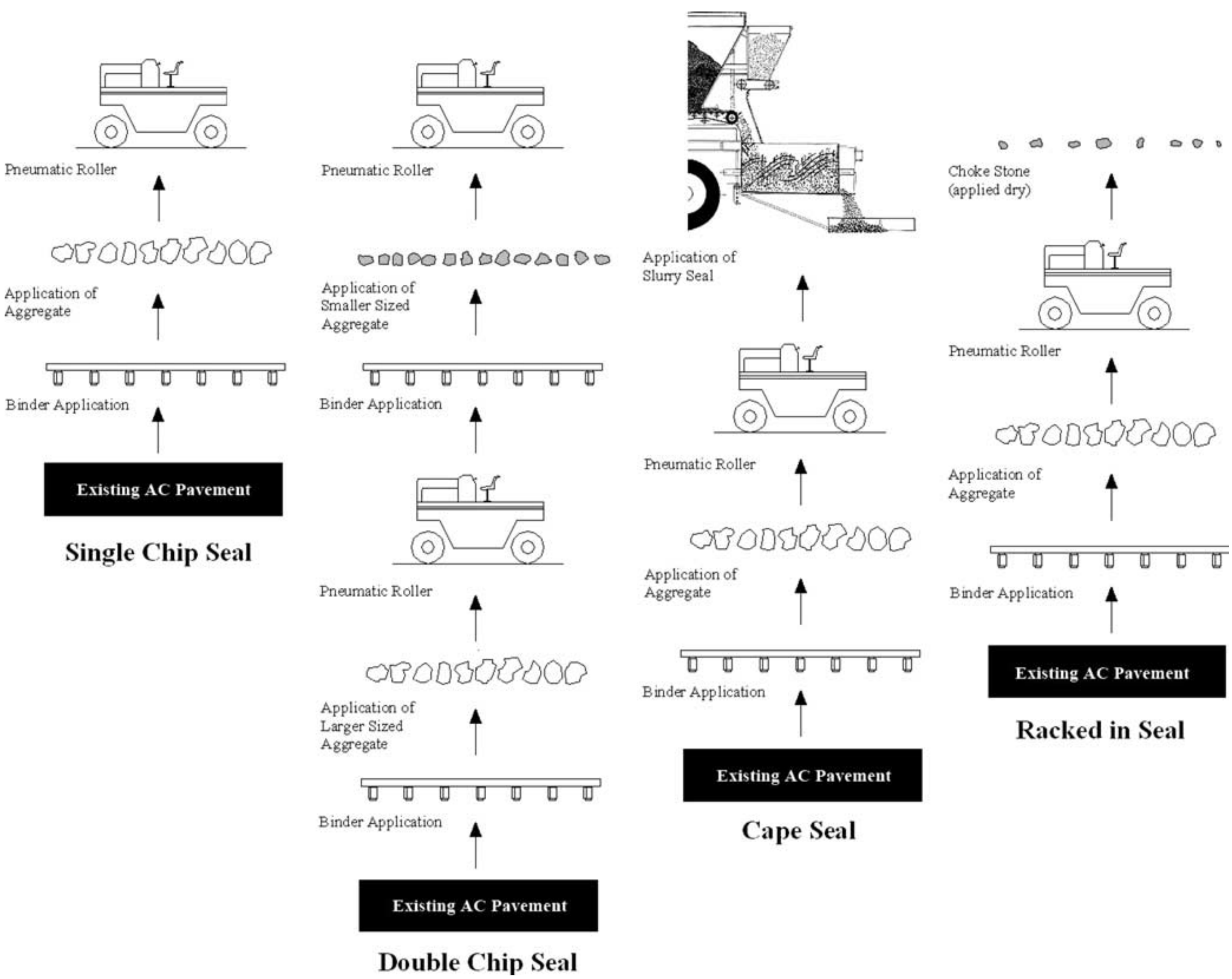


FIGURE 53 Preventive maintenance chip seal construction practices (adapted from Peshkin et al. 1999).

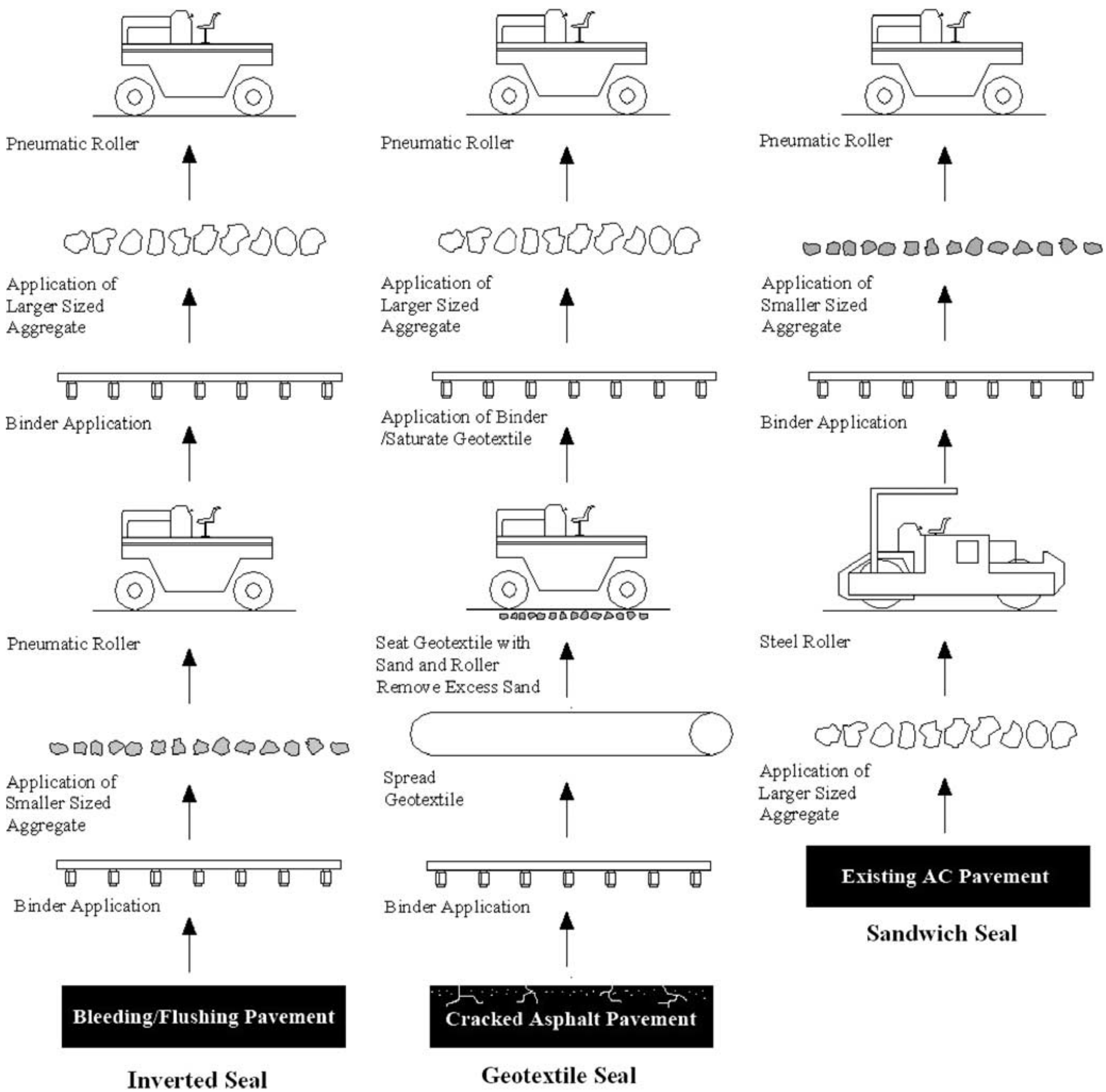


FIGURE 54 Chip seal construction practices for distressed pavements (adapted from Peshkin et al. 1999).

LABORATORY DESIGN AND MATERIALS TESTING

Chip seal material testing should be performed both in the laboratory and in the field. In regard to quality, it is essential that an aggregate sample be provided to the materials laboratory performing the design of the chip seal. The critical reason for providing binder and aggregate samples during the design phase is to ensure that the binder is compatible with the aggregate selected for use on the project. Failure to design the chip seal based on the binder and aggregate that the contractor will use could lead to failure if the specifications require the use of a binder that is incompatible with the aggregate. The compatibility of aggregate–binder combinations should be tested in the laboratory (Yazgan and Senadheera 2003). Table 12 illustrates the aggregate–binder compatibility tests identified in the literature review.

FIELD TESTING

There is a significant material testing QA and QC concern in regard to aggregate testing in the field. With chip seal material

TABLE 11
QUALITY CONTROL TESTS FOR CHIP SEALS

Name of Test	Property Measured	Standard Test Number
Manufacturing Control		
Sieve analysis	Gradation	AASHTO T26, ASTM C136
Cleanness value	Fine materials	Caltrans Test 227
No. 200 washed sieve	Fine materials	AASHTO T11, ASTM C117
Foreign materials	Clay and friable particles	AASHTO T19, ASTM C29
Decantation	Dust	Tex-217-F, Part 1
Plasticity index	Deleterious material	AASHTO T90, ASTM D4318
Aggregate Soundness		
Los Angeles abrasion	Abrasion resistance	AASHTO T96, ASTM C131
British pendulum test	Skid resistance	AASHTO T278, ASTM E303
British wheel	Polishing	AASHTO T279, ASTM D3319
Sodium sulfate loss	Freeze–thaw degradation	AASHTO T104, ASTM C88
Magnesium sulfate loss	Freeze–thaw degradation	AASHTO T104, ASTM C88
Aggregate Shape		
Percent fracture	Roundness	ASTM D5821
Flakiness index	Flatness/elongation	ASTM D4791
Asphalt Binder		
Emulsion penetration	Penetration	ASTM 244
Emulsion viscosity	Saybolt viscosity	ASTM 244
Emulsion sieve test	Gradation	ASTM 244
Asphalt cements	Penetration	AASHTO M226, ASTM D3381
Float test	Drain-off, high float	AASHTO T50, ASTM D139

testing, most aggregate properties are considered only in the design process. In general, survey responses indicated that field sampling is very limited for aggregates. If the aggregate is to be stockpiled on site or at a local plant, it is important to test samples from the pile to ensure that the material has not been susceptible to segregation or degradation during the period following its manufacture. Aggregate transport and stockpiling can significantly alter the gradation of aggregate and generally increase the amount of fine material in the aggregate (Gransberg et al. 2000). In such conditions, the original gradation of the stockpile can adversely change. However, it is intuitive to carry out field sampling, especially in regard to gradation, at the stockpile site. In addition, the only logical way to confirm that the same materials tested in the laboratory are being used for the project is to perform random samples at either the stockpiles or from the aggregate spreader applying the material.

In addition, binders can become contaminated by foreign substances inside the tanks of transports. Survey responses indicated that field testing of binders is more prevalent than is field testing of aggregate. Figure 55 shows that 44% of North American respondents and 75% of overseas respondents perform field tests on their binders.

Qualified Field Personnel

Engineers or other qualified personnel generally administer the quality management program during the construction phase of a chip seal project. Generally known as field inspectors, these personnel ensure that specifications are being adhered to and specified quality standards are met. A noteworthy feature of chip seal construction is the requirement for knowledge and judgment in forming decisions that are the result of those same site-specific conditions that have caused many authorities to perceive chip sealing as an art (Wegman 1991). In terms of field inspection personnel, an important distinction between North American and international practices results because U.S. and Canadian agencies do not adjust surface texture before the construction phase of the project. Some road surface conditions may require that adjustments be made during binder application. These adjustments are sometimes quite subjective, with the magnitude of the adjustment based on an

TABLE 12
AGGREGATE–BINDER COMPATIBILITY TESTS

Name of Test	Agency	Characteristic
Aggregate Retention	TxDOT, Tex-216-F	Light sweep test
Vialet	French Public Works	Inverted tray, ball impact
Pennsylvania Retention	Pennsylvania DOT	Inverted tray, sieve shaker
BST Sweep	ASTM WK139	Replicates sweeping
Film Stripping	Caltrans and San Diego County, CT 302	Aggregate-emulsion compatibility
Macrosurfacing Sweep	Koch Materials TM101	Replicates sweeping

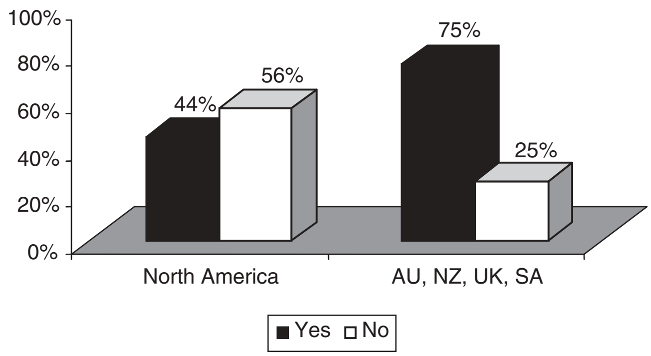


FIGURE 55 Proportion of agencies performing field tests on binders.

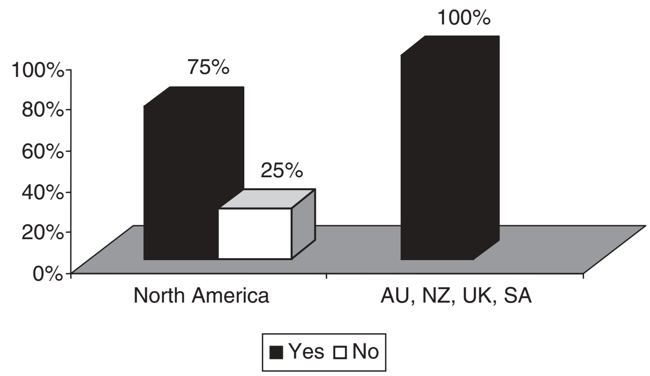


FIGURE 56 Proportion of agencies requiring distributor calibration.

individual's experience. Therefore, a considerable portion of the field inspector's responsibilities are to adjust the application rates as the texture of the pavement's surface changes (Janisch and Gaillard 1998). As a result, North American field personnel have an expanded role in comparison with their international counterparts.

In general, qualified personnel need to be responsible for the following:

- Ensuring that all equipment is calibrated,
- Sampling and testing of materials,
- Verifying material application rates, and
- Monitoring construction methods.

Calibrating the Distributor

To maintain accuracy, several calibration procedures and checks should be regularly performed on the binder distributor. Calibrating the binder distributor ensures that the distributor spray bar is applying the appropriate designed application rate from each nozzle, and that the spray bar height is correct so that that the appropriate fanned spray pattern results. A standardized method for calibrating the transverse application rate of a distributor can be found in ASTM 2995, *Standard Recommended Practice for Determining Application Rates of Bituminous Distributors.* Given the significant quality issues that derive from accurate binder application, Figure 56 shows that 25% of North American agencies do not require the distributors on their projects to be calibrated.

Calibrating the Aggregate Spreader

The calibration of the aggregate spreader is crucial to the satisfactory performance of chip seals (Janisch and Gaillard 1998). Calibrating the aggregate spreader ensures that all gates are applying the same rate of aggregate across the entire spread width and therefore that the aggregate spreader is applying the desired amount of aggregate per square yard. The recommended procedure for calibrating an aggregate spreader is ASTM D5624, *Standard Test Method for Determining the Transverse-Aggregate Spread Rate for Surface Treatment Applications.* Figure 57 shows a significant disparity in philosophies concerning aggregate spreader calibration; the overseas respondents show little concern with their aggregate application, with only 29% of these agencies requiring spreader calibration.

When the survey results for both the binder distributor and aggregate spreader calibration are taken together, they show a fairly widespread disregard for basic QC practices in the chip seal project. Perhaps this finding accounts for the perception that chip seal is more art than science and for that reason it cannot be reliably designed and applied. A number of the states reporting that they no longer use chip seals cited uncontrollable variability as their reason for discontinuing its use. Perhaps adopting the best practices identified in this report could reduce this variability.

Verifying and Adjusting Material Application Rates

The methods used to verify actual application rates have been identified. Respondents also provided details of their policies toward accepted tolerances allowed for binder and aggregate

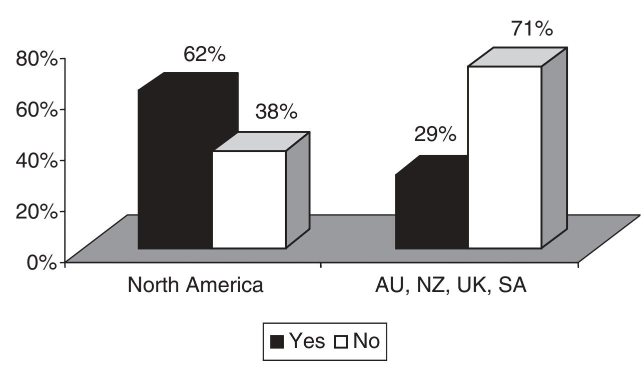


FIGURE 57 Proportion of agencies requiring spreader calibration.

rates. The most important reason for scrutinizing field application is to ensure that application rates are within the tolerances of the project's design standards. The field inspector scrutinizes the binder application during construction. Immediately preceding and following each shot, a procedure known as "strapping the distributor" occurs, which involves measuring the amount of binder remaining in the distributor's tank and allows the inspector to calculate the actual rate of binder being applied (*A Basic Emulsion Manual* 1997). This field test means that the amount of binder remaining in the tank is measured to determine precisely how much binder was used on every shot.

The North American philosophy toward chip seal application rates is that the chip seal design process can be used only as a guideline; the actual binder application rate must be verified in the field. The main responsibility of the project's inspection personnel is to verify if the binder and aggregate rates are being properly applied. In addition, these personnel generally need to be knowledgeable about how to adjust material application rates to account for localized variations in road surface characteristics. Survey respondents were requested to provide the application rate tolerances they typically allow for in their contracts. A common response is to allow a tolerance rate of ±10% for aggregate spreading and ±5% for binder application.

Monitoring Construction Operations

Field inspection responsibilities include ensuring that construction operations are conducive to high-quality workmanship specified in the contract. Perhaps most important, every distributor shot needs to be carefully observed to monitor a number of spray characteristics. The operation of the distributor is judged by visual observation. A uniform application both in the transverse and longitudinal directions is particularly important in chip seal work. Streaking is the most observable characteristic and is usually caused by one of the following four conditions: applying the binder at an inappropriate temperature, high binder viscosity, improper spray bar height, or incorrect pump pressure. Fan patterns and the appearance of a "uniform sheet of binder" need to be observed (Gransberg et al. 2000). Desired fan width is usually obtained with a double lap and needs to be equal for all nozzles (*Asphalt Surface Treatments—Construction Techniques* 1988).

The actual rate of aggregate spread needs to be regularly compared with the design rate, to ensure that overapplication is not occurring. Experienced field personnel can generally observe any variation. It is essential that a uniform "curtain" of aggregate be applied across the entire binder shot width (Gransberg et al. 2000).

The depth at which the aggregate is embedded into the binder should be continuously monitored during rolling. For the chip seal to be successful, the inspector must be able to determine if the proper embedment is being obtained. Many agencies perform embedment checks in the field. In practice, aggregate is removed from the freshly constructed seal, and the percentage of embedment of the average chip is subjectively estimated (Janisch and Gaillard 1998). A 50% embedment after initial rolling and a 70% embedment after 2 or more weeks of traffic application are typically recommended (Jackson et al. 1990). If adequate embedment is not achieved owing to inadequate rolling, the chip seal will be susceptible to raveling between wheelpaths and along edges of the lane where the lowest levels of embedment are present as a result of less traffic action (Jackson et al. 1990; Gransberg et al. 1998).

CONSTRUCTION CONCLUSIONS AND BEST PRACTICES

Construction was the one area in which best practices are plentiful. This underscores the idea that there is only one chance to properly construct chip seal projects. As a result, both the literature review and the survey responses offered many examples of practices that can be observed to achieve successful chip seal projects. Thus, there is one overarching conclusion for this chapter. Both the agency and the contractor must understand the chip seal construction process and be prepared to execute the project in strict observance to the required procedures. This conclusion is underscored by the responses from agencies that use chip seals on high-volume traffic roads. Those responses were from agencies that not only rated their chip seal performance as good or excellent, but they were also from agencies that applied a more detailed set of specifications to the construction process. In other words, those agencies see chip seal as a science that can be replicated through adherence to strict technical guidelines during construction, rather than as an art that must follow a recipe to work properly.

Another conclusion deals with the importance of the roller to chip seal success. The idea that the rolling can be ignored because the rollers are not trying to achieve a specified level of compaction is without merit. The major mode of early chip seal failure is loss of aggregate. The rolling operation is the tool in the chip seal paving train that ensures that proper initial embedment is achieved. Therefore, greater attention must be given to both the specifications for rolling and inspections in the field to ensure that those specifications are being met. Because the roller is the slowest member of the chip seal train, it is critical to ensure that a sufficient number of rollers are both furnished and maintained, so that the aggregate is embedded when the binder is as soft as possible and, in the case of emulsions, before the emulsion has broken, as indicated with a color change from brown to black.

Recognition that chip seal construction QC is very visual should not be contested. However, many performance concerns do not appear during construction. Therefore, a QA/QC program for chip seals needs to consist of more than just qualified personnel; it must also be a well-planned system of scientific tests and engineering principles to ensure that quality materials conform to performance expectations. Additionally, it is very difficult to correct an error that was made during chip seal construction. The contractor must literally get it right the first time. A number of best practices were observed in this area:

1. All types of chip seals are best applied in the warmest, driest weather possible.
2. Ambient air temperature at the time of application should be a minimum of 50°F (10°C) when using emulsions, and 70°F (21°C) when using asphalt cements with a maximum ambient air temperature of 110°F (43°C).
3. The temperature of the surface should be a minimum of 70°F (21°C) and no more than 140°F (54°C) when using emulsions.
4. Complete patches at least 6 months in advance and apply crack seals at least 3 months before the application of chip seals.
5. Variable nozzles permit the application of a reduced rate of binder in the wheelpaths and combat flooding in the wheelpaths, a defect that makes chip seals prone to bleeding. Conversely, the Australian use of prespraying is another method for adjusting the transverse surface texture of a pavement surface before construction of a chip seal.
6. Either hand-raking or drag-brooming can correct minor aggregate spread deficiencies such as corrugation, uneven spread, or missed areas.
7. Aggregate should be applied as quickly as possible with both emulsified and asphalt cement binders. Waiting for the emulsion to break reduces the effectiveness of the rollers in achieving the desired embedment depth of the aggregate.
8. The Montana field-sweeping test (*Maintenance Chip Seal Manual* 2000) curtails the bias to spread excess aggregate created by paying for it by the ton. Montana requires that the amount of excess chips be less than 10% of the design rate and adjusts the pay quantities based on the sweeping test results. This may also reduce the potential for windshield damage claims.
9. Have the most experienced inspector predrive each shot and paint binder rate adjustment on the pavement to facilitate field rate adjustments.
10. In areas where extensive stopping and turning movements take place, the application of a small amount of excess aggregate may reduce scuffing and rolling (Janisch and Gaillard 1998). The use of a racked-in seal (see Figure 13) as used in Australia and South Africa may be a viable engineered solution for determining the precise amount of aggregate for these problematic areas.
11. Rolling guidelines and specifications for roller coverage, rolling patterns, and minimum rolling time or passes achieve full lane coverage and a similar number of passes for all areas of the lane (see Table 9). Minimum rolling times are generally in the range of 3,000 to 5,000 yd^2/h.
12. The required number of rollers is a function of desired binder distributor production and required rolling time or passes for each shot width on the project.
13. Have rolling follow as closely as practical behind the aggregate spreader.
14. Do not sweep the loose aggregate from the roadway immediately following rolling, because the residual binder has not yet cured enough to bond to the aggregate and underlying road surface. Accordingly, it is important to control the sweeping and not dislodge the embedded aggregate particles from the binder.
15. Maintain traffic control for as long as possible to give the fresh chip seal the maximum amount of curing time before opening it to traffic.
16. Assign experienced personnel who understand the dynamics of chip seal construction as field QC and QA persons.
17. Regularly calibrate both the distributor and the chip spreader.
18. Evaluate aggregate–binder compatibility tests, as shown in Table 12, for local appropriateness and before and during construction.
19. Field test binder at both the distributor and aggregate stockpiles daily to ensure that material has not degraded as a result of handling during transportation.

CHAPTER EIGHT

CHIP SEAL PERFORMANCE MEASURES

INTRODUCTION

Defining chip seal performance criteria, and how to quantify them, is perhaps the most difficult consideration for any public owner with chip seal projects. Throughout the literature review, an effort was made to identify any particular acceptance criteria or performance specifications that would illustrate chip seal performance measures. The objective of this chapter is to identify performance specifications and become familiar with their attendant performance measures. Two separate schools of thought in regard to performance measurement have been identified. Chip seal performance is primarily either measured quantitatively through engineering principles or rated qualitatively through expert visual assessment. The literature review and survey results discovered little beyond measuring skid resistance for quantitative chip seal performance measurements in North America, but quantitative performance measures are widespread in Australia, New Zealand, South Africa, and the United Kingdom.

ENGINEERING-BASED PERFORMANCE INDICATORS

Quantitative chip seal performance measurement techniques were evaluated by a study at the Pennsylvania Transportation Institute (Roque et al. 1991). Performance measurements of rutting and roughness are widely used on other wearing courses such as asphalt pavement. Chip sealed surfaces look and perform differently from asphalt pavement surfaces; therefore, their performance needs to be based on a different set of visual evaluation methods than for asphalt pavements (Walker 2001). As such, asphalt pavement performance measurements are not often applicable to measuring chip seal performance, because none of those methods will formally measure the two most common chip seal distresses, bleeding and raveling. Measuring skid resistance and measuring texture depth are the only two repeatable and objective quantitative methods that may be applicable.

Skid Resistance

Skid resistance, an important safety characteristic for all roads, can be used as a performance measure on chip sealed surfaces (Roque et al. 1991). The skid resistance or friction, which develops between a vehicle's tires and the surface of the road, is a function of two components, macrotexture and microtexture (Abdul-Malak et al. 1993). Basically, the microtexture is determined by the frictional properties of the aggregate, whereas the macrotexture is determined by the size, shape, and spacing of the aggregate particles (Abdul-Malak et al. 1993). Although there are other acceptable methods for measuring skid resistance, the most common method for a chip seal is according to ASTM E274, *Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire* (Seneviratne and Bergener 1994). This method measures the sliding friction force developed between a tire and roadway surface and expresses the result as a skid number. The justification behind using skid numbers as a determinant of chip seal performance, and thus also the service life of the chip seal, is that skid numbers drop over time owing to deterioration of the pavement's surface texture (Seneviratne and Bergener 1994). Most agencies have a specified cycle on which skid resistance is measured as a part of their pavement management system. These data are invaluable to making the decision as to which roads to chip seal.

Texture Depth

The literature review identified several methods for measuring a pavement's macrotexture (Abdul-Malak et al. 1993). Of these, the survey results indicated that the only measurement with widespread acceptance by the international respondents is the sand patch method (ASTM E965). In the Pennsylvania study, the mean texture depth (MTD) as obtained by the sand patch method was found to give the best indication of chip seal performance, in addition to being an objective manner of comparing chip seals on a relative basis (Roque et al. 1991). Aggregate retention and resistance to bleeding are both evident by evaluating MTD. The study in Pennsylvania proposed that the rationale for using MTD as the best indication of performance is that greater macrotexture generally implies greater skid resistance (Roque et al. 1991). This same study found that the MTD, as indicated by macrotexture, decreased with time as a result of both aggregate wear and embedment. Assuming such, chip seal deterioration models can evaluate the effects of different variables on expected chip seal life (Roque et al. 1991). The study in Pennsylvania, which proposes that MTD is the best indication of chip seal performance, is in agreement with New Zealand and United Kingdom philosophies in the development of performance specifications (*Design Guide* . . . 2002; *Notes for the Specifications* . . . 2002). Texture depth appears to be the performance measure of choice.

Engineered Performance Specifications

In a previous NCHRP synthesis, a performance specification was defined as "how the finished product should perform over time" (Chamberlain 1995). Specification of design life expectations is an effective means of determining long-term chip seal performance. The most prominent example of a chip seal performance specification is Transit New Zealand's, *Notes for the Specification of Bituminous Reseals* (P17) (2002). The philosophy behind this specification is that the texture depth after a 12-month inspection is the most accurate indication of the performance of the chip seal for its remaining life. The New Zealand specification contends that "the design life of a chip seal is reached when the texture depth drops below 0.035 in. (0.9 mm) on road surface areas supporting speeds greater than 43 mph (70 km/h)" (*Notes for the Specifications* . . . 2002). The deterioration models developed in New Zealand have directed the P17 specification to require the following minimum texture depth 1 year after the chip seal is completed, using Eq. 4.

$$Td_1 = 0.07\,ALD \log Y_d + 0.9 \qquad (4)$$

where

Td_1 = texture depth in 1 year (mm),
Y_d = design life in years, and
ALD = average least dimension of the aggregate.

The entire specification is based on the assumption that chip seals fail as a result of bleeding (*Notes for the Specifications* . . . 2002). Within the specification, noise or aesthetic factors are the only reasons for specifying a maximum texture depth. The final acceptance is based on the achievement of the required texture depth, without any significant chip loss. More on the detailed methodology behind New Zealand's performance-based specification can be found in Appendix D.

QUALITATIVE PERFORMANCE INDICATORS

It must be noted here that although the measurement of skid resistance is common throughout North America, the researchers could find no instances where public highway agencies were using skid numbers to directly evaluate the performance of chip seals. Skid numbers, however, were used as trigger points for making the decision to apply a new chip seal on a road. Therefore, the only true form of chip seal performance measure identified among the North American survey respondents was the rating of visual distresses that materialize during the design life of the chip seal. Figure 58 shows the distress modes that survey respondents commonly identified in their chip seals.

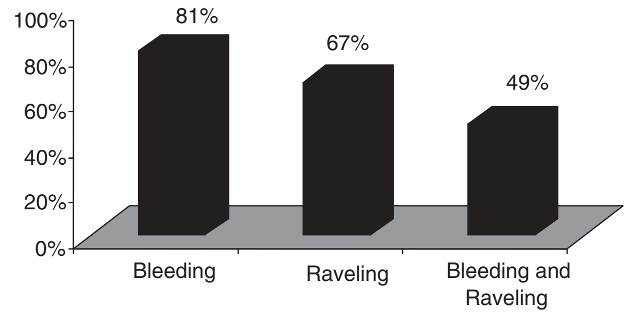


FIGURE 58 Most common distress modes identified by survey respondents.

It is obvious that raveling and bleeding are widespread distresses. The literature review shows that chip seal performance is generally a function of the following factors (Elmore et al. 1995a and b):

- Quality of design,
- Quality and consistency of construction,
- Quality and consistency of materials,
- Environmental conditions, and
- Traffic conditions.

Visual Surface Ratings

Chip seal performance is commonly measured through a system that provides for visual rating of the chip seal's condition. Visual rating of chip seal performance by apparent distress modes is justified because these distresses generally determine the life of a chip seal. The role that aesthetics play in the chip seal process also makes objective decision making difficult. The idea that the road should look good after it is completed is an important driver of chip seal performance perception (Gransberg et al. 1998). Visual performance assessment is irreplaceable, even though it is inherently subjective. Therefore, agencies should ensure that experienced personnel are employed to make these assessments. Furthermore, there is evidence that technical vocabulary for chip seal performance is considerably variable within a state, let alone on national and international levels. One can see how establishing any objective metric to assist inspection forces based on visual assessment is problematic (Gransberg et al. 1998).

Visible Chip Seal Distress

Chip seals generally deteriorate as a result of binder oxidation, wear and polishing of aggregate, bleeding, and aggregate loss (*Sprayed Sealing Guide* 2004). These processes are expressed graphically in the Austroads chips seal distress model (Figure 59). Performance evaluation pertaining to surface appearance, reflective cracking, aggregate loss, and texture loss can all be subjectively observed and rated based on their extent and severity of distress. As evident from the both the survey responses and confirmed in the literature review, bleeding and raveling are the most common distresses found with a chip sealed surface (Benson and Gallaway 1953; Holmgreen et al. 1985).

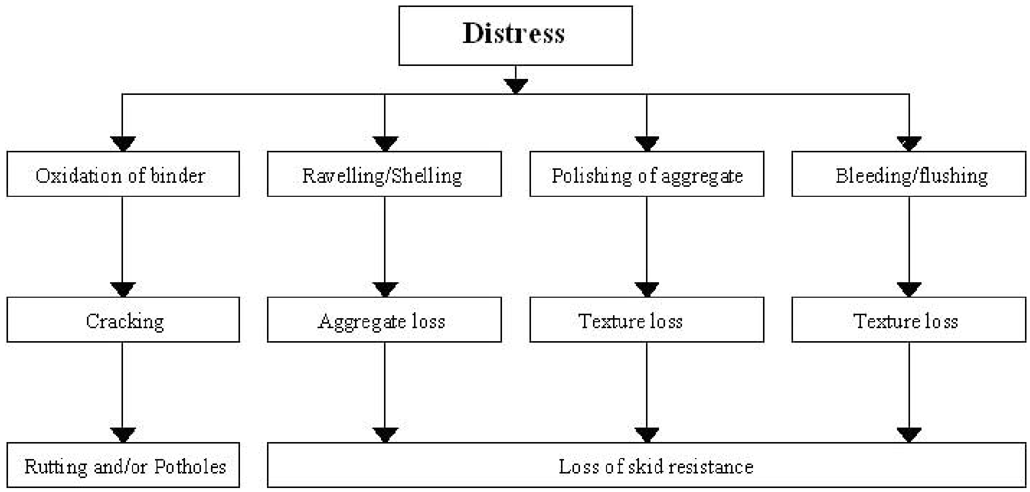


FIGURE 59 Chip seal distress model (adapted from *Sprayed Sealing Guide* 2004).

Bleeding

Bleeding is normally distinguished by black patches of excess binder appearing on the surface of the chip seal (Gransberg et al. 1998). In other words, a bleeding surface has a smooth and slick appearance where the aggregates are less visible. Figure 60*a* and *b* illustrates this condition. Bleeding is caused by either an excess of binder in proportion to the aggregate or where the aggregate is forced to achieve levels of embedment beyond the design embedment depth (*Sprayed Sealing Guide* 2004). Such distress is usually observed in the wheelpaths where the repetitive load cycle of tires causes subsequent embedment of aggregates. Bleeding problems are generally associated with high binder rates and nonuniform aggregate gradations, and bleeding is accelerated by high temperatures (Gransberg et al. 1998). During hot weather, underlying asphalt layers may soften to a point that these aggregate particles may penetrate into the underlying binder, leaving excess asphalt on the surface (Senadheera and Khan 2001).

Raveling

Raveling is the loss of aggregate from the chip seal's surface. Such chip seal surfaces have a very irregular appearance, because the surface is not completely covered by the aggregate, as shown in Figure 61*a* and *b*. Raveling occurs when the bond between the aggregate and binder fails, causing the aggregate to become displaced from the binder. Raveling is most common in areas outside of the wheelpaths where embedment is lowest (Senadheera and Khan 2001).

Defects

In addition to the distresses that form from the deterioration of the chip seal over time, two common defects need to be mentioned: poor construction and placing a chip seal on a structurally inadequate pavement. Such defects commonly cause the chip seal to fail before its planned service life.

(a) (b)

FIGURE 60 (*a* and *b*) Results of excess binder—Bleeding in wheel paths.

(a)

(b)

FIGURE 61 (*a* and *b*) Results of aggregate loss—Raveling.

Streaking, also known as drilling, is the formation of alternating lean and heavy lines (streaks) in the chip seal that result from a failure to apply the binder uniformly across the road's surface (Senadheera and Khan 2001). Streaking, shown in Figure 62, is mostly an aesthetic problem, but it can reduce the design life of the chip seal when aggregate loss begins to take place.

Rutting on the pavement surface is the result of deformation in the layers of the pavement's structure (Senadheera and Khan 2001). It is directly related to the structural strength of the underlying material. As one can see from Figure 63, chip seals will not benefit a pavement susceptible to rutting; these pavements need rehabilitation or reconstruction. Additionally, sealing a rutted pavement will likely cause the ruts to be flooded with binder and fail as the result of bleeding in a very short time.

Ohio Visual Evaluation Method

For integration into Ohio's *Supplemental Specification 882, Chip Seal with Warranty,* the state has established the following performance criteria for chip seal construction, as detailed in Table 13. This table is a particularly useful way to quantify the subjective nature of visual distress assessment by demanding remediation of the distress when the illustrated extent of severity is met.

In addition, the Ohio DOT prescribes the following chip seal acceptance criteria:

- Finished surface has minimal tears and binder streaking.
- Joints appear neat and uniform without buildup, uncovered areas, or unsightly appearance.
- Longitudinal joints have less than a 2 inch (50 mm) overlap.

FIGURE 62 Streaking (Senadheera and Khan 2001).

FIGURE 63 Rutting (*Asphalt Surface Treatments—Construction Techniques* 1988).

TABLE 13
OHIO DOT's CHIP SEAL PERFORMANCE CRITERIA, 2002

Defect	Severity	Extent
Surface Patterns	Severe—light and heavy lines over the pavement surface	Greater that 40% of segment length affected, continuous, or localized
Bleeding/Flushing	Moderate—excess binder on surface (loss of stone/tire contact) not subject to wearing off quickly	Greater than 5% of segment length affected continuously or total of 20% localized problems
Loss of Aggregate	Moderate—patches of aggregate loss	Greater than 10% of segment length affected continuously or total of 20% localized problems

Source: Supplemental Specification 882, Chip Seal with Warranty 2002.

- Transverse joints have no more than 0.25 inch (6.5 mm) difference in elevation across the joint as measured with a 6 foot (2 m) straightedge.
- Chip seal edge is neat and uniform along the roadway lane, shoulder, and curb lines.
- Chip seal edge has no more than 2 inches (50 mm) variance in any 100 feet (30 m), along the roadway edge or shoulder (Ohio DOT 2002).

PERFORMANCE CONCLUSIONS AND BEST PRACTICES

The performance of chip seals is affected by a variety of factors related to design, materials, and construction. The literature review and survey results confirm that bleeding by far leads the predominant distress category. Therefore, an effort needs to be made to quantitatively measure bleeding and identify any means that can minimize it. Chip seal conditions deteriorate with age, and as such, measuring texture is a useful tool in developing a pavement condition index for the seal.

Chapter four discusses performance risk distribution in chip seal contracts. This is extremely important in the context of this chapter, in that performance risk can be measured only by performance indicators. As a performance indicator's measurement grows more objective, the agency's capacity to enforce a construction warranty increases. Therefore, the following best practices were identified from this chapter's analysis:

1. An approved method, such as the sand patch method, to measure chip seal macrotexture can furnish an objectively measured chip seal performance indicator.
2. The use of the chip seal deterioration model expressed in the New Zealand P17 Specification will furnish an objective definition of chip seal performance based on engineering measurements.
3. The two aforementioned methods can be supplemented with a continued visual distress rating based on the Ohio DOT's chip seal performance criteria, as shown in Table 13.

CHAPTER NINE

BEST PRACTICE CASE STUDIES

INTRODUCTION

On the basis of the survey responses, case studies were identified to detail findings that have the potential to disseminate chip seal best practice in a timely manner. Each of the case studies was drawn from a best practice case study form, which was sent to those survey respondents indicating the performance of their chip seals as "excellent." This chapter first looks at those factors that the agencies with excellent results have in common with regard to their chip seal procedures and processes. Then it presents the salient elements of individual responses for representative programs in a standard format, permitting the reader to compare and contrast the various programs.

COMMON CHARACTERISTICS OF EXCELLENT CHIP SEAL PROGRAMS

The following respondents reported that they achieve excellent results from their chip seal programs. Their responses were separated from those of respondents in general for additional analysis.

- Arkansas State Highway and Transportation Department;
- Colorado DOT—Alamosa, Grand Junction, Montrose, Sterling, and Trinidad;
- Idaho Transportation Department;
- Nevada DOT;
- Oklahoma DOT;
- Texas DOT—Austin District;
- WSDOT;
- Austin, Texas; and
- Lubbock, Texas.

The most striking factor among just those respondents that rated their chip seal program results as excellent is that all responded that they use chip seals as a PM tool by following a specific PM cycle. Those agencies reported that they typically use a 5-year PM cycle and expect to get a 6-year service life from their seals. These two numbers are significant in that the planned PM cycle is shorter than the expected life of the chip seal. This confirms that these agencies are truly committed to using chips seal as a pavement preservation technique. Their level of confidence is further confirmed, because they have an average of 7,000 lane miles of sealed pavement surfaces (DOT district level for all but the two cities), and that they do chip sealing on a range of 150 to 20,000 lane miles per year at an average cost of about $2.6 million annually. Most use both in-house and contract crews to apply their chip seals and achieve satisfactory results with both types of crews, although 10 of 13 agencies believe that in-house seals produce a better final result.

The major distress observed with the in-house chip seals is bleeding, especially at intersections, and the major distress observed with contract chip seals is early loss of aggregate. This finding makes sense, because chip seal contractors will have a strong incentive to maximize production rates that may lead to less attention being given to achieving adequate embedment.

Design and Material Selection

All but one of the best practice case study agencies formally design their chip seals (including empirical design usage based on past experience), and they use a procedure that has been in use for an average of 21 years. Eight respondents entrust the design to their own maintenance engineers, using qualitative design input factors to develop the design. All use modified binders, with polymers and crumb rubber being the most common modifiers. These agencies also select roads that have a distress level rated at moderate or less and whose structural cross section is rated as fair or better. They use some type of pavement condition rating as the trigger point to consider the selection of chip seals for extending the life of the pavement. This finding is highly significant, in that as a group, the agencies demonstrate their understanding of both the advantages and limitations of chip seal technology. In other words, they are "putting the right seal on the right road at the right time" (Galehouse 2003).

Contracting and Construction

The group's chip seal season typically runs from May to September, and they use unit-price contracts. They generally are not concerned about restricting chip seals to roads with low-volume traffic, with 11 of the 13 agencies chip sealing roads having ADT of more than 5,000 vehicles, including 3 agencies that use chip seals on roads with ADTs greater than 20,000 vehicles. The agencies appear to be interested in keeping up to date with the state of the art in chip seal construction equipment, as evidenced by the knowledge that most require computerized controls on the distributor, and half require computerized controls on the chip spreader as well. All require the use of pneumatic rollers and specify some control on rolling by specifying roller passes, maximum roller speed, or roller weight. Most perform crack sealing to prepare the surface for chip sealing.

The agencies' specifications require the ambient air temperature to be in the range of 60°F to 70°F before chip sealing can begin. The majority impose reduced speed limits of an average of 35 mph on newly sealed roads. They enforce those limits by using flaggers and/or pilot cars for a time after sealing from as little as 30 min to as much as 3 days before opening, with an average of approximately 4 to 6 h. All of these agencies perform their own inspection and require distributor calibration before sealing. Nine of these agencies also require spreader calibration in their contracts or in their internal procedures, or both.

Performance

Bleeding is the most prevalent reported long-term distress that appears in their chip sealed roads, and these respondents noted the use of rigorous QC testing. The major cause of failure shortly after construction is weather related (rain or an unexpected temperature drop), followed by dusty or dirty aggregate. The major public-user complaint is damage caused by loose aggregate. Eleven of 13 described the pavement ride of their roads as either good or excellent after chip sealing. Finally, they also undertake follow-up to maintain their chip seals with routine crack sealing and sometimes fog sealing to maintain the integrity of the asphalt membrane for the life of the chip seal.

SPECIFIC DATA FROM PROGRAMS WITH EXCELLENT RESULTS

Tables 14 and 15 have been developed to furnish the reader with specific details on agencies that reported excellent results from their chip seal programs. Three states, Colorado, Idaho, and Texas, provided multiple responses to the survey. These responses were not consolidated, for each was unique to a given district. Both tables reflect practices grouped according to the traffic volume limitations imposed by the local chip seal usage policy.

The impression that one gets from looking at these tables is that all the agencies that reported excellent chip seal performance appear to not only have introduced a high degree of prescriptive specification into their programs, but they also are using the benefits that can be accrued by the advances in material science, such as the use of modified binders, robust QC testing programs, and state-of-the-art construction equipment in their chip seal programs. One also notices that there is very little difference between those agencies that restrict chip seal usage to lower-volume roads and those that routinely use the system on high-volume roads. The one major difference is that those that apply PM chip seals on high-volume roads ensure that the underlying pavement's condition is generally good. Thus, they are not trying to use their chip seal program for short-term repair.

CASE STUDY CONCLUSIONS AND BEST PRACTICES

Two major conclusions were reached in view of the aforementioned case studies in chip seal excellence. First, those agencies that use chips seals as a PM measure appear to be able to replicate success. They treat the technology as a science and use formal design procedures that have been adjusted by the experience gained over a large number of years. Because they use chip seals for PM, they do not apply it to roads with severe distress or poor structural conditions, and once they do apply chip seals, they invest in maintaining the asphalt membrane by routine crack sealing and/or fog sealing. Second, these agencies transfer a high degree of specificity from their design process to their construction contracts or in-house maintenance procedures. Again, such a procedure allows them to replicate past success.

The following best practices can be gleaned from this chapter's analysis:

1. Viewing chip sealing as a PM tool to be applied on a regular cycle reinforces the pavement preservation benefits of the technology.
2. Chip seals can be successfully used on high-volume roads if the agency's policy is to install it on roads where pavement distresses are minimal and the structural integrity of the underlying pavement is in good condition.
3. Both hot asphalt cement and emulsified asphalt binders can be used successfully on high-volume roads. The selection of binders modified by polymers or crumb rubber seems to reinforce success.
4. In-house maintenance personnel are best used to install chips seals in areas where the greatest care must be taken to achieve a successful product.
5. Requiring chip seal contractors to use state-of-the-art equipment and to control the rolling operation enhances chip seal success.
6. An aggressive QA and QC testing program combined with close inspection leads to chip seal success.

TABLE 14
CASE STUDIES FOR CHIP SEAL USE ON LOW-VOLUME ROADS

Item	Colorado DOT Alamosa	Idaho DOT Boise	WSDOT Olympia
Average ADT Limitation	ADT < 5,000	ADT < 5,000	ADT < 2,000
Chip Seal Season	May to September	June 15 to Sept. 1	May to August
Major Binders Used	HRFS, HRFS-2P	CRS-2P	CRS-2, CRS-2P
Modifiers Used	Polymers, anti-stripping agents	Polymers, crumb rubber	Polymers
Aggregate Used	Natural gravels	Trap rock, natural gravels	Granite, natural gravels, basalt
Aggregate Sizes Used	3/8 in.	3/8 in.	1/2 in. and 3/8 in.
Design Method	Individual	Kearby	Empirical
Design Done By	In-house maintenance engineer	No response	In-house design engineer
Design Method Usage	13 years	10 years	30 years
Distress Level of Underlying Surface	Moderate	Moderate	Moderate
Structural Condition of Underlying Surface	Good	Fair	Fair
Computerized Control Required on Distributor/Chip Spreader	Yes/Yes	Yes/No	Yes/Yes
Specified Controls on Rolling	Number of passes and maximum speed	Roller weight and maximum speed	Roller weight
Traffic Control Measures	Reduced speed, interim pavement markings, flaggers, pilot cars	Reduced speed, interim pavement markings, flaggers, pilot cars	Reduced speed, interim pavement markings, flaggers, pilot cars
Time to Open to Reduced Speed Traffic	10 min	4 h	As soon as possible
Aggregate QC Tests			
% fracture	X	X	
Flakiness		X	
Anti-strip	X	X	
Presence of clay		X	X
Gradation	X	X	X
Methods to Maintain Seal after	None reported		
construction		X	X
Crack seal			X
Chip seal patch		X	
Sanding		X	X
Fog seal			

TABLE 15
CASE STUDIES FOR CHIP SEAL USE ON HIGH-VOLUME ROADS

Item	Colorado DOT Grand Junction	Texas DOT Austin	City of Lubbock, Texas
Average ADT Limitation	ADT > 20,000	ADT > 20,000	ADT > 20,000
Chip Seal Season	May to September	May to October	May to October
Major Binders Used	HRFS-2P	AC15, AC15-5TR	CRS-2P
Modifiers Used	Polymers	Polymers, latex, anti-stripping agents crumb rubber	Polymers
Aggregate Used	Natural gravels, lightweight	Precoated trap rock, precoated limestone, precoated lightweight	Natural gravels
Aggregate Sizes Used	1/2 in. and 3/8 in.	1/2 in. and 3/8 in.	1/2 in. and 3/8 in.
Design Method	Individual	Modified Kearby	Empirical
Design Done By	In-house maintenance engineer	In-house design engineer	In-house design engineer
Design Method Usage	Not reported	22 years	5 years
Distress Level of Underlying Surface	None to moderate	Moderate	Moderate
Structural Condition of Underlying Surface	Excellent	Good	Not reported
Computerized Control Required on Distributor/Chip Spreader	Yes/No	Yes/No	Yes/Yes
Specified Controls on Rolling	Rolling pattern	Roller weight and maximum speed	Rolling pattern
Traffic Control Measures	Reduced speed, interim pavement markings, flaggers, pilot cars	Reduced speed, interim pavement markings, flaggers, pilot cars	Reduced speed, interim pavement markings, flaggers
Time to Open to Reduced Speed Traffic	3 h	Varies	30 min
Aggregate QC Tests	Not reported		
% fracture		X	X
Flakiness		X	X
Decant		X	X
Anti-strip			
Presence of clay		X	X
Gradation		X	X
Methods to Maintain Seal after construction			
Crack seal	X	X	X
Chip seal patch		X	
Lime slurry			X
Fog seal		X	

CHAPTER TEN

CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH

CONCLUSIONS

Maintenance chip seals can play an important role in the nation's pavement preservation program. Therefore, they deserve the same level of technical engineering rigor that is reserved for the hot-mix asphalt pavements whose design life the chip seals extend. The most surprising finding of this study was that advances in the state of the art in chip seal design essentially ended in North America in the 1960s when N. McLeod proposed his design method based on F.M. Hanson's work, and it was accepted by the Asphalt Institute and most North American departments of transportation as the theoretical basis on which chip seals would be delivered to the traveling public. The development further stalled as public agencies evolved a system whereby no design is performed and only empirical rates are used to develop estimated quantities for unit-price chip seal contracts.

Five of the U.S. states that responded to this study's survey reported that they do not use maintenance chip seals. This is an indication that the value placed on chip seals by the states reporting excellent results from their programs is not shared across the nation. Some states rate their chip seal experiences as "unacceptable," whereas neighboring states may rate their experiences as "good." Such differences in practice are difficult to explain.

It is likely that part of the decision not to use maintenance chips seals flows from the idea or experience that chip seal is an "art" that cannot be easily or predictably replicated. That finding is supported by this study's literature review, survey responses, and interviews. However, this synthesis demonstrates that chip seals can be reliably designed and installed. Engineers in Australia, New Zealand, the United Kingdom, and South Africa did not allow their search for a better-engineered chip seal to cease in 1970. Because Australia, New Zealand, and South Africa literally depend on chip seals to maintain large percentages of their national transportation systems is evidence that chip seal pavement preservation technology can be reliably and predictably engineered. These countries, as well as Canada, routinely impose warranties on the performance of their chip seal projects, demonstrating that chip seal contractors can construct chip seals that perform satisfactorily, and they can do so profitably without driving the price of chip seal projects to the point where hot-mix asphalt overlays become economically competitive.

This study has found that maintenance chip seal practices can be instituted that will improve the reliability of maintenance chip seals. Many of the best practices identified fell in the areas of construction procedures and equipment management practice. This is not surprising, in that construction is the most critical portion of the chip seal project life cycle.

The area that apparently has the greatest potential for enhancement is chip seal design. This is also the area in which advancements in technical understanding will have the greatest potential to dispel the view that the use of chip seals is merely an art. The major issue in chip seal design lies in accurately characterizing the surface on which the seal will be applied, through using engineering measurements of macrotexture and hardness. Such knowledge allows engineers in Australia and New Zealand to select both binder types and aggregate gradations that are compatible with the surface on which they will be applied. This discussion leads to the overall conclusion of this synthesis.

Americans and Canadians can learn from the procedures that are used in Australia and New Zealand. Those countries, whose highway authorities have joined forces under the name Austroads, have built on the legacy of Hanson and McLeod and have kept advancing chip seal state of the art to the point where they have developed specialized equipment and scientific design and quality control methodologies. They use performance-based contracts for chip seals in which final payment is based not on quantities and unit prices but on the 12-month performance of the completed seal. Perhaps most surprising of all, this has been achieved in partnership with the construction industry through the use of alternative project delivery methods. This circumstance then leads to a discussion of where the U.S. transportation industry needs to proceed with its pavement preservation research.

SUGGESTIONS FOR FUTURE RESEARCH

That some of the references cited in this study date back to the 1950s and 1960s (and even earlier) indicates the need for new research in pavement preservation. A number of areas from this study deserve further research and study.

Research is needed to base chip seal design methods on sound engineering principles and scientifically measured design input data. The methods used in Australia, New Zealand, and South Africa may be adapted to U.S. and Canadian chip seal projects. The tests for macrotexture and surface hardness may be adapted for road conditions in North America. Output from these surface condition tests may then be used as input for the chip seal design process. A robust design process such as that used in those three countries might lend itself to the development of chip seal projects whose inherent variability is reduced and whose potential for replicable success is greatly increased. These assumptions could be investigated by research and field tests.

Two other design features that could be investigated for use in the United States and Canada are the inverted seal and the racked-in seal. The inverted seal is used to correct a bleeding pavement. In the United States, chat or fine aggregate is used to temporarily restore the skid resistance on a failed, bleeding chip seal. All that the addition of fines does is to effectively change the gradation of the chip seal aggregate on the surface of the road. If a contractor had proposed to install an aggregate with the gradation that exists after fines are spread, that aggregate probably would have failed the sieve analysis and been rejected. Experience has shown that this measure merely exacerbates the bleeding after a period of time as the fines work their way down into the seal and flush more binder to the surface. The racked-in seal shows good promise for use in those areas of road to receive a chip seal that experience a large amount of turning and stopping. The "sacrificial" stone should lock in the primary chips and allow them to resist rolling and dislodging. Both types of chip seals deserve to be tested and evaluated in the United States to determine if they can adequately address these problems.

In line with studying international chip seal design methods, another suggestion pertains to transferring chip seal construction technology to North America. Of particular interest are the methods for retexturizing the road's surface. If retexturizing can be economically performed in the United States, it could eliminate the single greatest source of uncontrolled variation in chip seal construction: the need to adjust binder and aggregate rates on the fly during construction. Through application of a constant rate of binder and aggregate, it would give the public agency the ability to require the chip seal contractor to comply with the design shown on the plans and specifications. Furthermore, retexturizing would allow designers to observe and adjust the next design based on actual performance of the rates and materials called out in the contract.

Also of interest is the special-purpose equipment developed to precoat aggregate as it is being installed and the low-drop chip spreaders used in Australia and New Zealand. These types of equipment were developed to minimize the degradation of the chips by reducing the number of times they are handled. Furthermore, these pieces of equipment are highly touted by their users in Australia and should be evaluated to determine the potential for improving the performance of chip seals in North America.

Australia and New Zealand cooperate under the umbrella of Austroads and have developed a national guide to chip sealing. Each state-level highway agency then develops its own adaptation to fit its climatic, legislative, and business environment. This situation could provide a model to study for use in the United States.

Both the literature review and the survey responses showed that the importance of the roller in achieving chip embedment is not well understood. Therefore, it is suggested that a comprehensive study of chip seal rolling practice be conducted in both the laboratory and, most important, in the field. All types of rollers, including rubber-covered drum vibratory rollers and vibratory pneumatic tire rollers, should be tested. Optimum size and weight for chip seal rolling should also be investigated. The result of such a study would be a comprehensive guide specification for chip seal rolling methods.

To implement chip seal warranties, research is needed to develop both performance-based specifications and end-product specifications. The finding that most of the non-U.S. responding agencies use some form of chip seal warranty makes this type of research both timely and important.

One major disadvantage of chip sealing cited in both the literature review and the survey responses was the increase in road noise caused by chip seals. Research is needed on the relationship between chip seal macrotexture and noise emissions. This research should quantify the expected level of noise based on aggregate nominal size and type of chip seal to furnish chip seal designers with engineering guidance when deciding on the aggregate size.

Data from Australia show that agencies in that country are willing to pay a premium to guarantee the quality of their chip seal aggregate. They justify the expense by using life-cycle cost analysis. A study on the life-cycle cost implications of paying the additional costs to transport high-quality aggregate is recommended to justify investing in chip seal materials, to maximize their abilities to extend pavement service life.

Montana's sweep test specification, to identify the quantity of excess aggregate left on the road, shows great promise for minimizing the negative effects of loose stone on newly chip sealed roads. Research could be undertaken to quantify the benefits of implementing this specification across the nation.

There is a strong need to be able to tie the construction process to the ultimate performance of the chip seal. The literature review indicated that a lot of the uncertainty associated with the forensic analysis of chip seal failures is the result of the inability of investigators to determine the exact rates of binder and aggregate installed at the failed section, as well as their being unable to determine the condition of the underlying surface. Therefore, a study of chip seal construction record keeping and performance monitoring is in order to provide a guide to agencies on this critical issue.

Finally, it is suggested that a uniform glossary of chip seal terms be developed and distributed throughout the nation. The effect would be to standardize the technical communication within agencies in the field.

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GLOSSARY

The following pages represent an attempt at developing a comprehensive glossary of chip seal terminology. One of the great challenges in this study was to determine the precise definition of much of the technical vocabulary that was found both in the literature review and the survey responses. It is strongly advised that readers use this glossary for definitions of terms used in this report, to ensure that the best practices that are cited are not unintentionally misunderstood.

Adhesion agents—Substances that improve the degree of wetting of the aggregate by the binder, thus enhancing the adhesion between the binder and aggregate.

Aggregate—A granular material usually crushed and screened to appropriate gradations, which is used as the cover stone in a surface treatment.

Asphalt binder—Commonly referred to as asphalt cement, pure asphalt binders are graded based on viscosity and penetration.

Average least dimension (ALD)—A metric that represents the expected chip seal thickness when the aggregate is oriented to lie on its flattest side.

Binder—A bituminous material that provides a waterproof seal and also bonds the cover stone to the pavement.

Bleeding—Upward movement of asphalt through the chip seal. Bleeding, also commonly referred to as flushing, can be identified by dark patches of asphalt forming on the surface, most commonly in wheelpaths or intersections.

Blotter material—See Chat.

Cape seal—A chip seal followed by a slurry seal that fill the voids in the surface of the cover aggregate. The slurry seal increases aggregate retention and reduces tire noise.

Chat—Fine aggregate used to spread on flushed/bleeding chip seals as an emergency repair measure to restore skid resistance.

Chip seal—A bituminous surface treatment that can be a single, double, or triple application of bituminous binder and cover aggregate on an existing paved surface.

Chip spreader—Also referred to as a spreader box or aggregate spreader, the machine that evenly applies the aggregate to the binder. Self-propelled spreaders with computerized rate controls are preferred.

Choke—A layer of sand applied to the chip seal after the cover stone has been rolled but before opening to traffic. Choke produces a tighter chip seal because it fills surface voids.

Choke stone—A layer of smaller size aggregate applied to the chip seal after the cover stone has been rolled but before opening to traffic. Choke stone fills the voids on the surface and "locks in" the cover stone against dislodgement that is the result of rolling in areas with traffic turning movements. Also called "sacrificial stone" or "scatter coat."

Crumb rubber—A modifier that can be blended into bitumen to enhance the elasticity and adhesion characteristics of the binder. Rubberized asphalt chip seals are successful at mitigating reflective cracking, improving aggregate retention, and reducing noise.

Cutback—Asphalt cement that has been diluted with a solvent such as kerosene or naphtha. The use of cutbacks is becoming less common because of environmental and safety concerns.

Distributor—An insulated tank with a circulating and heating system that is mounted on a truck and distributes binder through a spray bar at the rear. It is critical for the distributor to apply the binder at a constant rate and to the correct width. Distributors with computerized rate controls are desirable.

Double seal—A seal characterized by two separate applications of both binder and aggregate. The design of a double-course seal requires the application rates for both layers of binder and aggregate to be determined as an integrated treatment. Multiple seals provide a quieter treatment.

Embedment—A measured percentage of the portion of the aggregate enveloped by the binder. Embedment checks are a visual inspection of the chip seal construction, with typical recommendations of at least 70% embedment.

Emulsified binder—A liquid mixture of asphalt binder, water, and an emulsifying agent. Emulsions are either anionic (negatively charged) or cationic (positively charged). Emulsions are not as sensitive to moisture, inherently contain antistripping agents, and require much lower application temperatures than do asphalt cements.

Emulsion break—The point in time, shortly after the application of the emulsified binder, when the emulsifying agent and water evaporate from the asphalt cement, leaving behind the asphalt cement that bonds the aggregate particles to the binder. A "breaking" emulsion can be observed when the binder changes color from brown to black.

Flakiness—A general description of the shape of aggregate. A flakiness index can be used to determine how cubical the aggregate used in a chip seal is. A lower flakiness index indicates a more cubical aggregate and better aggregate shape for a chip seal.

Flushing—See Bleeding.

Fog seal—An application of asphalt applied on top of a pavement surface. Fog seals are commonly used on oxidized pavements to provide resistance to water intrusion and raveling. Fog seals are also used on newly constructed chip seals to promote adhesion and enhance aggregate retention.

High float emulsions—Emulsions that result in a thicker asphalt film and are believed to show less susceptibility to the defects associated with unclean and dusty aggregate.

The thicker asphalt film characteristics result in high float emulsions preventing drain-off of the binder.

Hunger factor—Kearby chip seal design terminology to describe the existing surface's potential to absorb binder and thereby require an adjustment in the design binder application rate to ensure that either sufficient binder is applied to achieve desired embedment when the surface is oxidized or that too much binder is not applied if the surface is flushed.

Geotextile seal—Geotextile-reinforced seals are used over cracked and weak surfaces. They provide a waterproofing membrane that not only seals the underlying moisture-sensitive base material from water infiltration, but also aids in retarding reflective cracking.

Glass fiber chip seal—A chip seal that entails blowing glass fibers onto an application of a binder, with the aggregate being spread quickly after this application. Characteristics of this seal are similar to a geotextile-reinforced seal.

Inverted seal—An Australian term for a seal that is used to correct flushing or bleeding pavement surfaces.

Ionic compatibility—Different types of aggregate are better suited to certain binders as a result of electrostatic charges. For sufficient adhesion, the binder and aggregate must have opposite charges.

Lightweight aggregate—A synthetic granular material that can be used to replace natural aggregates as the cover stone for a surface treatment. These materials have a low specific gravity and do not have the same potential for windshield and vehicle damage.

Lump-sum contract—A contract whereby the contractor is required to furnish a single sum for the cost of completing the scope of work described in the plans and specifications. The contractor assumes the risk that in the event actual quantities exceed the contractor-estimated quantities the contractor is not paid extra.

Modified binder—Binder modifiers that include polymers, latex, rubber crumb, and antistripping agents. Modifiers have proven successful at enhancing flexibility, minimizing bleeding, increasing aggregate retention, and extending the service life of chip seals.

Otta seal—A Norwegian term, adopted in many places including parts of Africa and the United States, that describes a low traffic volume–graded aggregate surface treatment.

Pavement preservation—The sum of all activities undertaken to provide and maintain serviceable roadways. This includes corrective maintenance and preventive maintenance, as well as minor rehabilitation projects.

Pneumatic roller—Pneumatic rollers have inflated tires that provide the required forces to properly orient the cover aggregate. Also referred to as a rubber-tired roller.

Pocked—A condition in which the surface of the chip seal has lost aggregate in numerous localized areas.

Polymer-modified binders (PMBs)—Polymer modification of binders reduces the binder's temperature susceptibility, provides increased adhesion characteristics, and increases the overall flexibility of the chip seal. Common polymers used are latex and crumb rubber.

Precoated aggregate—Aggregate precoated with asphalt cement to improve the adhesion of the aggregate to the binder on dusty or dirty aggregate.

Prespraying—Australian terminology for shooting a preparation coat of binder outside and between the wheelpaths to adjust the surface texture of the previous chip seal to a uniform transverse depth.

Preventive maintenance (PM)—A planned strategy of cost-effective treatments that preserves and maintains or improves a roadway system without substantially increasing structural capacity.

Racked-in seal—A surface treatment where the first course, which has a larger nominal size aggregate, is locked in with a light application of smaller aggregate. This is particularly useful for increasing aggregate retention during the curing process.

Raveling—Commonly referred to as shelling, it is the loss of aggregate from the surface treatment. Low binder application rates, inadequate rolling, cool weather construction, and incompatible binder and aggregate types are common factors that lead to raveling.

Reseal—A term used in New Zealand to describe a process for recycling chip seals, in which construction methods are designed to minimize the bleeding and flushing characteristic of sealing over an existing seal. Sandwich seals and water blasting are two construction methods used by a reseal.

Rock land—The length over which one truck's load of aggregate is spread when spread at the design aggregate application rate.

Sacrificial stone—See Choke stone.

Sand patch—A test for determining texture depth of a pavement surface (refer to ASTM E 965). Also known as the sand circle test.

Sand seal—An application of a binder followed by a sand cover aggregate.

Sandwich seal—A two-course surface treatment where aggregate is spread on an existing binder rich surface, before the application of a single-course surface treatment.

Scatter coat—See Choke stone.

Seal coat—A bituminous surface treatment that is a single application of bituminous binder and cover aggregate on an existing paved surface. A seal coat is essentially a single-course chip seal.

Shelling—See Raveling.

Shot—The distance that a distributor sprays binder from start to finish.

Slurry seal—A mixture of graded aggregate and binder applied with a squeegee or broom device. Slurry seals are commonly used for mass crack filling or on pavements with highly oxidized surfaces that are raveling.

Spray bar—A series of spray nozzles at the rear of the distributor that serve to spray a fan-shaped pattern of binder directly on the road surface. Typically, a double- or triple-lap spray pattern is desirable. It is critical for the spray bar to be properly adjusted and at the correct height.

Sprayed seal—Australian term, essentially synonymous with a chip seal, that refers to the application of a bituminous binder and cover aggregate on various surfaces.

Steel roller—Steel rollers provide a rolling energy necessary for some surface treatments such as those with rubber crumb modifiers. Care must be taken to ensure that aggregate is not being crushed or degraded by the steel roller. Also referred to as a flat-wheeled roller.

Streaking—An aesthetic and construction defect caused by nonuniform application of binder across the lane width. Streaking leads to a considerable shortening of the life expectancy of a chip seal.

Stripping—Separation of the binder from the aggregate. See Raveling.

Surface dressing—Term used in the United Kingdom, essentially synonymous with a chip seal, to describe the application of binder and aggregate as a means of maintenance on flexible pavements.

Surface enrichment—A light application of a bituminous material, without the use of a cover aggregate, to an existing chip sealed surface to increase the binder content of the seal. Essentially the same as a fog seal, surface enrichment can assist with aggregate retention on seals with insufficient binder.

Surface texture—The macroscopic and microscopic characteristics of the pavement surface. Surface texture depth is a metric that influences material application rates, design life, skid resistance, and road noise.

Surface treatment—A surface treatment, commonly referred to as a bituminous surface treatment or asphalt surface treatment. It is an application of asphalt binder and cover aggregate on a prepared gravel or crushed stone base.

Texturizing—An Australian/New Zealand practice whereby excess binder is removed before chip sealing to allow a constant rate of binder to be shot during binder application operations.

Unit-price contract—A construction contact whereby the contractor furnishes unit prices (i.e., dollars per pay unit) for each pay item in the contract, and the contract is awarded to the lowest bidder computed by multiplying the contractor-furnished unit price with the engineer's estimated quantity for each pay item and extending that to a total bid price. The contractor is then paid its unit price for the actual quantities even if exceeding the engineer's estimated quantities.

Variable spray bar—A spray bar whose purpose is to put more binder outside the wheelpaths to combat raveling outside the wheelpaths and bleeding within the wheelpaths.

Void—The space between the aggregate particles after they have been spread on the road's surface that is filled with binder.

Wheelpaths—The longitudinal areas of a pavement's surface where the greatest proportion of vehicle tires track. Wheelpaths are particularly sensitive owing to bleeding and flushing when application rates are not strictly adhered to, or when flaky or elongated aggregate has been used.

Whip-off—McLeod's definition for aggregate loss owing to traffic dislodging the aggregate during and shortly after construction.

APPENDIX A

Chip Seal Synthesis Questionnaire

The following pages contain the questionnaire that was distributed to state department of transportation (DOT) maintenance directors, similar positions in 10 foreign countries, points of contact at the county and municipal level, as well as a number of chip seal contractors that expressed an interest in the project. Table A1 is a list of the respondents from which the results of this report are drawn.

TABLE A1
SUMMARY OF CHIP SEAL SYNTHESIS SURVEY RESPONSES

U.S. DOTs	U.S. Local Agencies	Canadian Province DOTs	Canadian Local Agencies	International Agencies	Other Responses
Alaska (2) Arizona Arkansas California Colorado (6)	Lubbock, TX Austin, TX Missoula, MT Des Moines, IA	Alberta British Columbia Manitoba	Ottawa, ON Halifax, NS	New Zealand Transit (3)	Faehrner Asphalt (WI contractor)
Connecticut Florida (NP) Georgia Hawaii (NP)	Salt Lake City, UT Tulsa, OK	Saskatchewan New Brunswick Ontario Quebec		Australia: Victoria Northern Territory	Koch Materials (Midwest MN)
Idaho (3) Indiana Illinois (NP) Iowa Kansas	Contra Costa County, CA Washington County, OR	Newfoundland Nova Scotia		Australia: Tasmania Mainroads (Western Australia)	
Kentucky Louisiana Maine (NP) Maryland	San Diego County, CA	Price Edward Island Yukon Territories (2)		South Africa United Kingdom	
Michigan Minnesota (2) Mississippi Missouri Montana Nebraska					
Nevada New Hampshire (NP) New Jersey (NP) New Mexico New York					
North Carolina North Dakota Oklahoma Ohio Pennsylvania Rhode Island South Carolina					
Texas (3) Vermont (NP) Virginia Washington Wyoming					

NP = No chip seal program.

NCHRP SYNTHESIS 35-02

CHIP SEAL BEST PRACTICES

PURPOSE OF THE SYNTHESIS

Chip seal is one of the most frequently used preventive maintenance treatments on flexible pavements. For purposes of this study and questionnaire, the term "chip seal" is defined as a single or double course of aggregate placed on an asphalt binder that has been applied to the surface of an existing pavement. Much of the practice is based on local anecdotal experience rather than sound engineering principles, and while the design and installation of chip seals involve a significant degree of "art," a strong body of knowledge on the subject has been developed and is scattered throughout the literature of transportation organizations, government agencies, and academia. Technical information is available on good practice for materials, design, construction techniques, and effectiveness of chip seals, and will be summarized in a synthesis. The project's scope will be limited to single- and double-course preventive maintenance chip seal surface treatments.

This questionnaire will take approximately 45 minutes to complete. The purpose of this questionnaire is to collect specific information on chip seal practices from sources ranging from the municipal to the international level. Additionally, those respondents that believe that they have a chip seal project that would make a good case study to illustrate a particularly successful chip seal best practice are invited to indicate their willingness to contribute detailed information about the project, and they will be contacted individually by the researcher to obtain the case study information.

The results of this synthesis will be shared and distributed through AASHTO, FHWA, TRB, and others, with the goal of assisting in the development and implementation of pavement preservation programs. I want to thank you in advance for your support for this project. We do not often get the opportunity to do substantive research in the field of highway maintenance and as this field is so vital to the health of a nation's transportation system, this project's results will furnish a means to disseminate the experience of maintenance engineers from around the world in a very straightforward fashion.

When you have completed this survey, please return it by **January 12, 2004** by any convenient means to

Douglas D. Gransberg, PE
University of Oklahoma
830 Van Vleet Oval, Room 162
Norman, OK 73019-6141
Fax: 405-325-7558
E-mail: dgransberg@ou.edu

RESPONDENT INFORMATION

Agency/organization name:
State:
Country:
☐ USA
☐ Other country, please specify:

Mailing address:
Point of contact name: ; Point of contact phone: ;
Point of contact fax: ; Point of contact e-mail address: ;
Type of agency/organization:
☐ Federal agency
☐ State/provincial agency
☐ County agency
☐ Municipal agency
☐ Other public agency, please specify:
☐ Private organization
If private, what type?
☐ Engineering/design/planning firm
☐ Construction company
☐ Material supplier
☐ Professional or trade organization
☐ Other private organization, please specify:
Chip seal involvement:
☐ Primary business activity or program
☐ Major portion of routine business activity or program
☐ Minor portion of routine business activity or program
☐ Occasional chip seal projects

Do you have a potential case study project that you would be willing to share specific detailed information about to illustrate an important "Best Practice" or "Lesson Learned" by your organization?
☐ Yes ☐ No
If the answer to the above question is Yes?
What is the name of the project?
What is the "Best Practice" or "Lesson Learned"?

Please answer the following questions to the best of your knowledge. If providing an exact answer will require more time than you can allow, please furnish your best estimate. If you are a non-U.S. respondent, when asked to furnish cost data, please indicate the national currency that you are using in your response. If you have questions on the proper interpretation of the questionnaire, please e-mail the researcher at dgransberg@ou.edu. We greatly appreciate your time and support for this synthesis project.

Questions for Respondents

A. General

1. At this time, what proportion of your highway lane miles have chip seals or surface treatments as the wearing course?
   Total centerline ☐ miles/☐ km ☐ miles/☐ km with chip seal
   Rural—local
   Rural—collector
   Rural—arterial
   Rural—interstate
   Urban—local
   Urban—collector
   Urban—arterial
   Urban—interstate

2. Do you follow a specific preventive maintenance cycle for chip seals?
☐ Yes ☐ No

3. If the answer to Question 2 is Yes, what is the cycle length?
Roughly every years.

4. What is the typical life span (age or traffic applications) of a chip seal in your agency?
Approximately years or approximately ESALs on major roads
Approximately years or approximately ESALs on minor roads

5. What percentage of your chip seal work is done with in-house crews?
Approximately %

6. How much chip seal work does your agency do each year?
Approximately US$/year
or other national currency /year
which includes approximately lane miles/year
or lane kilometers/year

7. How do you rate your organization's experience with the performance of in-house chip seals? (Check one box only.)
☐ Excellent; we have very little difficulty with in-house chip seal performance.
☐ Good; we have minor difficulties with in-house chip seal performance.
☐ Fair; we have routine, manageable difficulties with in-house chip seal performance.
☐ Poor; we have serious difficulties with in-house chip seal performance.
☐ Unacceptable; we use in-house chip seals when it is the only alternative.
☐ Not applicable; we do not use in-house chip seals.

8. How do you rate your organization's experience with the performance of contract chip seals? (Check one box only.)
☐ Excellent; we have very little difficulty with contract chip seal performance.
☐ Good; we have minor difficulties with contract chip seal performance.
☐ Fair; we have routine, manageable difficulties with contract chip seal performance.
☐ Poor; we have serious difficulties with contract chip seal performance.
☐ Unacceptable; we use contract chip seals when it is the only alternative.
☐ Not applicable; we do not use contract chip seals.

9. What are the primary problems associated with in-house chip seal work? (Check all that apply and indicate the *single problem* that is most common.)

	Check only one
☐ Early loss of aggregate	☐ most common
☐ Loss of aggregate due to cool evenings	☐ most common
☐ Premature flushing/bleeding	☐ most common
☐ Loss of aggregate over patches	☐ most common
☐ Flushing/bleeding over patches	☐ most common
☐ Flushing/bleeding at intersections and turning areas	☐ most common
☐ Other, please specify:	☐ most common

10. What are the primary problems associated with contract chip seal work? (Check all that apply and indicate the *single problem* that is most common.)

	Check only one
☐ Early loss of aggregate	☐ most common
☐ Loss of aggregate due to cool evenings	☐ most common
☐ Premature flushing/bleeding	☐ most common
☐ Flushing/bleeding over patches	☐ most common
☐ Flushing/bleeding at intersections and turning areas	☐ most common
☐ Other, please specify:	☐ most common

11. Which approach seems to yield a better final chip seal product?
☐ Agency constructed ☐ Contractor constructed ☐ No difference

B. Design

12. Does your organization design chip seal projects?
    - ☐ Yes ☐ No

    If No, please skip down to Section C, Contracting Procedures.

13. How do you characterize existing pavement conditions during the design of chip seal applications?
    - ☐ Penetrometer ☐ Level of oxidation (hunger factor) ☐ Qualitative factors
    - ☐ Other method, please specify:
    - ☐ Don't characterize existing conditions

14. What is the major reason for your organization's decision to apply a chip seal to a given pavement? (Check one box only.)
    - ☐ Distress (cracking)
    - ☐ Improve skid resistance
    - ☐ Prevent water infiltration
    - ☐ Provide a wearing surface
    - ☐ Oxidation
    - ☐ Raveling
    - ☐ Eliminate surface rutting
    - ☐ Improve night vision
    - ☐ Improve contrast between stripes and road surface
    - ☐ Other, please specify:

15. What is the "trigger point" in your chip seal decision-making process?
    - ☐ Pavement condition rating or index
    - ☐ Level/amount of cracking
    - ☐ Skid number
    - ☐ Amount of oxidation
    - ☐ Age of the surface
    - ☐ No trigger point
    - ☐ Other reason, please specify:

16. What is the design procedure you use?
    - ☐ Kearby Method
    - ☐ McLeod Method
    - ☐ Modified Kearby Method
    - ☐ Penetrometer per U.K. *Road Note 39*
    - ☐ Asphalt Institute Method (MS-19)
    - ☐ Modified Marshall Hammer per New Zealand TNZ P17 Method
    - ☐ Sand patch testing
    - ☐ Empirical method based on past experience
    - ☐ No formal design method
    - ☐ Individual organizational method

    Please briefly describe your process or attach a copy of your design method to this questionnaire when you submit it.
    - ☐ No design. Chip seal is treated as a commodity and the chip seal contractor or the agency in-house staff determines the appropriate design

17. What design criteria are used? (Check all that apply.)
    - ☐ Pavement condition
    - ☐ Absorption factor/oxidation
    - ☐ Traffic volume
    - ☐ Turning movements
    - ☐ Percent trucks
    - ☐ Texture factor
    - ☐ Weather (cold/hot/rain/humidity)
    - ☐ Precoat condition (green/dry)
    - ☐ Source of asphalt
    - ☐ Residual factor
    - ☐ Number and width of lanes
    - ☐ Other, please specify:

18. Who performs the design?
    - ☐ Agency in-house design section.
    - ☐ Agency in-house construction group.
    - ☐ Agency in-house maintenance group.
    - ☐ Design consultant under design contract.
    - ☐ Chip seal contractor under the construction contract.
    - ☐ Other, please specify:

19. For how long has the current design procedure been used? years.

20. How do you determine the binder rates?
 ☐ Compute using design procedure ☐ Based on past experience
 ☐ Chip seal contractor sets the rates ☐ Agency in-house staff set the rates
 ☐ Other, please specify:

21. How do you determine the aggregate rates?
 ☐ Compute using design procedure ☐ Based on past experience
 ☐ Chip seal contractor sets the rates ☐ Agency in-house staff set the rates
 ☐ Other, please specify:

22. How would you describe the level of distress (cracks) on roads that generally receive a chip seal?
 ☐ Severe ☐ Moderate ☐ Slight ☐ None

23. How do you characterize the pavement's structural cross section on roads that generally receive a chip seal?
 ☐ Excellent ☐ Good ☐ Fair ☐ Poor ☐ Very Poor

C. Contracting Procedures

24. Do you feel that an adequate number of experienced chip seal contractors bid on your jobs?
 ☐ Yes ☐ No

25. How many chip seal contractors typically bid on your jobs?
 ☐ 1–3 ☐ 4–6 ☐ 7–9 ☐ Over 10

26. Do you have a prequalified list of contractors that are allowed to bid on your chip seal projects?
 ☐ Yes ☐ No

27. Do you require warranties in your chip seal projects?
 ☐ Yes ☐ No
 If so, what is the length of the warranty? weeks/months/years

28. What is your typical chip seal construction season?
 From the month of to the month of

29. Do you require different binder–aggregate combinations for chip seals in different types of highways?
 ☐ Yes ☐ No

30. If the answer to Question 29 is Yes, what is the factor that differentiates between the different requirements?
 ☐ Number of lanes ☐ Average daily traffic ☐ Proximity to urban areas
 ☐ Proximity to specialized aggregate sources like lightweight aggregates
 ☐ Other, please specify:

31. What types of contracts do you use for chip seal projects? (Check all that apply.)
 ☐ Unit price–low bid ☐ Lump sum/firm fixed price
 ☐ Cost plus ☐ Indefinite delivery/indefinite quantity
 ☐ Design–build

32. What is the range for the length of a typical chip seal project?
 lane miles or lane kilometers

33. What is the maximum traffic volume on roads on which your agency constructs chip seals?
 ☐ ADT < 500 ☐ ADT < 1,000 ☐ ADT < 2,000
 ☐ ADT < 5,000 ☐ ADT < 20,000 ☐ ADT > 20,000

D. Materials

34. What uniformly graded aggregates gradation(s) do you use for your chip seal jobs? (Check all that apply.)
    ☐ ⅝ in. or ☐ 16.0 mm
    ☐ ½ in. or ☐ 12.5 mm
    ☐ ⅜ in. or ☐ 10 mm
    ☐ Other, please specify:
    Which gradation is most commonly used?

35. What well-graded aggregates gradation(s) do you use for your chip seal jobs? (Check all that apply.)
    ☐ ⅝ in. minus or ☐ 16.0 mm minus
    ☐ ½ in. minus or ☐ 12.5 mm minus
    ☐ ⅜ in. minus or ☐ 10 mm minus
    ☐ Other, please specify:
    Which gradation is most commonly used?

36. Are any special gradations used?
    ☐ Yes ☐ No
    If Yes, please specify the special gradations:

37. Do you use more than one gradation of aggregate if doing a two course surface treatment?
    ☐ Yes ☐ No
    If Yes, please specify the special gradations:

38. Do you use precoated aggregates on
    Asphalt cement chip seals? ☐ Yes ☐ No
    If Yes, what do you use for precoating material?
    Emulsion chip seals? ☐ Yes ☐ No
    If Yes, what do you use for precoating material?

39. Have you ever used synthetic aggregates for your chip seals?
    ☐ Yes ☐ No
    If Yes, do you use
    ☐ Lightweight aggregate? ☐ Crushed slag aggregate?
    ☐ Other, please specify:
    If you regularly use synthetic aggregates, please indicate those situations where you typically specify these aggregates:

40. What is the typical cost for your aggregates?

Natural stone or gravel chip seal aggregate:	$/ton or	currency/ton
Lightweight chip seal aggregate:	$/ton or	currency/ton
Crushed slag chip seal aggregate:	$/ton or	currency/ton
Other, please specify:	$/ton or	currency/ton

41. What types of natural aggregate are typically used on your chip seal projects?

☐ Limestone	% of program
☐ Quartzite	% of program
☐ Granite	% of program
☐ Trap rock (igneous)	% of program
☐ Sandstone	% of program
☐ Natural gravels	% of program
☐ Other, please specify:	% of program

42. What binder types do you normally use in the organization? Please indicate the percent usage on an annual basis and average unit price for each type.

☐ AC 2.5	% of program	$/gal or	currency/liter
☐ AC 5	% of program	$/gal or	currency/liter
☐ AC 5-latex	% of program	$/gal or	currency/liter

☐ AC 10	% of program	$/gal or	currency/liter
☐ AC 10-latex	% of program	$/gal or	currency/liter
☐ AC 15P	% of program	$/gal or	currency/liter
☐ AC15-5TR	% of program	$/gal or	currency/liter
☐ AC20	% of program	$/gal or	currency/liter
☐ AC 40	% of program	$/gal or	currency/liter
☐ CRS-1	% of program	$/gal or	currency/liter
☐ CRS-1H	% of program	$/gal or	currency/liter
☐ CRS-1P	% of program	$/gal or	currency/liter
☐ CRS-2	% of program	$/gal or	currency/liter
☐ CRS-2H	% of program	$/gal or	currency/liter
☐ CRS-2P	% of program	$/gal or	currency/liter
☐ HFRS	% of program	$/gal or	currency/liter
☐ HFRS-2P	% of program	$/gal or	currency/liter
☐ Other	% of program	$/gal or	currency/liter

43. How do you select the binder type for chip seal jobs?
    ☐ Local climate ☐ Traffic level of road to be sealed
    ☐ Season in which seal will be applied ☐ Past experience
    ☐ Design procedure determines it
    ☐ Other, please specify:

44. Do you use modifiers with your asphalt or emulsions?
    ☐ Yes ☐ No
    If Yes, what modifiers are allowed for use? (Check all that apply.)
    ☐ Polymers ☐ Latex ☐ Rubber crumb
    ☐ Anti-stripping agents ☐ Additives
    ☐ Other, please specify:

45. Has your agency constructed any geotextile-reinforced chip seals?
    ☐ Yes ☐ No
    If Yes, have the geotextile-reinforced chip seals been successful?
    ☐ Yes ☐ No

E. Equipment

46. Do you require computerized controls on your distributors?
    ☐ Yes ☐ No

47. Do you require computerized gate controls on your chip spreaders?
    ☐ Yes ☐ No

48. What roller types are considered appropriate for use on chip seals using emulsion binders?
    ☐ Static steel ☐ Vibratory steel ☐ Pneumatic-tired
    ☐ Combination pneumatic/steel ☐ Combination vibratory/pneumatic
    ☐ Other, please specify:

49. What roller types are considered appropriate for use on chip seals using asphalt binders?
    ☐ Static steel ☐ Vibratory steel ☐ Pneumatic-tired
    ☐ Combination pneumatic/steel ☐ Combination vibratory/pneumatic
    ☐ Other, please specify:

50. Do you require any specific makes and models (proprietary specifications) for the chip seal equipment?
    ☐ Yes ☐ No
    If Yes, for which of the following equipment? (Check all that apply.)
    ☐ Binder distributors ☐ Aggregate spreaders

- ☐ Rollers/rolling equipment ☐ Sweeping equipment
- ☐ Traffic control equipment/devices
- ☐ Other, please specify:

F. Construction

51. Prior to chip sealing, what road preparation methods are typically performed for the existing surface?
    - ☐ Chip seal placed on freshly paved asphalt surface ☐ Crack sealing
    - ☐ Fog coat ☐ Cold mix patch and level
    - ☐ Geotextile to retard reflective cracking
    - ☐ Other, please specify:

52. What are your specifications for ambient air temperature to do chip seal work? degrees ☐ No specification

53. What are your specifications for pavement temperature to do chip seal work? degrees ☐ No specification

54. How soon after the binder spray operation is aggregate spread? minutes
    Is this different for asphalt concrete and emulsion? ☐ Yes ☐ No

55. What is the typical time span between aggregate spread and initial rolling?

56. What is the typical number of pneumatic-tired rollers required?
    - ☐ One ☐ Two ☐ Three ☐ Four
    - ☐ Other, please specify:

57. What is the typical number of steel-wheeled rollers required?
    - ☐ One ☐ Two ☐ Three ☐ Four
    - ☐ Other, please specify:

58. Which of the following controls are in place for your roller operations?
    - ☐ Number of passes ☐ Rolling patterns
    - ☐ Speed limits ☐ Roller weight
    - ☐ Other, please specify:

59. What is the typical time span between final rolling and initial brooming?

60. What is the typical number of broom passes?
    - ☐ One ☐ Two ☐ Three
    - ☐ Other, please specify:

61. What traffic control measures are typically required?
    - ☐ Reduced speed ☐ Interim pavement markings and devices
    - ☐ Pilot vehicles ☐ Flaggers
    - ☐ Other, please specify:

62. What is the typical maximum reduced speed allowed? mph/km/h

63. What is the typical time span between final rolling and opening to reduced speed traffic? minutes/hours

64. What is the typical time span between final rolling and opening to full speed traffic? minutes/hours

65. Do you require a scrub seal or fog seal to be applied on a fresh chip seal?
    - ☐ Yes ☐ No

    If Yes, please indicate how long after the seal.
    - ☐ Next day ☐ hours
    - ☐ Other, please specify:

G. Quality Control

66. Who performs the final inspection?
☐ Your agency ☐ Private consultant ☐ Contractor
How many people perform the inspection?
☐ Individual ☐ Team

67. Which of the following tests are performed on your aggregate?
☐ Percent fracture ☐ Flakiness index ☐ Decant test
☐ Anti-strip test (compatibility with binder) ☐ Tests for the presence of clay
☐ Percent sodium sulfate loss (resistance to freeze–thaw)
☐ Other, please specify:

68. Do you perform any field tests to monitor the quality of the binder?
☐ Yes ☐ No If Yes, what are they?

69. Do you require calibration of binder spray equipment?
☐ Yes ☐ No If Yes, how often?

70. Do you require calibration of aggregate spreading equipment?
☐ Yes ☐ No If Yes, how often?

71. What tolerances are allowed for binder spray and aggregate spread rates?
Binder spray ± gal/sy or L/sm
Aggregate spread ± lb/sy or kg/sm

72. Beyond calibration of chip spreader and binder distributors, do you perform any other field tests to check material application rates? ☐ Yes ☐ No

73. If Yes, what is it called?
Please attach a copy of the test to this questionnaire if possible.

74. Are any special quality control tests employed by your agency?
☐ Yes ☐ No
If Yes, please specify:

H. Performance

75. What common distresses are observed in your chip seals? To the right, please indicate the top three distresses in order of occurrence.
☐ Potholes
☐ Raveling
☐ Bleeding 1. __________
☐ Corrugation
☐ Crack reflection 2. __________
☐ Streaking
☐ Transverse joints 3. __________
☐ Longitudinal joints
☐ Other, please specify:

76. Which factor is most important in minimizing defects? (Check one box only.)
☐ Construction procedure ☐ Design method ☐ Better binder
☐ Better aggregates ☐ Quality control ☐ Double seal
☐ Other, please specify:

77. What is the most common public-user complaint about a chip seal? (Check one box only.)
☐ Loose stone ☐ Road noise ☐ Vehicle ride
☐ Appearance ☐ Other, please specify:

78. How would you describe the pavement ride on roads that generally receive a chip seal?
☐ Excellent ☐ Good ☐ Fair ☐ Poor ☐ Very Poor

79. Of your organization's chip seal failures, which of the following was a likely cause? To the right, please indicate the top three distresses in order of importance.
☐ Weather
☐ Insufficient rolling
☐ Improper binder application rate
☐ Improper aggregate rate
☐ Aggregate spread early
☐ Aggregate spread late
☐ Dirty or dusty aggregate
☐ Aggregate gradation
☐ Improper binder viscosity
☐ Improper binder temperature
☐ Other, please specify:

1. __________
2. __________
3. __________

80. Which factors are most critical in determining the life of your chip seals?
☐ Original quality ☐ Traffic ☐ Underlying structure
☐ Maintenance spending ☐ Friction loss
☐ Cold climate considerations (freeze–thaw cycles, snowplowing, etc.)

81. Which methods do you use to maintain your chip seals? (Check all that apply.)
☐ Crack sealing ☐ Seal patch ☐ Sanding or chat
☐ Lime slurry ☐ Fog seal ☐ Local strengthening
☐ Other, please specify:

If there is anything that you would like to add that was not covered in this questionnaire that you feel would benefit this study, please write your comments below:

THANK YOU FOR SUPPORTING THIS IMPORTANT EFFORT

Please respond by January 12, 2004

APPENDIX B

Survey Responses

INTRODUCTION

This appendix furnishes the details of the chip seal survey responses. Tables B1 and B2, a synopsis of North American survey responses by state and province, respectively, are furnished as a quick reference for the reader. The second section of the appendix contains the summary of detailed survey responses on a question-by-question basis rolled up as appropriate for each question.

TABLE B1
CHIP SEAL PROGRAM SYNOPSIS BY U.S. STATE

	Reason to Seal	Traffic	Design	Binders	Performance
Arizona	Distress	ADT<2,000	Empirical	AC15-TR, CRS-2H	Fair
Arkansas	Wearing Surface	ADT<5,000	Asphalt Institute	CRS-2P	Excellent
Alaska	Wearing Surface	ADT<20,000	Emp./McLeod	HFMS-2P, CRS-2P	Good
California	Water Infiltration	ADT>20,000	None	CRS-2P	Good
Colorado	Wearing Surface	ADT>20,000	None	HFRS-2P	Excellent
Connecticut		ADT<5,000	None	CRS-2	Good
Georgia		ADT<2,000	None	AC20, CRS-2H	Good
Idaho	Skid Resistance	ADT<5,000	Mod. Kearby	CRS-2P	Excellent
Indiana			None	CRS-2P, HFRS-2	Good
Kansas	Distress	ADT<5,000	Empirical	CRS-1HP	
Kentucky	Distress		None	RS-1, RS-2,	Unacceptable
Louisiana	Water Infiltration	ADT<5,000	None	CRS-2P	
Maryland				CRS-2	
Michigan			None	CRS-2	
Minnesota	Water Infiltration	ADT<20,000	McLeod	CRS-2P	Good
Mississippi	Water Infiltration	ADT<2,000	None	CRS-2P	Good
Montana	Wearing Surface	ADT>20,000	Asphalt Institute	CRS-2, CRS-2P	Good
Nebraska	Oxidation	ADT<2,000	Empirical	CRS-2P	Fair
Nevada	Wearing Surface	ADT<5,000	Empirical	CRS-1,CRS-2, CRS-2H	Excellent
New Mexico	Wearing Surface	ADT<2,000	Empirical	Polymer Modified	Good
New York	Water Infiltration	ADT<2,000		CRS-2,CRS-2P,HFRS-2P	
North Carolina	Various	ADT<2,000	None	CRS-2P,CRS-2	
North Dakota	Oxidation		Empirical	CRS-2P	Fair
Ohio	Distress	ADT<2,000	Empirical	Polymer Modified	Good
Oklahoma	Distress	ADT<5,000	Empirical	CRS-2, CRS-2P	Excellent
Pennsylvania	Oxidation	ADT<20,000	Own method	CRS-2, CRS-2P	Good
Rhode Island		ADT<20,000	None	PG 58-28, 20% TR	Good
South Carolina				CRS-2	
South Dakota	Various		Empirical/McLeod	CRS-2, HFRS-2	
Texas	Water Infiltration	ADT<20,000	Modified Kearby	AC15-P/TR, CRS-2H,	Excellent
Virginia	Age		None	CRS-2	Fair
Washington	Distress	ADT<2,000	Empirical	CRS-2, CRS-2P	Excellent
Wyoming	Water Infiltration	ADT<2,000	Empirical	CRS-2P, HFRS-2P	Good

TABLE B2
CHIP SEAL PROGRAM SYNOPSIS BY CANADIAN PROVINCES

	Reason to Seal	Traffic	Design	Binders	Performance
Alberta	Wearing Surface		McLeod	CRS	Unacceptable
British Columbia	Wearing Surface	ADT<20,000	McLeod	HF150, HF150P	
Manitoba	Water Infiltration	ADT<20,000	McLeod	HFRS	Good
New Brunswick			Asphalt Institute	CRS, HFRS	
Newfoundland	Illumination	ADT<2,000	None	Polymer Modified	Fair
Nova Scotia		ADT<5,000	None	CRS-2P, HF-150S	Good
Ontario	Surface Condition	ADT<2,000	Visual (own)	CRS-2P, HF-150S	
Saskatchewan	Wearing Surface	ADT<20,000	Own Method	HFRS, HFRS-2P	Good
Quebec	Wearing Surface	ADT<1,000	Asphalt Institute	HFRS, HFRS-2P	Good
Yukon	Wearing Surface	ADT<2,000	Empirical	HFRS	Excellent

DETAILED SURVEY RESPONSES

The following set of tables synopsizes the responses to each question in the chip seal survey. Questions for which a given respondent did not provide a response are denoted by NR. It should be noted that not all responses were complete. However, all responses received to each question are shown.

1. At this time, what proportions of your highway lane miles have chip seals or surface treatments as the wearing course? (All international responses are converted from metric to lane-miles.)

Country	Total Lane Miles
United States	139,713
Canada	39,482
Australia	272,832
New Zealand	71,900
United Kingdom	213,150

2. Do you follow a specific preventive maintenance cycle for chip seals in years?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Yes	17	2	3	0	1	0
No	24	7	1	2	0	1

3. If the answer to Question 2 is Yes, what is the cycle length in years? Averages provided.

United States	Canada	Australia	New Zealand	South Africa	U.K.
5.4	6	10	NR	11	NR

4. What is the typical life span of a chip seal in your agency in years?

United States	Canada	Australia	New Zealand	South Africa	U.K.
5.76	5.33	10	7	12	10

5. What percentage of your chip seal work is done with in-house crews?

United States	Canada	Australia	New Zealand	South Africa	U.K.
54%	35%	15%	0%	NR	30%

6. How much chip seal work does your agency do each year?

United States	Canada	Australia	New Zealand	South Africa	U.K.
150 k–80 mi	500 k–7.5 mi	NR	NR	NR	NR

7. Self-rated in-house chip seal performance.

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Excellent	15	2	1	2	0	0
Good	18	2	1	0	0	1
Fair	6	0	0	0	0	0
Poor	0	0	0	0	0	0
Unacceptable	1	1	0	0	0	0
NR	7	5	2	0	1	0

8. Self-rated contractor chip seal performance.

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Excellent	7	0	1	2	0	0
Good	19	5	1	0	0	1
Fair	8	3	0	0	0	0
Poor	3	0	0	0	0	0
Unacceptable	0	0	0	0	0	0
NR	5	2	2	0	1	0

9. Primary problems with in-house chip seal work. (Check all that apply.)

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Early Aggr. Loss	18	3	0	1	0	0
Aggr. Loss Evenings	4	2	0	0	0	0
Premature Flushing	15	1	1	1	0	0
Aggr. Loss Patches	5	1	0	1	0	1
Flushed Patches	9	2	1	1	0	1
Flushed Intersections	14	2	0	1	0	0

10. Primary problems with contract chip seal work. (Check all that apply.)

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Early Aggr. Loss	25	6	0	1	0	0
Aggr. Loss Evenings	6	3	0	0	0	0
Premature Flushing	13	3	2	2	0	0
Aggr. Loss Patches	1	1	0	0	1	1
Flushed Patches	13	3	1	1	0	1
Flushed Intersections	15	4	0	1	0	0

11. Which approach yields a better chip seal?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
In-House	16	4	0	0	0	0
Contractor	9	2	2	2	0	0
No Difference	8	2	2	0	0	1

12. Does your organization design chip seal projects?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Yes	30	4	3	1	1	1
No	9	5	0	0	0	0

13. Characterize pavement conditions for design. (Check all that apply.)

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Hardness	0	0	4	2	1	1
Sand Patch	0	0	4	2	1	1
Oxidation	9	2	0	1	0	1
Qualitative	13	1	1	0	1	1

14. Reason for chip sealing.

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Distress	9	1	0	0	0	0
Water Infiltration	7	2	1	0	0	1
Oxidation	5	0	0	0	0	0
Skid Resistance	2	0	1	1	0	1
Wearing Surface	8	1	0	1	0	0

15. What causes the decision to select a road for a chip seal? Trigger point.

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Pavement Condition Rating	13	3	1	0	0	1
Skid Number	4	0	1	0	0	0
Age of Surface	8	2	2	0	0	0
Cracking	12	2	1	0	0	0
Oxidation	8	1	0	0	0	0

16. North American design procedures.

	United States	Canada
Kearby/Modified Kearby	2	0
McLeod/Asphalt Institute	3	4
Own Method	5	3
Empirical/Past Experience	10	0
No Design	7	2

17. Design criteria used in design method.

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Pavement Condition	29	4	4	2	1	1
Traffic Volume	25	1	4	2	1	1
Percent Trucks	7	1	4	2	1	1
Weather	6	0	4	2	1	1
Source of Binder	2	0	0	0	0	1
Absorption	15	2	4	2	1	1
Turning Movements	11	1	4	2	1	1
Texture	12	0	4	2	1	1
Precoat Condition	4	0	0	0	0	0
Residual Factor	5	0	4	1	0	0
Lanes of Traffic	3	0	0	1	0	0

18. Who performs the chip seal design? (Check all that apply.)

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Agency—Design Group	11	1	1	0	0	1
Agency—Construction Group	3	1	1	0	0	0
Agency—Maintenance Group	16	2	2	0	0	0
Design Consultant	1	0	1	1	1	0
Contractor	5	3	4	2	0	1

19. How long has design procedure been used?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Range (yr)	5–40	1–20	2–8	30*	6	30*

*Has been continuously improved since original version.

20. How are binder rates determined?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Design	8	2	4	2	1	1
Experience	24	2	0	0	0	0
Contractor	2	2	0	0	0	0
Agency	11	3	0	0	0	0

21. How are aggregate rates determined?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Design	8	2	4	0	1	1
Experience	20	2	0	1	0	0
Contractor	2	2	0	1	0	0
Agency	11	3	0	0	0	0

22. Level of distress on roads that are sealed.

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Severe	4	0	1	0	0	0
Moderate	22	4	2	2	1	1
Slight	12	2	1	0	0	0
None	1	1	0	0	0	0

23. Pavement's structure cross-section condition on roads that are sealed.

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Excellent	1	0	3	0	0	0
Good	24	3	1	0	1	0
Fair	6	3	0	2	0	1
Poor	2	1	0	0	0	0

24. Adequate number of experienced contractors.

	U.S. States	Canada	Australia	N.Z.	S. Africa	U.K.	Counties and Cities
Yes	18	7	4	2	1	1	1
No	15	2	0	0	0	0	7

25. How many contractors bid on your jobs?

	U.S. States	Canada	Australia	N.Z.	S. Africa	U.K.	Counties and Cities
1–3	19	7	2	0	0	0	1
4–6	13	2	2	0	1	1	7
7–9	0	0	0	0	0	0	0
>10	0	0	0	1	0	0	0

26. Are contractors prequalified?

	U.S. States	Canada	Australia	N.Z.	S. Africa	U.K.	Counties and Cities
Yes	11	1	2	1	0	1	1
No	24	8	2	1	1	0	7

27. Warranties on chip seals.

	U.S. States	Canada	Australia	N.Z.	S. Africa	U.K.	Counties and Cities
Yes	6	8	2	1	1	1	5
No	26	1	0	0	0	0	2

28. Typical construction season: Variable by region; generally runs from April through September with southern states running about 1 month longer than northern states.

29. Do you require different aggregate–binder combinations for different highways?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Yes	18	6	3	2	1	1
No	20	4	1	0	0	0

30. If answer to Question 29 is Yes, what differentiates?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
ADT	16	5	2	2	1	1
Urban Areas	4	2	1	0	1	0
Proximity to Special Aggregate	2	0	0	0	0	0

31. What types of contracts do you use? (Check all that apply.)

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Unit Price	30	10	3	2	1	1
Design Build	0	0	0	1	0	1
Lump Sum	2	0	2	2	0	0

32. What is the range of your chip seal projects (miles)? All international responses are converted from kilometers.

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Range	4–250	8–30	NR	37.2	40	60–600

33. What is the maximum traffic volume on roads on which your agency constructs chip seals?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
ADT < 500	2	1	0	0	0	0
ADT < 1,000	1	1	0	0	0	0
ADT < 2,000	12	2	0	0	0	0
ADT < 5,000	11	2	0	0	0	0
ADT < 20,000	12	3	3	1	0	0
ADT > 20,000	7	0	1	1	1	1

34 and 35. What gradations do you use for your chip seals? (Check all that apply.)

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
⅝ in./16 mm	4	0	0	2	0	0
½ in./12.5 mm	19	4	0	2	1	0
⅜ in./10 mm	25	1	4	2	0	0

36. Do you use any special gradations?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Yes	11	2	1	1	1	1
No	25	6	3	0	0	0

37. Do you use different gradations for multiple course seals?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Yes	20	3	2	2	1	1
No	15	5	2	0	0	0

38. Do you use precoated aggregate with asphalt cement chip seals?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Yes	9	0	4	2	1	1
No	31	8	0	0	0	0

Do you use precoated aggregate with emulsion chip seals?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Yes	3	0	0	0	0	0
No	26	8	4	2	1	1

39. Have you ever used synthetic aggregate?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Yes	12	0	1	1	0	1
No	27	8	3	1	1	0

40. What is the typical binder and aggregate cost? Question universally ignored.

41. Types of aggregate used. (Check all that apply.)

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Limestone	19	2	1	0	0	0
Quartzite	6	1	2	1	1	1
Granite	14	4	3	0	0	1
Trap Rock	7	0	2	0	0	1
Sandstone	5	0	0	0	0	1
Natural Gravels	24	7	2	1	0	1

42. Binders typically used. (Check all that apply.)

	United States	Canada
Hot Applied Asphalt Cements	3	0
Conventional Emulsions	36	9
Polymer-Modified Emulsion	36	8
High Float Emulsions	6	4

43. How do you select the type of binder? (Check all that apply.)

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Climate	11	4	1	2	0	0
Traffic	8	5	0	0	1	0
Season	5	0	0	0	0	0
Experience	27	4	1	0	0	0
Design	2	2	0	0	0	1

44. Do you use modifiers with your binders?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Yes	12	0	1	1	0	1
No	27	8	3	1	1	0

What types of modifiers? (Check all that apply.)

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Polymers	34	8	2	2	1	1
Latex	10	1	0	1	1	0
Crumb Rubber	8	0	2	0	1	0
Anti-Stripping	9	5	1	2	0	1

45. Has your agency constructed any geotextile-reinforced seals?

	U.S. States	Canada	Australia	N.Z.	S. Africa	U.K.	Counties and Cities
Yes	3	0	4	2	1	1	2
No	37	9	0	0	0	0	6

If yes, have the trials been successful?

	U.S. States	Australia	N.Z.	S. Africa	U.K.	Counties and Cities
Yes	1	4	2	1	1	2
No	3	0	0	0	0	2

46. Computerized controls on distributors required.

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Yes	26	5	2	2	1	1
No	15	5	2	0	0	0

47. Computerized controls on spreaders required.

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Yes	15	1	0	1	0	0
No	25	9	4	1	1	1

48 and 49. Rollers considered appropriate for use. (Check all that apply.)

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Pneumatic	36	8	3	2	1	1
Static Steel	0	5	0	1	0	0
Vibratory Steel	2	2	0	0	0	1
Combination Pneumatic/Steel	8	2	0	1	0	0
Rubber-Clad Steel	0	1	2	0	0	1

50. Any proprietary specifications for equipment?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Yes	2	0	0	0	0	0
No	49	9	4	2	1	1

51. Road preparation methods.

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Chip Seal on Fresh Pavement	7	0	1	0	0	0
Crack Sealing	29	6	2	1	0	0
Patch and Level	20	2	3	1	0	1
Texturizing (other)	0	0	1	1	1	0

52. Ambient air temperature specifications. (All metric temperatures converted to degrees Fahrenheit.)

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Range (F)	40–80 min. 110 max.	>50	>60	>50	NR	50 min. 95 max.

53. Pavement temperature specifications. (All metric temperatures converted to degrees Fahrenheit.)

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Range (F)	40–85 min. 130–140 max.	32–41 min.	60–68 min.	NR	77 min.	NR

54. How soon is aggregate spread after binder application?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Time Range (min)	Immediate– 5 min	Immediate– 5 min	1–10 min	All aggregate spread within 5 min	>5 min	>1 min

55. What is the typical time span between aggregate spread and initial rolling?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Time Range (min)	Immediate– 5 min	Immediate	Immediate– 3 min	NR	NR	NR

56. What is the typical number of pneumatic rollers?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
No. of Rollers	1–3*	1–5**	NR	NR	NR	NR

*Mode of two.
**Mode of two; Manitoba requires five.

57. What is the typical number of steel-wheeled rollers?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
No. of Rollers	1–2*	1–2**	Not allowed	Not Allowed	NR	Not permitted, use rubber clad steel

*Twelve state highway agencies don't allow; Caltrans only allows on rubber seals.
**Mode of one, allowed by five provinces.

58. Which controls are in place on rolling operations? (Check all that apply.)

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
No. of Passes	27	5	3	0	1	0
Patterns	15	2	2	0	0	0
Speed Limits	17	3	3	0	0	1
Weight	17	6	2	0	1	0
Rolling Time (other)	0	0	2	2	0	0

59. What is the typical time span between final rolling and initial brooming?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Time (range)	1–48 h*	Immediate to 48 h	1 day	NR	NR	NR

*Consensus seems to be 2 to 3 h.

60. What is the typical number of broom passes?

	U.S. States	Canada	Australia	N.Z.	S. Africa	U.K.	Counties and Cities
One	7	2	0	1	0	0	4
Two	17	4	1	0	0	0	3
Three	11	2	0	1	1	0	2
Four	0	0	0	0	0	0	0
Other			Residual stone count, similar to Montana			Only suction permitted	

61. What traffic control measures are typically required? Check all that apply.

	U.S. States	Canada	Australia	N.Z.	S. Africa	U.K.	Counties and Cities
Reduced Speed	9	9	4	2	1	1	9
Interim Pavement Markings	6	6	4	0	1	0	6
Pilot Vehicles	8	8	1	0	0	1	8
Flaggers	10	10	3	1	0	0	10
Other	N.Y. has reduced speed for 3 days	B.C. has traffic control for 24 h		Cones moved around to direct traffic on untrafficked areas			Highway patrol and computerized arrow boards common

62. What is the typical maximum reduced speed allowed? (All metric responses converted to U.S. units.)

	U.S. States	Canada	Australia	N.Z.	S. Africa	U.K.	Counties and Cities
Average (mph)	29	28	NR	NR	NR	20	25

63. What is the typical time span between final rolling and opening to reduced speed traffic?

	U.S. States	Canada	Australia	N.Z.	S. Africa	U.K.	Counties and Cities
Range	1–6 h	0.5–48 h	10–30 min	Immediate	4 h	0.5 h	0–4 h

64. What is the typical time span between final rolling and opening to full speed traffic?

	U.S. States	Canada	Australia	N.Z.	S. Africa	U.K.	Counties and Cities
Range	0.5–72 h	0.5–48 h	0.5–48 h	24–48 h	NR	24 h	0–2 weeks

65. Do you require a scrub seal or fog seal to be applied on a fresh chip seal?

	U.S. States	Canada	Australia	N.Z.	S. Africa	U.K.	Counties and Cities
Yes	8	0	0	0	0	0	2
No	31	9	4	2	1	1	6

66. Who performs the final inspection?

	U.S. States	Canada	Australia	N.Z.	S. Africa	U.K.	Counties and Cities
Agency	40	8	3	0	0	1	9
Consultant	0	1	1	2	1	0	0
Contractor	0	1	1	0	0	0	0

How many people perform the inspection?

	U.S. States	Canada	Australia	N.Z.	S. Africa	U.K.	Counties and Cities
Individual	23	6	3	1	0	1	6
Team	16	3	1	1	1	0	1

67. Which of the following tests are performed on your aggregate? (Check all that apply.)

	U.S. States	Canada	Australia	N.Z.	S. Africa	U.K.	Counties and Cities
Percent Fracture	23	9	1	1	0	0	2
Flakiness	9	4	4	1	1	1	3
Decant	5	1	1	0	0	0	4
Anti-Strip	13	5	1	2	0	0	3
Presence of Clay	14	4	0	0	0	0	2
Sodium Sulfate Loss	10	1	1	0	0	1	1
Other	LA abrasion in 8 states	LA abrasion in 3 provinces	ALD in 4 responses	Polished stone value	Hardness and durability	Polished stone value, LA abrasion	

68. Do you perform any field tests to monitor the quality of the binder?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Yes	19	3	3	1	1	1
No	21	7	1	1	0	0

69. Do you require calibration of binder spray equipment?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Yes	32	4	4	2	1	1
No	7	5	0	0	0	0

70. Do you require calibration of aggregate spreading equipment?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Yes	28	3	1	0	1	1
No	12	7	3	1	0	0

71. What tolerances are allowed for binder spray and aggregate spread rates?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Binder (range)	10%	10%	5%	NR	5%	10%
Aggregate (range)	10%	10%	5%	NR	5%	10%

Question had poor response; therefore, most accurate representation was selected.

72. Beyond calibration of chip spreader and binder distributors, do you perform any other field tests to check material application rates?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Yes	17	3	2	2	1	1
No	20	7	2	0	0	0

73. If Yes, what is it called? Various.

74. Special quality control tests? Various.

75. What common distresses are observed in your chip seals? (Check all that apply.)

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Potholes	4	6	2	0	0	0
Raveling	24	8	1	2	1	1
Bleeding	54	9	4	2	1	1
Corrugation	41	2	1	0	0	0
Cracking	30	5	3	2	0	0
Streaking	43	5	0	1	0	1
Transverse Joints	29	4	0	0	0	0
Longitudinal Joints	17	3	1	0	1	0

76. Which factor is most important in minimizing defects?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Construction Procedure	27	7	1	0	1	0
Design Method	29	0	2	1	0	1
Better Aggregates	3	0	0	0	0	0
Better Binder	4	0	0	0	0	0
Quality Control	13	2	1	0	0	0
Double Seal	14	1	0	0	0	0

77. What is the most common public-user complaint about a chip seal?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Loose Stone	35	7	3	2	1	1
Road Noise	4	2	1	0	0	0
Vehicle Ride	1	0	0	0	0	0
Appearance	3	2	0	0	0	0

78. How would you describe the pavement ride on roads that generally receive a chip seal?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Excellent	5	0	3	0	0	0
Good	24	7	1	1	1	0
Fair	9	3	0	1	0	1
Poor	1	0	0	0	0	0
Very Poor	1	0	0	0	0	0

79. Of your organization's chip seal failures, which of the following was a likely cause?

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Weather	27	7	3	2	1	1
Insufficient Rolling	7	3	1	1	0	0
Improper Binder Application Rate	21	6	3	2	1	1
Improper Aggregate Rate	16	4	1	2	0	0
Aggregate Spread Early	4	0	0	0	0	0
Aggregate Spread Late	11	0	1	1	1	0
Dirty or Dusty Aggregate	22	4	3	2	1	1
Aggregate Gradation	8	0	0	1	0	0
Improper Binder Viscosity	8	2	0	1	0	0
Improper Binder Temp.	3	2	0	2	0	0

80. Which factors are most critical in determining the life of your chip seals? (Check all that apply.)

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Original Quality	20	5	2	2	1	0
Traffic	12	5	1	1	1	0
Underlying Structure	18	3	1	2	0	1
Maintenance Spending	6	0	0	0	0	0
Friction Loss	5	0	0	2		
Cold Climate Considerations	14	7	0	0	0	0

81. Which methods do you use to maintain your chip seals? (Check all that apply.)

	U.S.	Canada	Australia	N.Z.	S. Africa	U.K.
Crack Sealing	28	6	2	2	1	0
Chip Seal Patch	5	3	1	2	1	0
Sanding/Chat	5	0	0	0	0	1
Lime Slurry	0	0	0	0	0	0
Fog Seal	14	0	0	0	1	
Local Strengthening	4	2	0	1	1	0
Patching (other)	3	3	3	0	0	0

APPENDIX C

Chip Seal Design Details

INTRODUCTION

The very early practitioners of chip seals appear to have used a purely empirical approach to their designs. Sealing a pavement was considered then, as it is now in many circles, an art. The design of a chip seal involves the calculation of correct quantities of a bituminous binder and a cover aggregate to be applied over a unit area of the pavement. Several design approaches outlined in the available literature are briefly described in this appendix.

The details of the various design methods in use in the United States, Canada, and overseas are reported here. An effort has been made to report the salient details of each method without describing the entire method in detail. Representative examples of design charts and tables are presented to illustrate the level of design detail that is involved in each method. The reader should refer to the literature for details.

HANSON METHOD

The first recorded effort at developing a design procedure for seal coats appears to have been made by a New Zealander, F.M. Hanson (1934/35). His design method was developed primarily for liquid asphalt, particularly cutback asphalt, and it was based on the average least dimension (ALD) of the cover aggregate spread on the pavement. Hanson calculated ALD by manually calipering a representative aggregate sample to obtain the smallest value for ALD that represents the rolled cover aggregate layer. He observed that when cover aggregate is dropped from a chip spreader on to a bituminous binder, the void between aggregate particles is approximately 50%. He theorized that when the layer is rolled, this value is reduced to 30% and it is further reduced to 20% when the cover aggregate is compacted by traffic. Hanson's design method involved the calculation of bituminous binder and aggregate spread rates to be applied to fill a certain percentage of the voids between aggregate particles. Hanson specified the percentage of the void space to be filled by residual binder to be between 60% and 75%, depending on the type of aggregate and traffic level.

McLEOD METHOD

Throughout the 1960s, N. McLeod developed a design procedure based partially on Hanson's previous work (McLeod 1969). McLeod's design determines the aggregate application rate based on gradation, specific gravity, shape, and a wastage factor. McLeod provided a correction factor owing to the fraction of voids. The binder application rate is determined by the aggregate gradation, pavement condition, traffic volume, and type of asphalt. McLeod made it apparent that correction factors for the quantity of binder lost by absorption of aggregate and texture of existing surface are recommended. McLeod's work also gives guidelines on the appropriate type and grade of asphalt for the selected aggregate and surface temperature at time of application. The Asphalt Emulsion Manufacturers Association and the Asphalt Institute have gone on to adapt this method in the form of recommendations for binder types and grades for various aggregate gradations, and correction factors to the binder application rate based on existing surface condition (*Seal Coat . . .* 2003).

KEARBY METHOD

In 1953, J.P. Kearby, an engineer with the Texas Highway Department, made one of the first efforts at designing chip seal material application rates in the United States. Kearby was quick to point out that "computations alone cannot produce satisfactory results and that certain existing field conditions require visual inspection and the use of judgment in the choice of quantities of asphalt and aggregate" (Kearby 1953). Kearby developed a method to determine the amounts and types of asphalt and aggregate rates for one-course surface treatments and chip seals. Kearby's work resulted in the development of a nomograph that provided an asphalt cement application rate in gallons per square yard for the input data of average thickness, percent aggregate embedment, and percent voids (Kearby 1953). The design methodology requires the knowledge of some physical characteristics of the aggregate, such as unit weight, bulk specific gravity, and quantity of aggregate needed to cover 1 yd^2 of roadway. The unit weight test, bulk-specific gravity test, is done for calculating unit weight and bulk-specific gravity. Figure C1 is the nomograph developed by Kearby for use in chip seal design.

In addition to developing the nomograph, Kearby recommended the use of a uniformly graded aggregate by outlining eight grades of aggregate based on gradation and associated average spread ratios. Each gradation was based on three sieve sizes. He also recommended that combined flat and elongated particle content not exceed 10% of any aggregate gradation requirement. Flat particles were defined as those with thickness less than half the average width of the particle, and elongated particles were defined as those with length greater than twice that of the other minimum dimension. Kearby suggested that when surface treatments are applied over existing hard-paved surfaces or tightly bonded hard base courses, the percentage of embedment should be increased for hard aggregates and reduced for soft aggregates. He also mentioned that

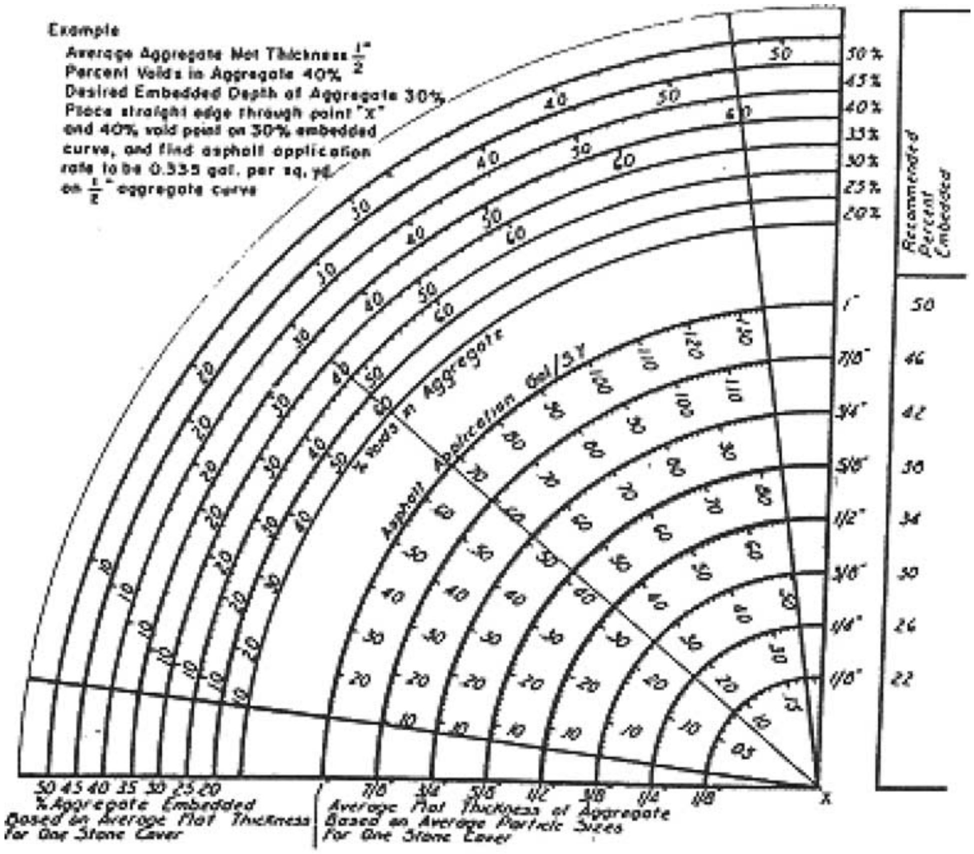

FIGURE C1 Nomograph to determine asphalt cement application rate in seal coats and one-course surface treatments (Kearby 1953).

some allowance should be made for highway traffic. It was suggested that for highways with high counts of heavy traffic, the percent embedment should be reduced, along with the use of larger-sized aggregates, and for those with low traffic, it should be increased with the use of medium-sized aggregates. However, Kearby did not recommend any numerical corrections.

Kearby also elaborated on the following construction aspects of surface treatments and seal coats based on his experience at the Texas Highway Department:

- Chip seals had been used satisfactorily on both high-volume traffic primary highways and low-volume traffic farm roads, with the degree of success largely depending on the structural strength of the pavement rather than on the surface treatment itself.
- Thickness of the surface treatment ranges from ¼ in. to 1 in., with the higher thickness being preferred. However, lighter treatments have, in general, proven satisfactory when the pavement has adequate structural capacity and drainage.
- In general, most specification requirements for aggregate gradation are very broad, resulting in considerable variations in particle shape and size as well as in percent voids in the aggregate.
- It is better to err on the side of a slight deficiency of asphalt to avoid a fat, slick surface.
- Considerable excess of aggregate is often more detrimental than is a slight shortage.
- Aggregate particles passing the No. 10 sieve act as filler, thereby raising the level of asphalt appreciably, and cannot be relied on as cover material for the riding surface.
- Suitable conditions for applying surface treatments are controlled by factors such as ambient, aggregate, and surface temperatures and general weather and surface conditions.
- Rolling with both steel-wheeled and pneumatic rollers is virtually essential.

During the same period, two researchers from the Texas Highway Department (Hank and Brown 1949) published a paper about their aggregate retention studies on seal coats. They conducted tests to determine the aggregate retention under a variety of conditions, including source of asphalt cement, penetration grade of asphalt, number of roller passes, binder type (asphalt cement versus cutback), aggregate gradation, and binder application temperature.

All of their tests were conducted under the same conditions, with only the test parameter being variable. Those

TABLE C1
EFFECT OF AGGREGATE GRADATION AND AGGREGATE TREATMENT ON RETENTION

Test Condition for Aggregate	Aggregate Loss as a Percentage of Original
12.6% passing No. 10 sieve	72.0
6.7% passing No. 10 sieve	57.4
0% passing No. 10 sieve	30.5
12.6% passing No. 10 sieve and rock preheated to 250°F	17.7
12.6% passing No. 10 sieve and rock precoated with MC-1	33.6

Source: Hank and Brown 1949.

authors concluded that aggregate retention was not significantly different from that of asphalt cements picked from five different sources commonly used by the Texas Highway Department at the time.

In the same study, the effect of aggregate gradation on the performance of chip seals was investigated. An OA-135 asphalt cement (close to an AC-5) applied at a rate of 0.32 gal/yd^2 was used under different aggregate treatments. The corresponding aggregate loss values are reproduced in Table C1. These results highlight the authors' contention that increased No. 10-sized aggregate content poses aggregate retention problems in seal coats. In addition, those researchers showed that a smaller portion of aggregate, less than ¼ in. in size, results in better performance of the seal coat.

MODIFIED KEARBY METHOD (TEXAS)

In 1974, Epps and associates proposed a further change to the design curve developed by Kearby for use in seal coats by using synthetic aggregates (Epps et al. 1974). On the basis of high porosity in synthetic aggregates, a curve showing approximately 30% more embedment than with the Benson–Gallaway curve was proposed. The rationale for this increase was that high-friction, lightweight aggregate may overturn and subsequently ravel under the action of traffic.

In a separate research effort, the Epps team (1980) continued the work done in Texas by Kearby (1953) and Benson and Gallaway (1953), by undertaking a research program to conduct a field validation of Kearby's design method. Data from before and after construction of 80 different projects were gathered and analyzed for this purpose (Holmgreen et al. 1985). It was observed that the Kearby design method predicts lower asphalt rates than what was used in Texas practice, and the study proposed two changes to the design procedures. The first one is a correction to the asphalt application rates based on level of traffic and existing pavement condition. The second is the justification of the shift of the original design curve proposed by the Kearby and Benson–Gallaway methods, as suggested for lightweight aggregates (Epps et al. 1974).

Eq. C1 was used to calculate the asphalt application rate (in gallons per square yard), which included two correction factors determined for traffic level and existing surface condition.

$$A = 5.61\frac{E}{d}\left\{1 - \frac{W}{62.5G}\right\}T + V \qquad \text{(C1)}$$

The modified Kearby method also recommends a laboratory "board test" method to find the quantity of aggregate needed to cover 1 yd^2 of roadway. The board test is performed by placing an adequate number of rocks on an area of 1 yd^2. The weight of aggregates that cover this area is determined and converted into a unit of pounds per square yard.

Epps and associates developed correction factors for the Kearby method, based on what seemed to be working well in practice (Epps et al. 1980). The binder application rate correction factors corresponded to traffic level and surface condition. Epps also suggested that consideration be given to varying the asphalt rate both longitudinally and transversely, as reflected by the pavement surface condition (Epps et al. 1980). Since that time, this design approach has been labeled as the modified Kearby method by both practitioners and researchers. Since the publication of that design procedure, the Texas Department of Transportation's Brownwood District has expanded on the asphalt application correction factors to include adjustments for truck traffic and existing surface condition.

Table C2 shows the design output that was used in a research study documenting chip seal performance on high-volume roads in Tulsa, Oklahoma, in 1989 (Shuler 1991). It reveals the differences in design binder and aggregate application rates when using the two different methods with the same design input parameters. One can see that there are considerable differences in the resultant rates calculated by each of the two methods. One must remember that both these methods are being used by agencies that then expect experienced field personnel to adjust the design rates to match the changing surface conditions found in the actual project. It must also be noted that the project carried an estimated 38,000 average daily traffic (Shuler 1991) and, therefore, these rates will probably appear higher than expected. However, most experienced chip seal personnel are used to seeing rates for low- to moderate-volume roads.

ROAD NOTE 39

The United Kingdom's Transport Research Laboratory has published several editions of a comprehensive design procedure for "surface dressing" roads in the United Kingdom (*Design Guide* . . . 1996). The technology that makes this design procedure so advanced is the extensive use of a computer design program based on decision trees (Colwill et al. 1995). Known as Road Note 39, this design procedure is

TABLE C2
COMPARATIVE DESIGN OUTPUT FOR THE MODIFIED KEARBY AND McLEOD CHIP SEAL DESIGN METHODS

Design Method Nominal Aggregate Size		Existing Surface Condition					
		Slight Bleeding		Normal		Slight Raveling	
		Modified Kearby	McLeod	Modified Kearby	McLeod	Modified Kearby	McLeod
3/8 in. Natural Aggregate	Emulsion Rate (gal/yd^2)	0.25	0.18	0.29	0.22	0.33	0.27
	Aggregate Rate (lb/yd^2)	21.2	17.1	21.2	17.1	21.2	17.1
5/8 in. Natural Aggregate	Emulsion Rate (gal/yd^2)	0.29	0.30	0.33	0.34	0.37	0.39
	Aggregate Rate (lb/yd^2)	24.6	25.6	24.6	25.6	24.6	25.6
3/8 in. Synthetic Aggregate	Emulsion Rate (gal/yd^2)	0.54	0.27	0.58	0.32	0.62	0.36
	Aggregate Rate (lb/yd^2)	17.1	14.0	17.1	14.0	17.1	14.0
5/8 in. Synthetic Aggregate	Emulsion Rate (gal/yd^2)	0.51	0.30	0.55	0.35	0.59	0.39
	Aggregate Rate (lb/yd^2)	14.3	18.3	14.3	18.3	14.3	18.3

Source: Shuler 1991.

highly advanced and uses a multitude of input parameters. Traffic level, road hardness, surface conditions, and site geometry are critical input factors. Skid-resistance requirements and likely weather conditions are secondary inputs into the program (*Design Guide* . . . 1996). This procedure includes the following five steps:

1. Selection of the type of dressing—The selection of surface dressing (surface treatment) is made from five treatments: single dressing, pad coat plus single dressing, racked-in dressing, double dressing, and sandwich dressing.
2. Selection of binder—Binders are selected from either emulsion or cutback asphalt, specified based on viscosity. Modified binders such as polymer-modified binders are also recommended if their need and additional cost can be justified. The grade of binder is selected based on the road traffic category and construction season.
3. Selection of aggregate—The nominal size of aggregate is selected based on traffic and hardness of existing surface. Specified are 20-, 14-, 10-, 6-, and 3-mm nominal-size aggregates. However, the 20-mm size is not commonly used, owing to the risk of windshield damage.
4. Binder spread rate—The required rate of binder spread depends on the size and shape of aggregates, nature of existing road surface, and degree of embedment of aggregate by traffic. The rate of binder spread should not vary by more than 10% from the target figure.
5. Rate of aggregate spread—The aggregate spread rate is determined based on a "tray test" and depends on the size, shape, and relative density of the aggregate.

The basic inputs into the decision trees include selection of the type of treatment and selection of grade and type of binder based on traffic and construction season. Table C3 is taken from the Road Note 34 design manual and lists the design inputs used in the chip seal design software.

The aggregate type and size are selected based on skid and friction requirements, likely weather conditions, and hardness of existing surface. The resulting design application rate of binder is determined by the size and shape of aggregates, nature of existing road surface, and degree of embedment of aggregate by traffic. The resulting design application rate of aggregate spread rate depends on the size, shape, and relative density of the aggregate (*Design Guide* . . . 1996).

AUSTROADS SPRAYED SEAL DESIGN METHOD

The 2004 Austroads' *Sprayed Seal Design Manual* provide a performance-based design method that uses an extensive list of input parameters for determining aggregate and binder application rates. Aggregate angularity, traffic volume, road geometry, ALD of aggregate, aggregate absorption, pavement absorption, and texture depth are the input variables for this

TABLE C3
ROAD NOTE 34 OPERATIONS IN DESIGNING SURFACE DRESSING

Operation	Task	Section*	Selection	Section*
Concept	Decide to surface dress	2.1		
Site	Type selection and Stage 1 binder-spread category parameters	6.2	Latitude	6.2.1
			Altitude	6.2.2
			Road hardness	6.2.3
			Traffic category	6.2.4
			Traffic speed	6.2.5
			General surface condition	6.2.6
			Highway layout	6.2.7
	Material selection	6.3	Skid-resistance requirements	6.3.1
			Season and weather conditions	6.3.2
Site	Consider existing condition of site	7.1		
	Divide up site	7.1		
	Select type of surface dressing	7.3	Single surface dressing	2.2.1
			Racked-in surface dressing	2.2.2
			Double surface dressing	2.2.3
			Inverted double surface dressing	2.2.4
			Sandwich surface dressing	2.2.5
			High-friction surface dressing	2.2.6
	Rationalize types of surface dressing	7.4		
Material Selection	Select type of chippings	8.1	Uncoated chippings	8.1.2
			Lightly coated chippings	8.1.3
			Artificial aggregate chippings	8.1.7
	Select size of chippings	8.2	6 mm, 10 mm, 14 mm, or combinations	
	Select type of binder	9.1	Unmodified bitumen emulsion, cutback bitumen	9.1.1
			Modified binder	9.1.2
			Resin binders	9.1.4
Rate of Spread of Binder	Unmodified bituminous binders			
	Stage 1 binder-spread category	9.2.2		
	Stage 2 binder-spread category (from aggregate properties)	9.2.4	Chipping shape	6.4.1
			Type of chipping	6.4.2
	Stage 3 adjustment factors (from site conditions)	9.2.5	Surface condition	6.5.1
			Gradient	6.5.2
			Shade	6.5.3
			Local traffic	6.5.4
	Target rate of spread of binder	9.2.5		
	Modified bituminous binders	9.2.2		
	Resin binders	9.3		

*Refers to paragraph in design manual that governs the specific aspect of chip seal design in that row of the table.
Source: Design Guide for Road Surface Dressings 1996.

method. The main assumption of this design model is that the aggregate in a seal is orientated approximately one layer thick and contains a percentage of air voids. Thus, filling a percentage of the voids with binder determines the binder application rate. The minimum binder application rate is determined by the percentage of voids to be filled, the total available voids, and the thickness of the seal.

The first step in the Austroads procedure is to determine a basic voids factor. Adjustments for aggregate characteristics and anticipated traffic levels are added to derive a design voids factor. That factor is then multiplied by the ALD of the aggregate to determine the basic binder application rate. This base binder application rate is then modified with allowances to cater to the texture and absorption of the pavement surface and the aggregate. Some aggregates are susceptible to absorbing binder, resulting in the decrease of effective binder and a possible loss of aggregate from the seal under traffic. Adding allowances to the basic binder application rate compensates for this characteristic. The amount of binder required depends on the size, shape and orientation of the aggregate particles, embedment of aggregate into the base, texture of surface onto which the seal is being applied, and absorption of binder into either the pavement or aggregate. The geometry of the road can affect the design of a seal, and it is necessary to make adjustments to the binder application rate. Geometric factors include narrow lanes, climbing lanes, and turning locations. Where traffic is channeled into confined wheelpaths, such as on single-lane bridges, tight radius curves, or pavements with confined lane widths, a traffic adjustment factor is necessary. The design binder application rate is calculated by adding all the allowances to the basic binder application rate. It should be noted that some of the allowances may be negative, and thus the design binder application rate may be lower than the base binder application rate.

For multiple course chip seals, the Austroads design methodology distinguishes between whether the additional courses are applied immediately or later. When it is planned that all courses of the chip seal will be placed on the same day, the design is essentially the same as for a single-course treatment, with a reduction in the design voids factor. Adjustments are made for designing as a reseal, but adjustments for surface texture and embedment are not performed. When it is planned to stage a delay in the application of the courses, the binder application rates for the additional courses are generally set at a minimum, and aggregate application rates are commonly reduced to 70% of conventional design. Figure C2 illustrates the Austroads Design Procedure for Single/Single (single course) Sprayed Seals.

SOUTH AFRICAN METHOD, TRH3

South Africa has an extensive and well-developed chip seal program on routes with up to 50,000 equivalent vehicle units (Beatty et al. 2002). The South African design process for chip seals is based on a number of input parameters. Traffic volume, preferred texture depth, and surface hardness are the primary inputs in the design process. Practical adjustments for

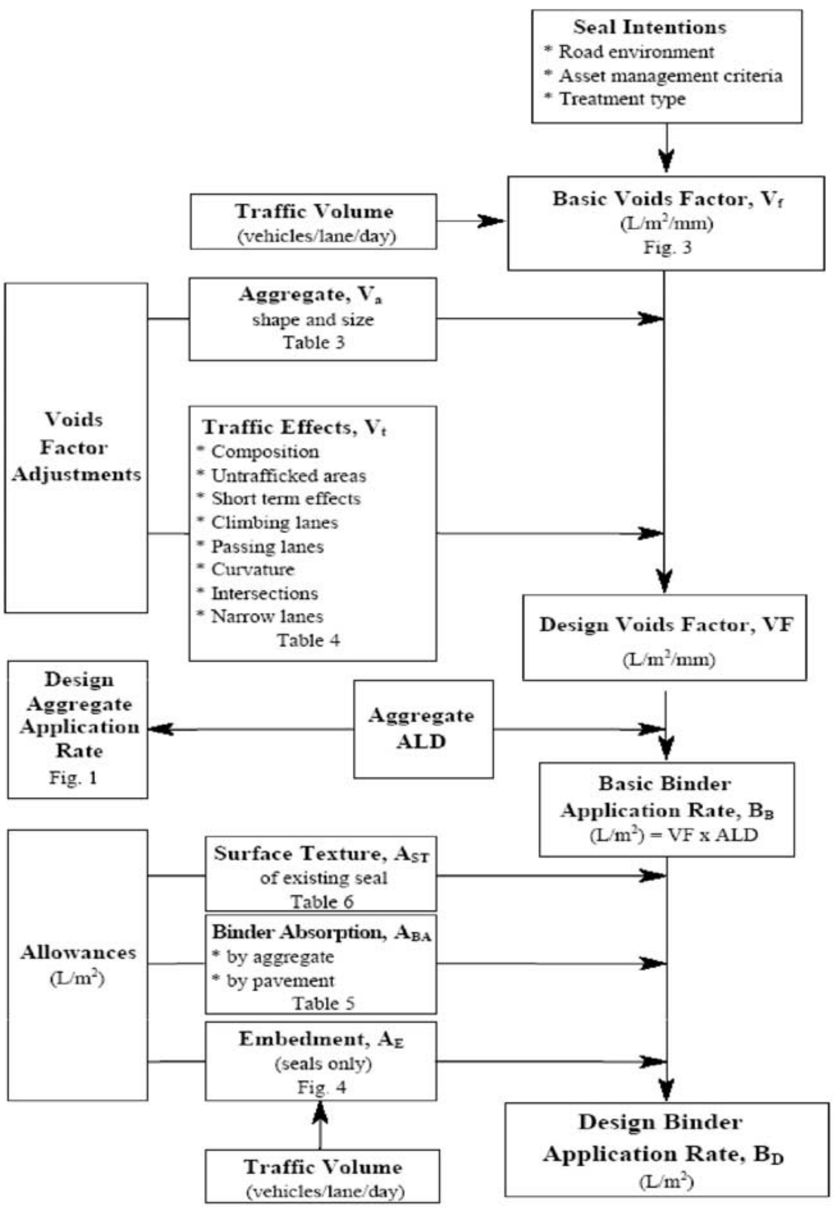

FIGURE C2 Austroads sprayed seal design procedure, 2000.

climate, gradients, existing coarse texture, hot applications, preferred aggregate matrix, and use of polymer-modified binders are common. The approach taken by the South African design method, TRH3, is a hybrid of the United Kingdom and Australian design methodologies. The selection of surfacing is made between single seal with modified binders, double seals, Cape seals, and sand seals. The decision is primarily based on the traffic level and pavement condition. Of particular interest is that this method measures and evaluates surface hardness by using a ball penetration test, corrected for temperature. The grade of binder is selected based on traffic level, road surface temperature, climatic region, and aggregate condition. The required rate of binder spread is determined by using charts that incorporate aggregate spread rate, traffic level, and ALD.

The aggregate spread rate is extrapolated from design charts based on the ALD of the aggregate and the required texture depth. The South Africans have eliminated single seal design without modified binder, because they do not construct any single-coarse seals without the use of a modified binder. Another important assumption of this design method is including correction factors to adjust binder application rates when using modified binders. Polymer-modified binder application rates are adjusted, because the South Africans have found that aggregate orientation is different in comparison with conventional seals. The design charts shown in Figure C3 are examples of typical TRH3 charts, and Figure C4 is a sample design spreadsheet illustrating the application of the TRH3 chip seal design method.

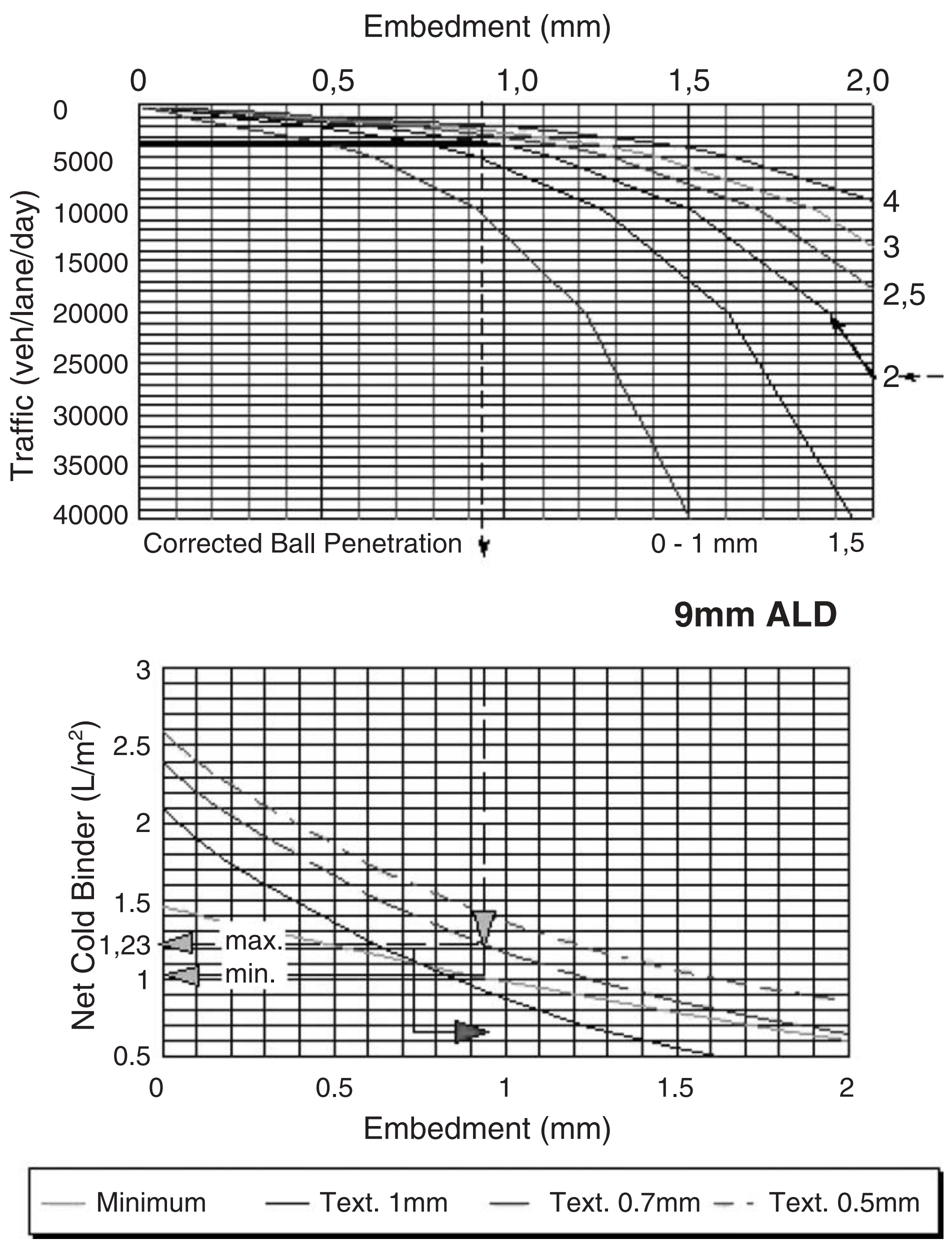

FIGURE C3 Example of South African chip seal design charts.

SOUTH AFRICA COLTO Committee of Land Transport Officials	Prepared by/date: Checked by/date: Approved by/date:	**Basic** **19,0/6,7 mm** **double seal design**

Road / Pad (Street / Straat) :	N1		
Carriageway / Padbaan :	Northbound and Southbound		
Lane / Laan :	Slow lane		
From / Van : Ch. 28 500	to / na : Ch. 62 800		
Seal Type / Seëltipe : 19,0/6,7mm double seal	Design method / Ontwerpmetode TRH 3 1998		
Binder Type / Bindmiddel Tipe :	Class S-E1 modified binder (SBR type of modifier) + 30% anionic emulsion diluted 50:50		
General / Algemeen			
Traffic Counts / Verkeerstellings	**slow lane**	**fast lane**	**Total / Totaal**
Heavy Vehicles per day / Swaarvoertuie per dag	680	170	850
Light Vehicles per day / Ligtevoertuie per dag (LV)	2 720	680	3 400
Equivalent LV per day / Ekwivalente LV per dag	29 920	7 480	37 400
Climatic Zone / Klimaatstreek	2/3 boundary		
Ave Ball Penetration / Gem. Balpenetrasie (corrected) (mm)	2,57		
Texture Depth / Tekstuur Diepte (Existing) (mm)	0,40		
Aggregate / Aggregaat			
Particulars of Aggregate / Besonderhede van Aggregaat	Dark grey dolorite		
Source / Bron	Petra quarry, Bloemfontein		
Type / Tipe	dolorite, precoated @ 14 l/m^3 with sacrasote 70 or similar approved		
Nominal Size / Nominale Grootte	19,0mm	6,7mm	
ALD / GKA (Meas. / Gemeet) (mm)	12,2mm	4,5mm	
Flakiness / Platheid (%)	24.0	7,1	
AIV / AIW (Dry/Droog // Wet/Nat)* (%)			
ACV/AVW (Dry/Droog // Wet/Nat) * (%)	11,7% dry : 16,8% wet	11,7% dry : 16,8% wet	

FIGURE C4 South African TRH3 chip seal design method sample. *(Continued on next page.)*

Data			
Method used:	TRH3 (Incorporating latest amendments)	Ball penetration:	1,53mm
Road description:	N1 Section 15: Sydenham to Glen Lyon	Corrected ball penetration:	T_0 = 1,53 - 0,04(17-43)
	(km 28,5 to 62,8) - Bloemfontein W. Bypass		= 2,57mm (TMH6)
Binder:	Class S-E1 (SBR modified)	Sand patch length:	1,96m
Aggregate (Bottom):	Precoated 19,0mm Grade 1 aggregate with	Existing texture depth	T = 250/(1000x0,3x1,96)
	ALD = 12,2mm and Flakiness Index = 24%		= 0,40mm
(Top):	Precoated 6,7mm Grade 1 aggregate with		
	ALD = 4,5mm and Flakiness Index = 8,6%		
Traffic conditions:	4 250 vehicles per day (of which 20% are heavy vehicles)		
	i.e. 3 400 light vehicles + 850 heavy vehicles		
	Assume slow lane 80% traffic, including 80% of heavy vehicles.		
	On slow lane: (0,8 x 3 400) + (40 x 680) = 29 920 elv/lane/day **(Design for slow lane)**		
Design			
Design texture depth:	0,7mm (Desired final texture depth)		
ALD of aggregate:	ALD of bottom layer + 50% of ALD of top layer		
	= 12,2mm + 2,25mm = 14,45mm	Adjustment for modified binder:	2,03 x 0,035 = 0,07 l/m² (Fig.9,TRH3)
Embedment (from charts):	2,32mm	Adjustment for existing texture:	0,14 litre/m² (Fig.7,TRH3)
Modified embedment:	0,5 x 2,32 = 1,16mm	Adjustment for climate:	2,03 x 0,01 = 0,02 l/m² (Fig.2, TRH3)
Nett cold binder (from charts):	2,03 l/m² *	Adjustment for new asphalt:	- 0,10 l/m² (discresionary)
		Adjustment for grade:	Nil
Nett cold binder (after adjustments):	2,03 + 0,07 + 0,10 + 0,02 - 0.10 = 2,12 l/m²		

Control check (Alternative design Methods)	
PAWC:	0,172 x 13,55 = 2,33 l/m²
F.S. Concept seal 1976 :	2,24 l/m²
Spray rates	
Adjustment for hot application:	1,08 x 2,12 = 2,30 l/m²
Tack coat (hot applied):	**1,15 l/m²**
Penetration/Tack coat (hot applied):	**1,00 l/m²**
Fog spray (60% anionic, diluted 50:50)	**1,00 l/m²** *(Effective = 1.0*0.3*50% = 0.15l/m2)*
Aggregate spread rate:	
19,0mm aggregate:	**70 m²/m³** (Fig.F-1, TRH3)
6,7mm aggregate (Applied in two layers):	110 m²/m³
Layer 1 :	**450 m²/m³ as choke layer**
Layer 2 :	**+ 155 m²/m³ as top layer on double seal and as single seal on sides**
	(Fig.F-1, TRH3)

FIGURE C4 *(Continued).*

APPENDIX D

Innovative Chip Seal Case Studies

On the basis of the survey responses, case studies were identified to detail findings that have the potential to disseminate chip seal best practice in a timely manner. Each of the case studies was drawn from a form sent to those survey respondents indicating that they had a chip seal best practice they wanted to share. The forms were then reviewed, and telephone interviews were arranged to clarify any details that were not self-evident. In this manner, two case studies were selected as representative of best practices that spoke to issues identified by the survey responses.

1. New Zealand Contractor, Fulton Hogan—Variable Transverse Application Design
2. San Diego County, California—Geotextile-Reinforced Chip Seals

The first case discusses one agency's method for dealing with the variation in road surface in the transverse direction. This is the issue that North American agencies try to overcome by using variable nozzles and adjusting binder rates in the field. The second case details the success in using geotextiles to combat reflective cracking through the seal and to eliminate the need to crack seal before chip sealing, which eliminates one source of flushing.

CASE STUDY—VARIABLE TRANSVERSE APPLICATION DESIGN

Agency: Fulton Hogan Limited, Christchurch, New Zealand
Name of Project or Practice: Variable Transverse Application Design

What Is the Best Practice?

Currently, Fulton Hogan is testing its design methods to calculate binder application rates for wheelpaths, between wheelpaths, shoulders, and centerline.

Discussion

The trials have shown that application rates calculated by using the traditional method can be adjusted downward by up to 30% in the wheelpaths and still produce a quality chip seal. The application rate can be adjusted upward by more than 30% on the shoulders and centerline. The traditionally calculated application rate appears to be appropriate for the area between the wheelpaths.

The results from the trials have given Fulton Hogan's chip seal designers the confidence to reduce their traditionally calculated application rates by 10% to 20% in the wheelpaths and higher where excess binder is evident in the wheelpaths for all reseals for which Fulton Hogan has the responsibility for the performance of the seal (Note: performance is measured by texture depth after 12 months). This practice is generally happening in the six regions where Fulton Hogan possesses Multispray variable transverse capable distributors.

Project Specific Data

The Tai Tapu trial in 2000 had the following results:

- First trial—included three short trial lengths within a 700-m reseal;
- Site—a straight section of two-lane state highway;
- Average annual daily traffic—2000;
- Design adjusted for 5% heavy trucks;
- Target application rate—1.90 L/m^2 of binder;
- Lowest application rate in wheelpath—1.47 L/m^2;
- Highest application rate on shoulder—2.46 L/m^2;
- Highest application rate between wheelpaths and centerline application rate—2.1 L/m^2;
- Chip used—Grade 3 single-sized 16-mm to 13-mm chip, with an average least dimension of 8.61 mm; and
- Average sand circle before sealing—177 mm.

Performance of Practice

The traditional design method calculates an average application rate for the whole road surface, which is not applicable to any particular area. The result of using this application rate is that the shoulders and centerline suffer chip loss and the wheelpaths receive an excess of binder that in the long term results in flushing. The use of variable transverse distribution to lower the application rates in the wheelpaths prevents the loss of texture in the wheelpaths, extending the life of the seal and the pavement surfacing. Conservative estimates based on results so far estimate a 25% to 30% increase in life cycle.

Plans for This Best Practice

Fulton Hogan will continue to construct trial sections for full monitoring. The monitoring includes texture and skid monitoring of the trials and the traditional treatment adjacent to the trial sections. Fulton Hogan plans to continue reducing the application rates in the wheelpaths as a matter of course where the organization's contractual relationships make them responsible for the long-term performance of the seal.

CASE STUDY—GEOTEXTILE-REINFORCED CHIP SEALS

Agency: San Diego County, California
Name of Project or Practice: Geotextile-Reinforced Chip Seals

What Is the Best Practice?

The county of San Diego's Department of Public Works has found chip sealing over pavement-reinforcing fabric (fabric) as a cost-effective method of preventive maintenance for roads in the desert area of the county. This method is done to eliminate the need to crack seal the thermal cracked bituminous surface, prevent premature aging of the roadway, and extend the life of the roadway. This practice has eliminated the need for crack sealing. Figure D1 shows the existing road's surface before installation of the geotextile and the chip seal.

The construction operation consists of three separate operations—placing fabric, chip seal, and fog seal—on high-speed and low-speed roads. The method of how and when the products are placed is determined by the traveling speed of the motoring public, not the volume of traffic.

Project Specific Data

The Borrego Springs Trial in 1987 had the following results:

- Maintenance contracts—1996, 1999, 2000, and 2001;
- Type—Conventional chip seal over pavement reinforcing fabric;
- Traffic data—1,300 or less annual daily traffic (Note: traffic speeds are typically 55 mph);
- Number of lanes—2;
- Binder used—PMCRS2h; and
- Aggregate used—Medium and medium-fine.

Construction Method 1 (High-Speed Roads)

Method 1 is used for roads that have high-speed traffic and require pilot car-assisted traffic control to reduce the speed of the traveling public to 25 mph (40 km/h) during construction operations.

- Phase 1—Apply paving asphalt, fabric, and sand cover, followed by rolling to seat the fabric into the paving asphalt. Remove excess sand. Apply polymer-modified asphalt emulsion and crushed aggregate (chips) and follow with rolling to seat the chips into the emulsion. Remove excess chips.
- Phase 2—Apply fog seal. Phase 2 is performed 7 to 14 days after Phase 1.

Construction Method 2 (Low-Speed Roads)

Method 2 is used for roads that have low-speed traffic. Posted speed limits are already 25 mph (40 km/h); therefore, pilot car-assisted traffic control is not required.

- Phase 1—Apply paving asphalt, fabric, and sand cover, followed by rolling to seat the fabric into the paving asphalt.
- Phase 2—Remove excess sand. Apply polymer-modified asphalt emulsion and crushed aggregate (chips) and follow with rolling to seat the chips into the emulsion. Phase 2 is performed 5 to 10 days after Phase 1.
- Phase 3—Remove excess chips. Apply fog seal. Phase 3 is performed 7 to 14 days after Phase 2.

The preferred method of placement is Method 2. This allows the paving fabric binder to harden overnight and to allow traffic to provide additional seating of the fabric for several days before the chip seal is placed. Both methods are placed successfully in Borrego Springs; each method has benefits depending on the roadway's environment (traffic speed).

Performance of Practice

This practice has eliminated the need for crack sealing in the desert area of the county. The test section set in 1987 is still in place and performing to date. A life-cycle cost analysis was performed on the trial section. Considering the width of the surface cracks on roadway surfaces in Borrego Springs, San Diego County found chip sealing over fabric to be more cost-effective than chip sealing with ground rubber/paving asphalt binder, or chip sealing without fabric.

Plans for This Best Practice

San Diego County plans to routinely use this practice in the desert community where thermal surface cracks on the asphalt concrete pavement are present. Fabric placement is not recommended for roads with steep grades, winding curves, or at intersections with controlled stops. The county anticipates not placing fabric on intersection radii, tight curves, steep grades, or the last 100 ft approaching a controlled stop intersection. The county will continue to place chip seals at these locations.

FIGURE D1 Geotextile installation on cracked road surface.

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation