MAINTENANCE TECHNICAL ADVISORY GUIDE (TAG)

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PREFACE

Highway agencies throughout the world face increasing demands and decreasing resources to maintain and preserve their highway networks. The demand to "do more with less" has been an operating slogan for many of these agencies. Historically, the emphasis has been on new facility construction, and rehabilitation or reconstruction of existing facilities. However, most agencies are currently in a maintenance and/or preservation mode, a trend that can be expected to continue in the foreseeable future.

Pavement preservation is a method by which roads are treated before significant failure has occurred. This has the advantage of allowing action before user complaints, and also saving the agency money over the life of the pavement.

This publication was prepared by HQ Maintenance to assist in making better and more informed decisions on maintenance practices. It is designed for several levels of use, ranging from general instruction to specific work practice descriptions. It should be of use to District Maintenance Managers, Maintenance Supervisors, Superintendents, and Field Personnel. Construction personnel and designers may also find use for the information.

This publication consists of several parts. The first chapter is a review of pavement preservation and maintenance principles, as well as a detailed technical discussion on the materials used in maintenance treatments. This is followed by a chapter describing a simplified treatment selection process. The remaining chapters 3-8 describe the various maintenance treatments currently in use by Caltrans and provide information on how to design and construct them. Chapters 3-8 can be used as stand alone documents for the respective treatments. Other chapters on new treatments may be added at a later time.

It is not the intent of this advisory guide to be exhaustive; however, it should serve as a useful reference Each treatment chapter has field information on troubleshooting problems, and a list of important issues is appended to each chapter to provide the reader guidance on what to consider in achieving a successful outcome. Diagrams and photographs are provided as illustration. Photographs not otherwise acknowledged are provided, by permission for this document, by Glynn Holleran. A training program will supplement this advisory. This will assist in understanding and optimizing its benefit.

ACKNOWLEGMENTS

This document was prepared under the technical direction of Dr. Shakir Shatnawi, Chief of the Office of Pavement Preservation. The document was reviewed by Caltrans Pavements Standards Team, the Caltrans Industry Maintenance Task Force, and by Caltrans Maintenance Personnel. For questions on the guide, please contact:

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Disclaimer

This chapter is 1 of 8 included in the Caltrans Maintenance Technical Advisory Guide (TAG). The information presented in this chapter is for educational purposes only. It does not represent a policy or specification nor does it endorse any of the products and/or processes discussed.

CHAPTER 1 INTRODUCTION

This chapter presents an overview of pavement preservation and how Preventive Maintenance treatments can be used to preserve the condition of a highway system. It presents a discussion of various pavement distresses and identifies the potential causes for the observed distress types. Also discussed are the various treatment types used in Preventive Maintenance including the selection of the most appropriate treatment. These topics are discussed in greater detail in the subsequent Chapters 2 through 8.

The required characteristics of the various materials are defined in the Caltrans specifications and these describe the measurable properties that lead to the desired field performance. These include characteristics not only of the materials at the time of application, but also to achieve good in service field performance. Caltrans has a range of published specifications and these include "Standard Specifications" and "Standard Special Provisions" (SSP). They may be found on the Caltrans Web page http://www.dot.ca.gov/hq/esc/oe/specs_html/index.html.

This chapter covers the basics of pavement preservation and important aspects of the materials requirements for the maintenance treatments described in subsequent chapters. This chapter also includes some aspects of the mechanisms by which these materials perform their function and how they should be stored, handled, and combined to achieve the desired outcomes and meet the required specifications.

1.0 WHAT IS PAVEMENT PRESERVATION?

The development of pavement preservation is a relatively new practice in the US, but is beginning to pay dividends in many states. In many places, pavement preservation is termed “Preventive Maintenance”. This implies an intervention in pavements, that is a treatment carried out, before distress has reached a level where the pavement’s structural integrity has been compromised. “Corrective Maintenance” is a term used to describe actions required to restore pavement to a level where Preventive Maintenance or pavement preservation can be used to keep the pavement in a serviceable condition into the future. Definitions for the various terms used in this document are provided in Appendix A.

The principal requirements for Preventive Maintenance are:

- Is it part of an overall program of Caltrans pavement management system (PMS)?
- Has it been scheduled in the maintenance plan as determined by the PMS?
- Is it timely? Is it cost effective?
- Is it technically sound?
- Have expectations for the maintenance treatment been considered?

Figure 1 shows the relationship between pavement life (or in terms of traffic volume) and the type of treatment required to prolong the life of the pavement.

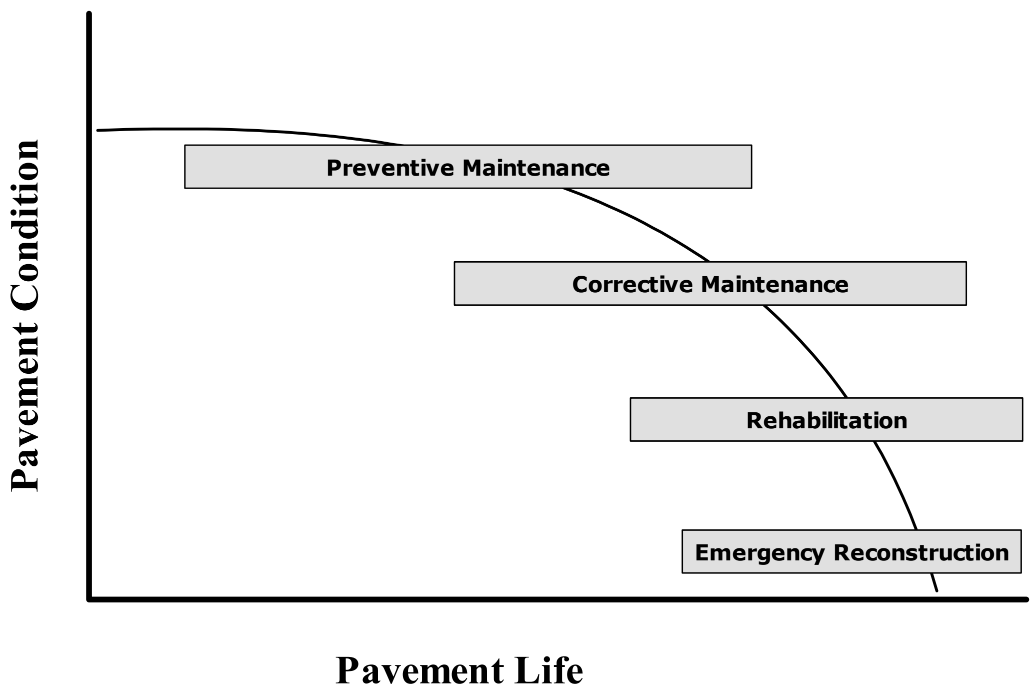


Figure 1: Pavement Condition vs. Life and Type of Work Required (1)

The timely application of preservation treatments is important as they can save money over the life of a pavement. Reconstruction or extensive dig-out and replacement treatments are far more costly than typical Preventive Maintenance treatments. Figure 2 shows the relative costs of Preventive Maintenance treatments versus major rehabilitation treatments or reconstruction. When properly timed, Preventive Maintenance can produce savings over the life of the pavement (1, 2). In addition, subsequent maintenance treatments can be applied in a relatively quick manner resulting in fewer disruptions to the traveling public and less exposure to traffic for maintenance employees as compared with major rehabilitation or reconstruction activities.

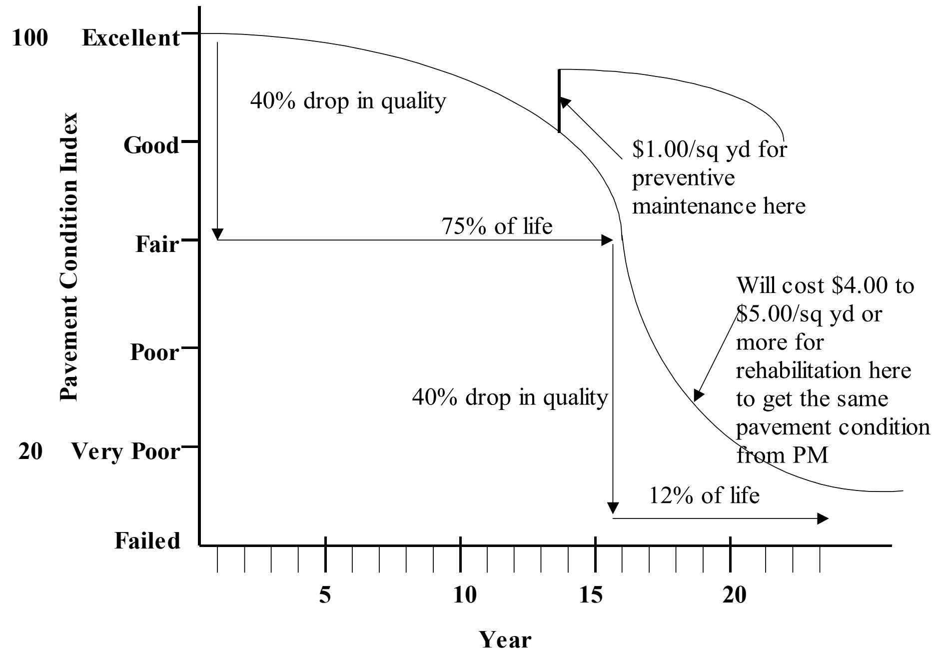


Figure 2: The Cost of <u>NOT</u> Carrying Out Maintenance in a Timely Way (2)

2.0 PAVEMENT STRUCTURE AND DESIGN

2.1 WHAT IS A PAVEMENT?

A pavement is a layer or layers of compacted material that is designed to withstand the stresses applied by vehicle or other traffic types and provide a smooth riding surface. Pavements are engineered structures by which stresses, applied from moving wheel loads, are transferred to the native soil (subgrade). Figures 3 and 4 illustrate conceptually the ways in which stress is applied to the roadway and how a pavement can reduce the stress applied to the subgrade. Cracking, deformation and disintegration are the main distress modes of pavements.

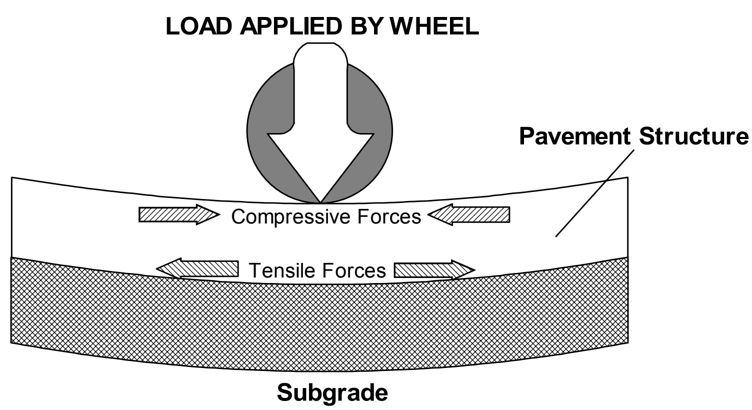


Figure 3: Stress in a Pavement from Wheel Loads (3)

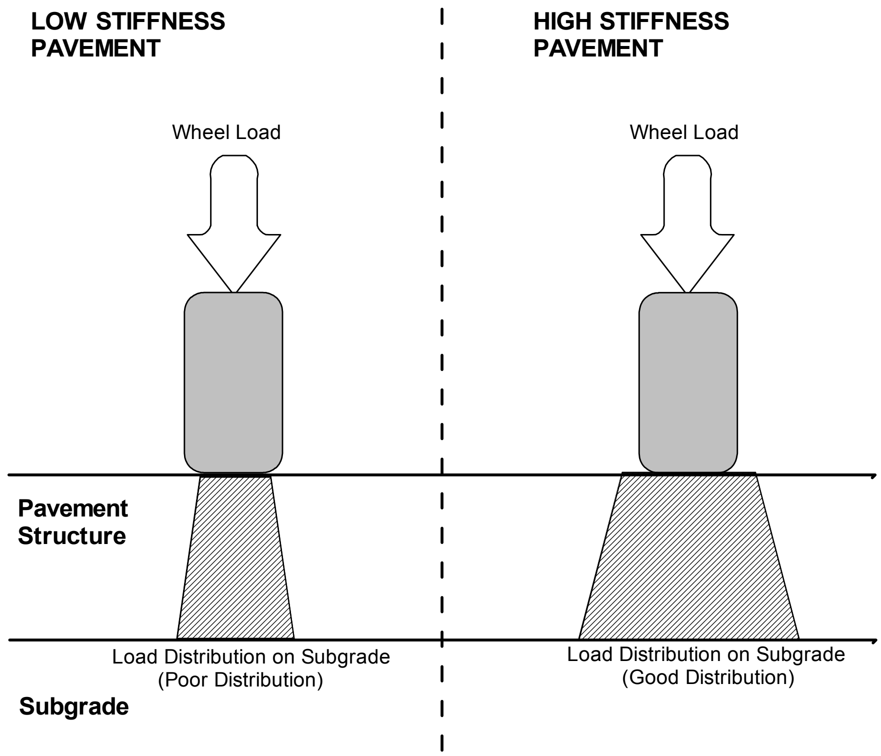


Figure 4: Load Spreading Effect on Subgrade (3)

2.2 FLEXIBLE AND RIGID PAVEMENTS

The pavement can be considered as the entire road structure. In this chapter, we are concerned primarily with the surface of the pavement, but the structural aspects of the remaining parts contribute greatly to the performance of any surfacing and must be understood.

The two main types of pavement in use in California are flexible and rigid pavements. The difference between the two is the manner in which they distribute the applied load to the subgrade. A rigid pavement (concrete), due to its high rigidity and high stiffness (modulus of elasticity) tends to distribute the loads over a wide area of subgrade; therefore, the slab itself carries the majority of the load. This is considered the major contributing factor to the performance of concrete pavements. This characteristic allows for minor variations in the subgrade strength, which have little effect on the structural capacity of the pavement. However, severe cracking problems can arise if the subgrade cannot support the slab.

Flexible pavements, on the other hand, consist of layers of granular materials and/or asphalt bound materials (such as hot mix asphalt or surfacing) with lower rigidity and stiffness as compared to rigid pavements. Such pavements generate their load bearing capacity based largely on the load distribution characteristics of the individual layers. The strength of a flexible pavement is built up using thick layers. These materials (layers) distribute the applied loads over the subgrade. As a result, the design thickness of the pavement is influenced by this load distribution mechanism and the strength of the subgrade. For these reasons, the material properties comprising each layer, their thickness, the subgrade strength, and the loading level are critical design parameters.

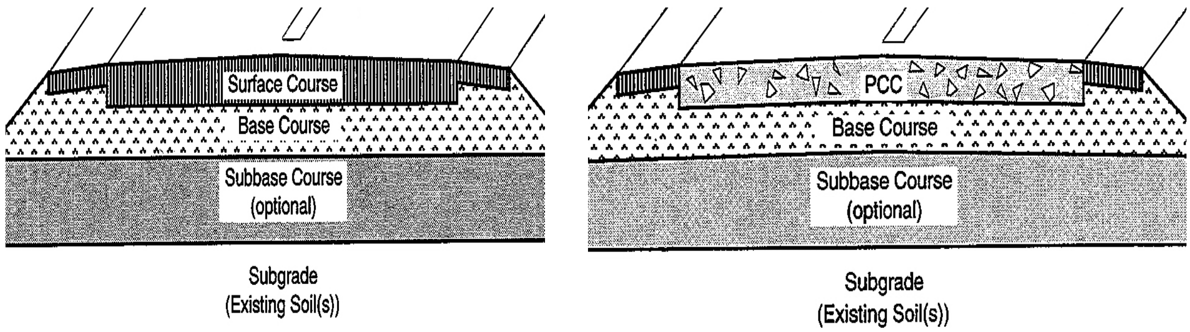
Pavement design is based on the structural analysis of multi-layered pavements subjected to traffic loading. A key to predicting performance is accurately modeling the stress and strain responses of the pavement and accounting for sub grade and environmental conditions affecting material properties.

2.3 PAVEMENT STRUCTURE

A pavement's structure can be broken down into three main components. Each component plays an important role in the overall performance of a pavement. These components are:

- Foundation
- Base
- Surfacing

Figure 5 shows typical pavement cross sections for both types of pavements.



a) Typical Flexible Pavement **b) Typical Rigid Pavement**

Figure 5: Typical Pavement Cross Sections (4)

2.3.1 Foundation

The foundation is comprised of the sub-grade and, in some cases, the sub-base. The foundation carries the loads created by construction traffic. Structurally, it is the final layer to which stress is transferred. As it is generally the weakest layer, stresses must be spread over as wide an area as possible. The foundation is characterized by its compressive strength or bearing capacity (e.g. in California using the "R" value).

2.3.2 Base Layer

The base layer is a main structural element of the design and can consist of several layers. It is required to spread the wheel load so that the foundation is not over-stressed. Its stiffness and its fatigue resistance (if stabilized) characterize its behavior in the pavement structure.

The base layer can consist of compacted high-grade aggregate, lean concrete, portland cement concrete or dense graded asphalt. In some areas, where drainage is poor or traffic is very heavy, a large stone mix with high voids can be used in the bottom part of this course. In situations where the subgrade is very weak, a binder rich layer may be used at the bottom of this course.

2.3.3 Surfacing Layer

The surfacing layer is provided to ensure adequate skid resistance and act as a protective layer for the underlying materials. It may or may not be structurally significant. Surfacings range from surface seals to thin hot mix overlays. If the surfacing is greater than 40mm (1.5 in) thick it will contribute to the structural integrity of the pavement, and must be considered in the design. The surface layer is where most rutting occurs. With this in mind, the design of this layer is very important.

Surface layers are characterized by their stiffness, creep resistance, moisture resistance, resistance to low temperature cracking, fatigue resistance and skid resistance. Figure 6 illustrates the main elements of the pavement structure with respect to the surfacing layer.

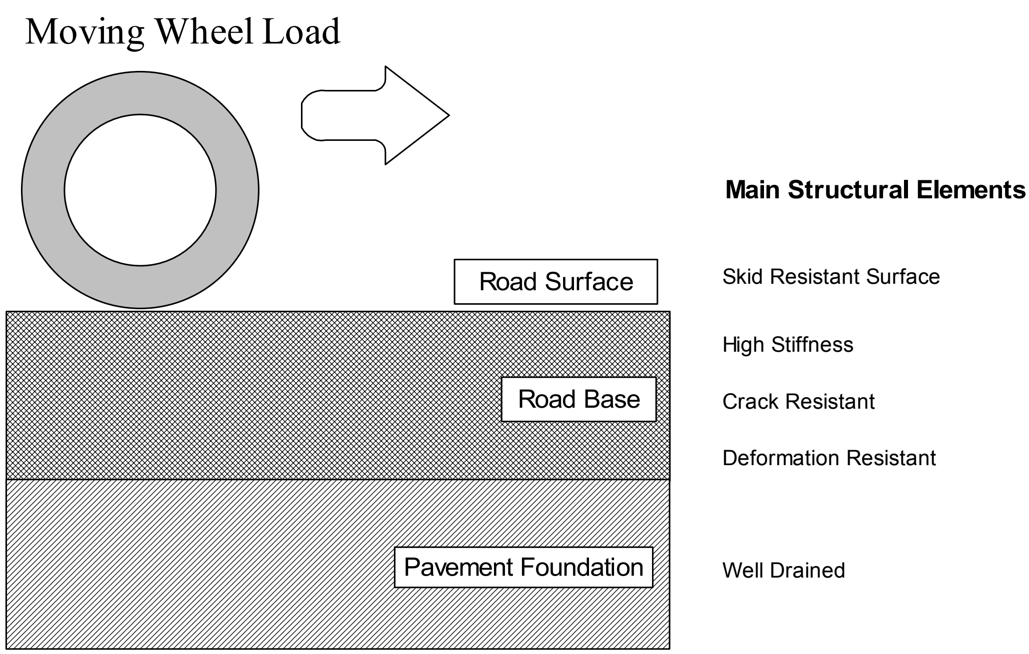


Figure 6: Elements of a Pavement Structure (3)

The integrity of the pavement structure is key to whether a road requires reconstruction, resurfacing or a maintenance treatment. The failure mode observed can be a structural failure or a surface failure. Structural failures can result from poor design, excess traffic volumes or weights, poor drainage, poor materials and/or poor construction practices. Structural failures may also be associated with poor bonding between the surface layer and the pavement which lead to slippage cracking.

Surface failures may look similar to those caused by structural failures but their causes are different. Surface failures result from aging, surface abrasion, poor design (inappropriate asphalt content), poor materials (weak aggregates), poor construction practices or inappropriate use of a treatment. It is important to identify the cause of a failure to allow the simplest and cost effective maintenance treatment to be used to solve the problem. It is very important to thoroughly evaluate and properly diagnose the cause of a failure; this will suggest the appropriate treatment. It is also important not to worsen a problem by applying an incorrect maintenance treatment.

In all cases, it is important to look at the real cause of failure and make adjustments in materials and practice, as well as future design, to reduce the frequency of such failures. A good pavement preservation or rehabilitation policy is a quality tool that when used properly can improve the entire pavement system.

The selection of the maintenance or rehabilitation treatment is a function of many factors including the pavement distress. In summary, the primary requirement of a treatment is to address the primary needs of the roadway. Once the needs for the roadway are determined, an appropriate treatment can be chosen that provides for the roadway needs. Table 1 provides a guide, based on the needs of the road users, to the appropriate surfacing characteristic.

Table 1: Surfacing Requirements (5)

ROAD USER REQUIREMENT AND SURFACE PROPERTIES	
ROAD USER REQUIREMENT	**KEY PROPERTY OF SURFACE**
Good low speed skid resistance	High polish resistant coarse aggregate
Good high speed skid resistance and prevention of hydroplaning	High polish resistant coarse aggregate and high surface texture
Visible road markings	High surface texture
Low spray generation	Porous surfacing (best) or high surface texture (high hydraulic conductivity)
Low glare and specular reflection	Sufficient surface texture
Low tire / road noise	Porous surfacing or low surface texture
Smooth ride	Smooth surface – thicker surfacing can reduce roughness in underlying layers
Low construction and maintenance costs	High durability surfacing, thin surfacing
Minimize delays during construction/maintenance	Durable surfacing (less frequent maintenance)
Minimum wear and tear on vehicle and load	Smooth surface – thicker surface can reduce roughness in underlying layers
No windshield breakage caused by construction operations	Use construction techniques that minimizes loose surface stones

3.0 COMMON DISTRESSES IN PAVEMENT STRUCTURES AND TYPICAL TREATMENTS

Pavement structures become distressed and deteriorate as a result of many factors. Common types of distress are discussed briefly in the following paragraphs while Chapters 3 through 8 provide more detailed information with regard to the appropriate level of distress for a given maintenance treatment.

3.1 DISTRESSES IN THE SUBSURFACE LAYERS

The distresses in the subgrade soil impact all layers above it. Distresses in the subgrade soil include excessive deflection, shear failures and consolidation, or settlement. Excessive deflection often results in areas of fatigue cracking in the surface layer of the pavement structure. Shear failures also occur on slopes often resulting in a large vertical displacement of the portion of the pavement surface located immediately above the distressed area.

Consolidation can occur over a large area resulting in the entire width of the pavement "sinking," or it can occur in localized areas, particularly below the wheel paths, resulting in rutting.

Although many factors affect the strength of the granular materials that make-up the base and subbase layers, the size distribution of the aggregate (particularly the proportion of fine to coarse aggregate) is considered to be the most important. Materials that are very dirty (i.e., contain a substantial amount of fine-grained soil) have low strength characteristics and are susceptible to frost heave. Low strength in the base and/or subbase layer can cause a number of problems to the surface layer such as cracking, rutting, depressions, etc. Also, heave due to frost action can cause significant vertical displacement of the surface layer, often resulting in cracking.

3.2 Distresses in the Surface Layer

A number of distresses occur to the hot mix asphalt (HMA) surface layer of a pavement structure, but these can be broadly categorized as distresses associated with cracking, deformation, deterioration, and mat problems. Cracking can occur as a result of traffic loading, thermal stresses as a result of low temperatures or due to oxidation at the surface. Deformation (e.g., rutting, shoving, etc.) in the HMA layer is often caused by traffic loading at elevated temperatures. Deterioration of the surface (e.g., raveling, stripping, etc.) is caused by a variety factors such as problems with the HMA materials, mix design problems, environmental conditions, and traffic loading. Finally, problems in the mat (e.g., segregated mix, bleeding.) are typically caused by problems associated with mix design or improper construction techniques.

3.3 Typical Treatments

Treatment of distresses in the subsurface layers requires removal and replacement of at least the surface layer and, thus, such operations are more expensive than treatment of distresses in the surface layer. Correcting problems with the subsurface layers usually requires major rehabilitation or reconstruction. Correcting problems with the surface layer, on the other hand, can be preventive or corrective in nature (Figure 1) if performed before the surface layer degrades substantially. The treatments described in Chapters 3 through 8 are appropriate preventive and/or corrective treatments for many of the distresses that commonly occur in HMA pavements.

4.0 MATERIALS

Materials play an important role in the efficient and effective use of maintenance treatments. Most materials used in maintenance treatments are covered in the Standard Specifications, SP's or SSP's that can be found on the Caltrans web site http://www.dot.ca.gov/hq/esc/oe/specs_html/index.html. Where the specifications are relevant, they are referenced in the specific treatment chapters 3 through 8. This section discusses the main materials used and provides a general explanation of their composition, manufacturing, storage and handling techniques, and addresses special application requirements. In some cases, the materials themselves are derived from a mixture of raw materials. This section will also address some of these issues.

The two main materials comprising maintenance treatments are binder and aggregate. Binders in use in California include:

- Standard Paving Asphalt – Aged Residue (AR) grade
- Asphalt Emulsion
- Polymer Modified Asphalts, including performance-based asphalts (PBA grades)
- Asphalt Rubber and Modified Binder (MB) grades

Aggregates in use in California cover a range of geological types. The general requirements, gradings and physical properties are covered in various sections of the Standard Specifications (9).

4.1 STANDARD PAVING ASPHALT – AGED RESIDUE (AR) GRADE

4.1.1 What is Standard Paving Asphalt?

Conventional paving asphalt is a complex hydrocarbon mixture derived from the refining of crude oil. The crude type and the processing method have a significant effect on the final physical properties (8). In California, steam distilled asphalts are mostly used and are described in the Standard Specifications Section 92.

4.1.2 How is Standard Paving Asphalt Manufactured?

Several processes are used to specifically manufacture asphalt including:

1. **Steam Distillation**: Steam distillation begins with the desalting and de-waxing of the crude oil. Once completed, the crude is heated to approximately 300°C (572°F) (8). A furnace is then used to heat the crude to 400°C (752°F) and the heated crude is continuously delivered to the flash zone of the atmospheric tower. The material is separated (by its boiling point) with the most volatile components rising to the top and the less volatile escaping on the sides of the tower. The residue in the tower is stripped using steam to remove volatiles. In some very heavy crudes, this residue may be suitable asphalt.

2. **Straight Run / Blending**: Vacuum tower residue may be suitable as paving asphalt or it may require blending with other feedstocks, fluxes from the vacuum tower, or from other parts of the process such as solvent de-asphalting.

3. **Solvent Refining**: Solvent refining takes advantage of the varying solubility of different asphalt fractions. A short chain hydrocarbon (propane usually) is injected into the asphalt rich fraction and precipitates asphalt fractions out, as they are not soluble in the hydrocarbon. The intent is to remove aromatic oil fractions from the asphalt for other uses (such as extender oils and solvents). Propane precipitated asphalt (PPA) is an asphalt and aromatic rich fraction that may be used as asphalt alone, although it often exhibits tenderness. It can also be blended with other straight run fractions.

4. **Air Blowing**: Air blowing has been used to harden asphalt to create higher viscosity grades. This process may be done continuously or in a batch process. However, this has often led to asphalts with poor aging resistance. Some processes have been developed whereby light blowing is employed to modify feedstocks of specific composition to create multi-grade asphalts of low thermal susceptibility.

The properties of the asphalt produced will depend on its chemical composition, the crude type and the processing method used. The key to producing asphalts that will perform well in the field is the specification.

4.1.3 Specification of Conventional Asphalts

Asphalt is specified by:

- Consistency (or Viscosity)
- Aging Characteristics
- Purity
- Safety

The main conventional asphalts used by Caltrans are aged residue (AR) grades. Table 2 provides the specification for various AR grades, whereas the following paragraphs provide additional details regarding this specification:

Table 2: AR Asphalt Grade Specifications (9)

STEAM-REFINED PAVING ASPHALTS						
SPECIFICATION DESIGNATION	**AASHTO TEST METHOD**	**VISCOSITY GRADE**				
		AR 1000	**AR 2000**	**AR 4000**	**AR 8000**	**AR 16000**
Tests on Residue from RTFO Procedure: (CT 346)[a]						
Absolute Viscosity at 60°C, Pascal second ($x10^{-1}$)	T202	750-1250	1500-2500	3000-5000	6000-10000	12000-20000
Kinematic Viscosity at 135°C, min., Square meter per second ($x10^{-6}$)	T201	140	200	275	400	550
Pen. at 25°C, 100 g / 5 sec., min.	T49	65	40	25	20	20
% of orig. Pen.[b] at 25°C, min.	—	—	40	45	50	52
Ductility at 25°C, mm, min.	T51	1000[c]	1000[c]	750	750	750
Tests on Original Asphalt:						
Flash Point, CL.O.C. °C, min.	T48	205	215	225	230	235
Solubility in Trichloroethylene, % min.	T44	99	99	99	99	99

a) *TFO (AASHTO Test Method T179) may be used but the RTFO shall be the referee method.*
b) *Original penetration as well as penetration after the RTFO loss will be determined by AASHTO Test Method T49.*
c) *If the ductility at 25°C is less than 1000 mm, the material will be acceptable if its ductility at 15°C is more than 1000 mm.*

1. **Viscosity**: Viscosity describes the fluidity of asphalt at a given temperature under a given rate of shear. The viscosity will vary depending on the conditions at the time of the test due to asphalt's viscoelastic properties. At temperatures of around 60°C (140°F), unmodified asphalt behavior becomes less shear dependent than at lower temperatures. For this reason, many specifications require that dynamic viscosity be measured at 60°C (140°F). Kinematic viscosity is often used for specifications at higher temperatures 135°C (275°F).

   Another consistency test used is penetration. Penetration involves the insertion of a standard needle into an asphalt sample under a standard weight (shear force) over a standard time. The amount that the needle penetrates at 25°C (77°F) loaded with a 100g (3.5 oz) weight over 5 seconds is normally used. Lower or higher temperatures can be used to provide and indication of the temperature susceptibility of an asphalt. California specifications are based on the AR system where consistency is measured on an aged residue. Further detail about aged residues is provided in the next section

   The relationship between penetration grade and viscosity grade asphalt is given in Figure 7. For example, a penetration grade 40-50 has similar viscosity characteristics as an AC-40 or AR 16000. In AR graded asphalts, the aging process increases the viscosity relative to un-aged material. Different asphalts age at different rates depending on the crude source and processing method. The initial un-aged properties, in applications not involving hot mix plants (i.e., emulsions) will vary.

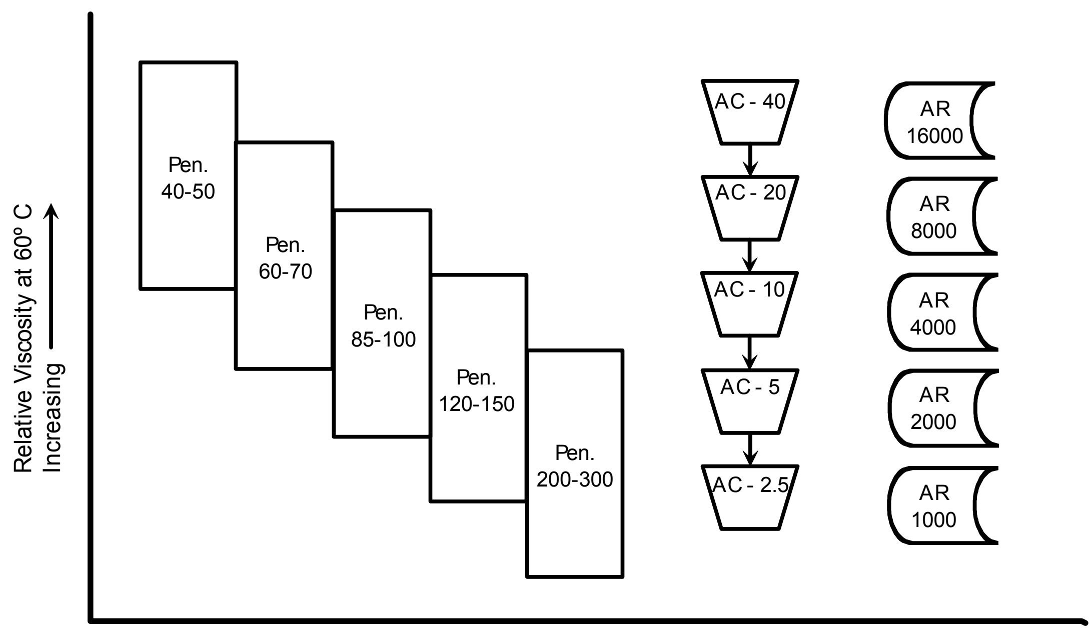


Figure 7: Relationships Between Asphalt Grades by Viscosity (10)

__Note__: Figure 7 above shows the relationship between grades of asphalt in general viscosity terms and in no way is to be interpreted to determine actual viscosity values.

Other consistency tests include the Ring and Ball Softening Point Test and the Ductility Test. The Ring and Ball Softening Point Test determines the temperature at which the weight of a ball bearing pushes through a circular sample of material. This is a measure of the temperature at which the penetration is approximately 800. Ductility is the elongation of a sample at a set temperature and set strain rate. Ductility indicates the colloidal stability or internal cohesion of the asphalt.

2. **Aging Characteristics**: Aging in asphalt is associated with oxidation and hardening of the asphalt. During processing and while in service in the pavement, asphalt will loose volatile materials. The loss of this volatile material can lead to hardening. Aging is one cause of asphalt failure as the material becomes brittle, shrinks, and cracks. Specification of short-term aging characteristics is usually determined after exposure to air in a thin film oven or rolling thin film oven. Aging during service life is measured using a pressure aging vessel test (AASHTO T-49). This is currently not used in California.

   In the AR specification, the properties of the asphalt are measured after these aging tests are performed. In California a rolling thin film oven test is used (California Test Method CT 374).

3. **Purity and Safety**: Purity tests are based on the solubility of the asphalt in solvent, with Trichloroethane the most commonly used. Safety tests are based on the flammability or flash point of the fumes emitted by asphalt during heating. Caltrans uses the Cleveland Open Cup test to determine the flash point for asphalt binder material.

AR asphalts are used in all conventional mixes. The higher the designation number the higher the in service viscosity. For example, AR 4000 has a higher in-service viscosity than AR 2000. The higher the in-service viscosity, the harder or stiffer the asphalt. Stiffer asphalt produces higher stability in mixes and resistance to deformation. Conversely, stiffer asphalt may result in lower resistance to cracking.

4.2 ASPHALT EMULSIONS

4.2.1 What is an Emulsion?

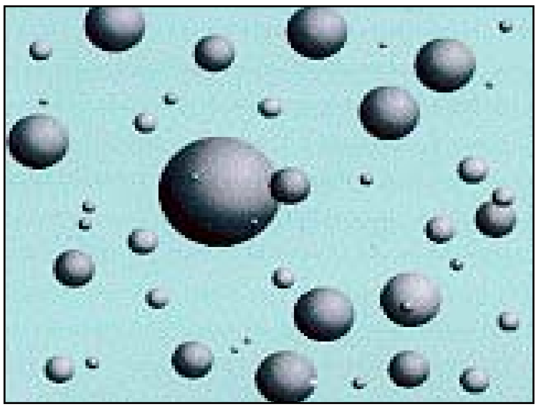
When two or more solid components are mixed together in water, several phenomena can occur depending on the chemistry of the components. If the solid materials are broken down or reacted with water, then a solution may form. In a solution, the solid phase is in an ionic form and is dispersed on a molecular level (e.g., salt in water). If the solid materials do not change or react with the water they may form a slurry or suspension (13, 14, 15).

An emulsion lies between these two extremes and is defined by the size of the particles involved. In an emulsion, the particle sizes range from 1 to 100 μm (3.94×10^{-5} to 3.94×10^{-3}) in diameter. This allows the particles (once chemically stabilized) to form a stable dispersion. When the particle size is less than one micron, the material is termed a colloid. Such systems may be stable without the use of extra chemical stabilizers as they are usually self-stabilizing (e.g., clay in water).

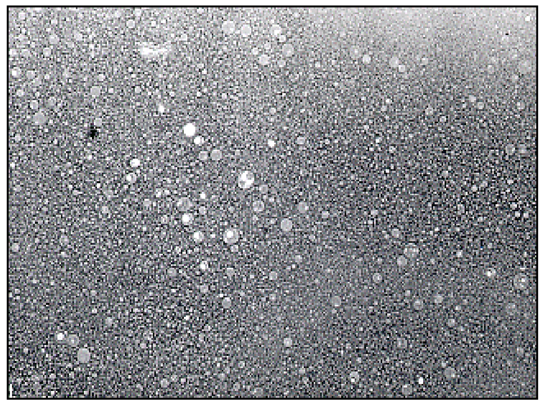
An emulsion is a dispersion of one immiscible phase in another. An asphalt emulsion is asphalt dispersed in water. This is not a solution as the two phases (oil in water) are susceptible to separation. So, like a good salad dressing, the oil is stabilized with an emulsifier to keep it dispersed. Figure 8 shows an emulsion in schematic and an emulsion micrograph.

The process of returning from this dispersed form to the asphalt form is called "breaking" (13). The process by which the asphalt expels water and dries to an integral film or layer on the aggregate or surface is termed "curing" (13). The mechanisms associated with breaking and curing are covered in Section 4.2.4.

Emulsions allow the formation of an asphalt binder with low enough viscosity for easy application. The dispersion in water gives the asphalt many of the properties of water such as low viscosity, lower temperature requirements for both application and storage, and less sensitivity to application on damp surfaces.



a) Emulsion Schematic



b) Emulsion Micrograph

Figure 8: Asphalt Emulsion Illustrations (13)

4.2.2 How are Emulsions Made?

Asphalt is semi-solid at ordinary temperatures 10 to 60°C (50 to 140°F). To make an emulsion, the asphalt must be sheared into small droplets and coated/reacted with a chemical stabilizer or emulsifier. Figure 9 shows the cross section of a typical colloid mill, the device that is used to shear the asphalt. It should be noted that there are other methods of shearing the asphalt to produce an emulsion. These include homogenizers, pressure reducers (venturi effect) and pumps. The colloid mill is the most commonly used to produce asphalt emulsions. The chemical emulsifier solution (also known as the soap solution) is combined with the asphalt and introduced into a gap between a high-speed rotor and a stator (or other rotor rotating at a lower speed). The resulting shear breaks the asphalt particles down to the required size. The geometry of the sheared particles has a big effect on the particle size distribution, which in turn affects the properties of the emulsion (16).

In an emulsion plant several operations must be carried out. Figure 10 shows the key elements of an emulsion plant.

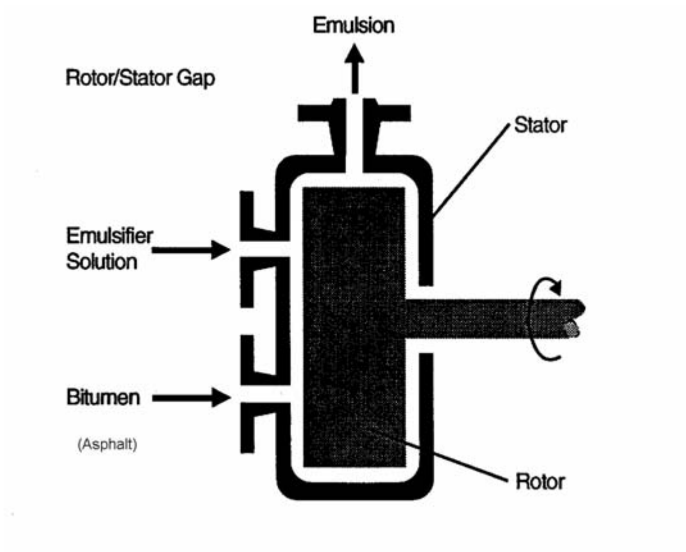


Figure 9: Colloid Mill Cross Section (13)

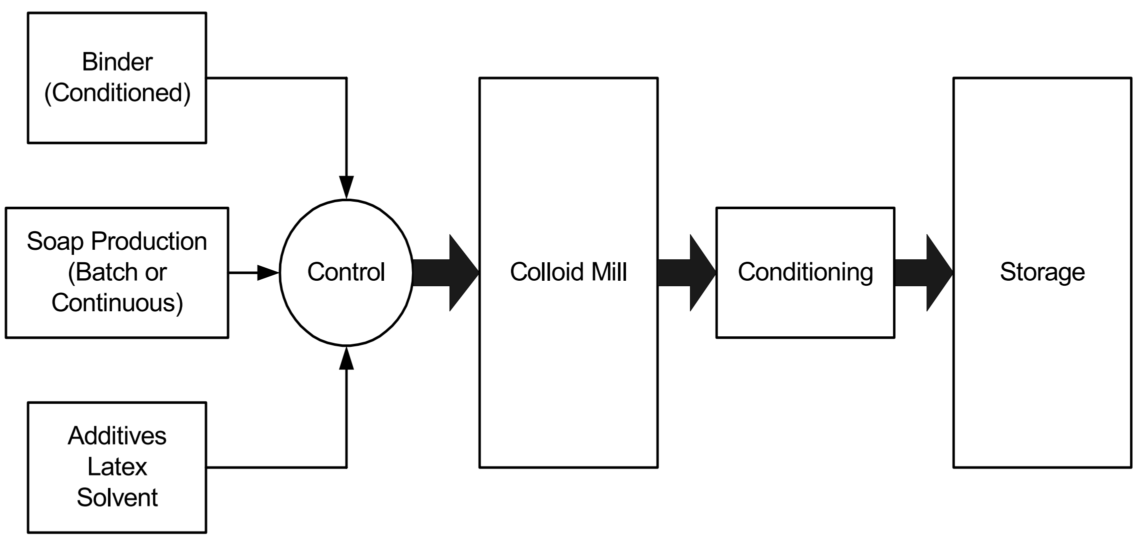


Figure 10: Emulsion Plant Operations Schematic (14)

The asphalt must be stored correctly and at the right temperature. For normal operation (non polymer binder emulsification), the storage temperature will range from 135 to 140°C (275 to 284°F). For polymer-modified binders, the storage temperature will range from 160 to 170°C (320 to 338°F). If higher temperatures are required, the colloid mill must be operated under back pressure, about 2 to 3 bar (29 to 43 psi) and a heat exchanger on the mill outlet is required to ensure that the emulsion is cooled to below boiling temperatures before the back pressure is reduced to atmospheric pressure. If the backpressure and heat exchange operations are not properly carried out, the emulsion will boil and be destroyed.

The soap solution (emulsifier solution) preparation is required because the emulsifiers usually need to be reacted with a base or acid to create the surface-active or emulsifying form (salt). This may be done in a continuous fashion or in a batch fashion. As the reactions are between an acid and an alkaline emulsifier (cationic systems) or an alkaline chemical and an acid emulsifier (anionic systems), the pH of the soap solution and the pH of the resulting emulsion are key factors in the quality of the emulsion.

In many cases, additives for emulsion stability or modification are introduced. The most common method of modifying an emulsion is through the addition of rubber latex (synthetic or natural). The latex is either introduced via the soap solution or directly injected into the mill via the soap line. This method has the advantage that no heat exchanger or pressure operation is required.

4.2.3 What are Emulsifiers and What Types of Emulsions are Used?

Emulsifiers in their neutralized state may have a negative charge (anionic), a positive charge (cationic), or no charge (nonionic) (13). The exact chemistry and type of emulsifier determines the application of the finished emulsion. Other factors that determine physical and application characteristics include pH of the emulsion, the binder content, the particle size and distribution, and the compatibility with the aggregate sources.

Anionic emulsifiers are based on fatty acids. These are reacted with a base such as caustic soda to produce an acid salt. This acid salt is the active emulsifier (see Figure 11). The emulsifier has a long fatty chain that is soluble in the asphalt and a polar head that provides a surface charge (see Figure 12). Repulsion created by these charges allows stabilization of the emulsion.

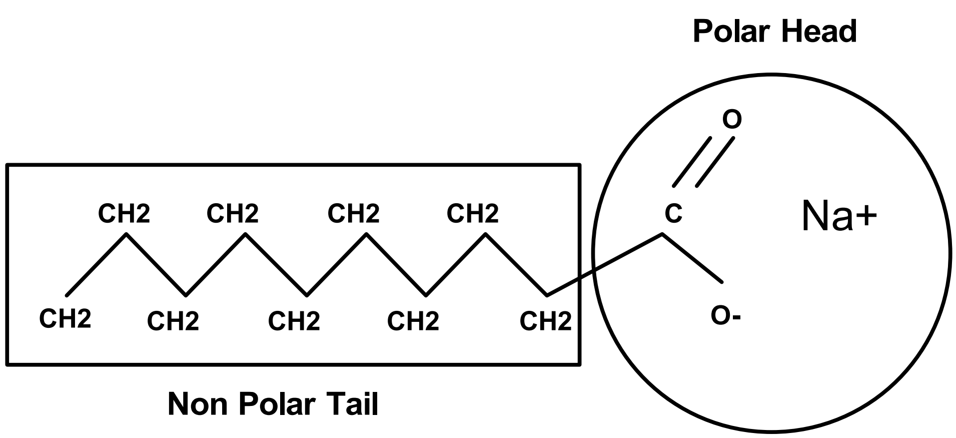


Figure 11: Chemical Structure of an Anionic Emulsifier (15)

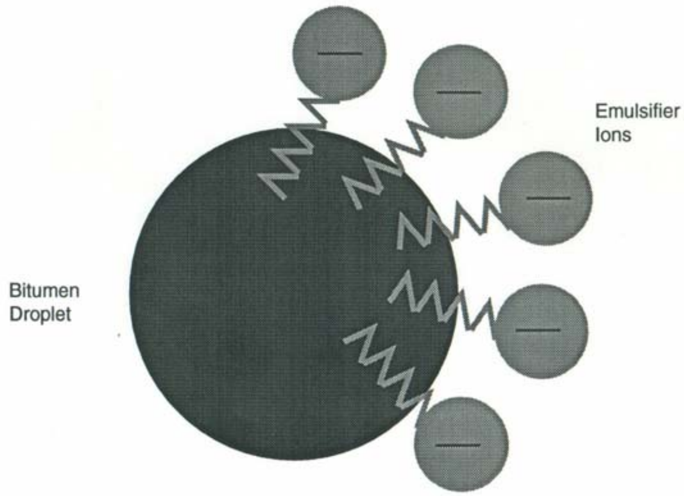


Figure 12: Anionic Emulsified Asphalt Particle (15)

Cationic emulsifiers are based on amines of various types. The exact type used will depend on the application. Some typical types include quaternary ammonium compounds (slow set), fatty diamines (rapid set), amidoamines (quick set) and immidazolines (microsurfacing). These are reacted with an acid such as hydrochloric acid to produce a salt, which is an active emulsifier. The emulsifier has a long fatty chain that is soluble in the asphalt and a polar head that provides a surface charge. Repulsion created by these charges allows stabilization of the emulsion as may be seen in Figures 13 and 14.

Nonionic emulsifiers are amphoteric; that is, at low pH they have a positive charge and can be cationic, at high pH levels they can have a negative charge and can be anionic emulsifiers.

The emulsifier type and concentration determines the emulsion's performance. The emulsifier type may control the break period. More rapid break times equal higher charge and lower concentrations of emulsifier. Slow break times equal lower charge, and higher concentrations of emulsifier.

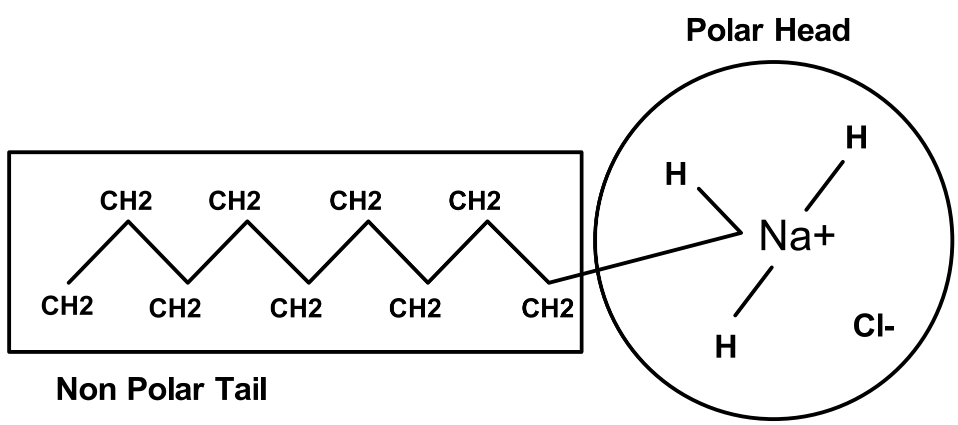


Figure 13: Chemical Structure of an Cationic Emulsifier Particle (15)

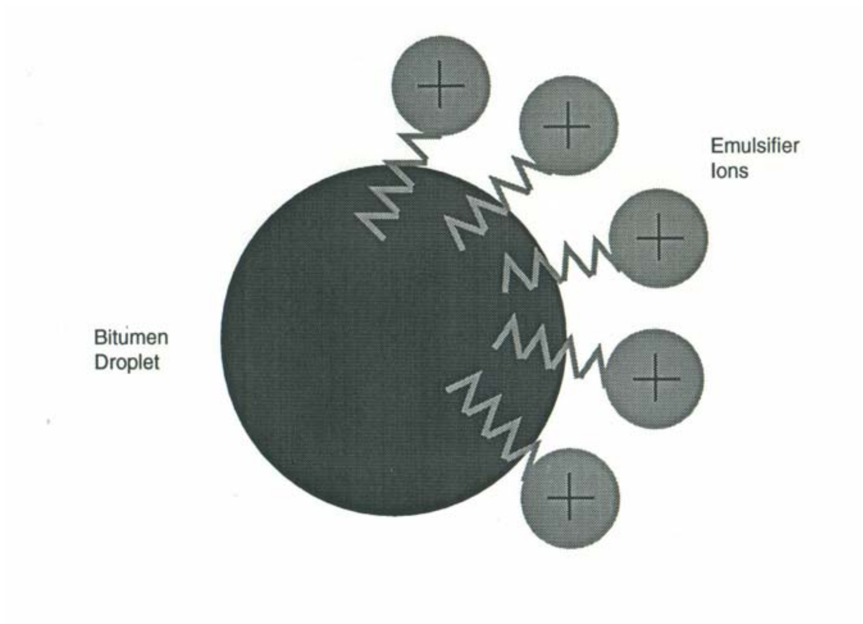
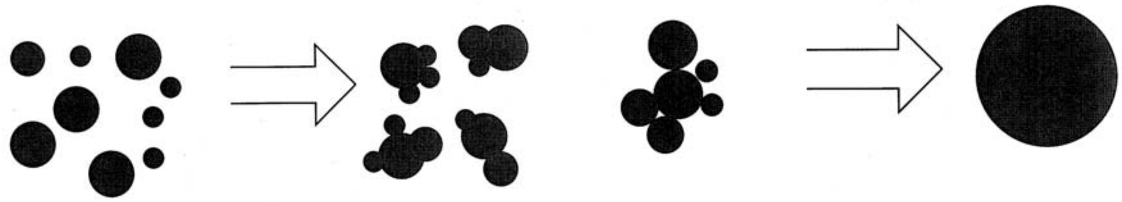


Figure 14: Cationic Emulsified Particle (15)

4.2.4 Anionic or Cationic: Which to Use?

Caltrans uses emulsions for various applications; however only anionic and cationic emulsions are utilized. The choice between anionic and cationic is made based on the application requirements and the characteristics of the aggregate to be used in the mix. Generally, anionic emulsions of the slow set variety are more compatible with soils and easier to dilute with water. Thus, they are normally chosen for soil stabilization and fog seals. Anionic emulsions break by flocculation and coalescence. In this process, as water evaporates from the emulsion and the particles come into close contact, they stick together, as illustrated in Figure 15. These particles then “floc” or coalesce into larger particles. This process continues until the particles begin to form films. No specific reaction occurs with siliceous aggregates, but with calcareous aggregates a reaction does occur (17). Thus, anionic emulsions are suitable for use with calcareous aggregates such as limestone.



a) Particles begin to stick together (Flocculation) **b) Particles coalesce to form larger particles**

Figure 15: Particle Coalescence Process (15)

Figure 16 illustrates material compatibility in general terms along with the associated breaking process. Cationic emulsions may be formulated for all application types and aggregates, which is also illustrated in Figure 17. These emulsions are most useful for rapid setting chip seals, slurry emulsions and microsurfacing emulsions. This is due to a cationic emulsion's specific reaction with all compatible aggregates that creates a stronger adhesive bond. For the same reason, cationic emulsions are also less susceptible to cooler conditions and dampness than anionic emulsions.

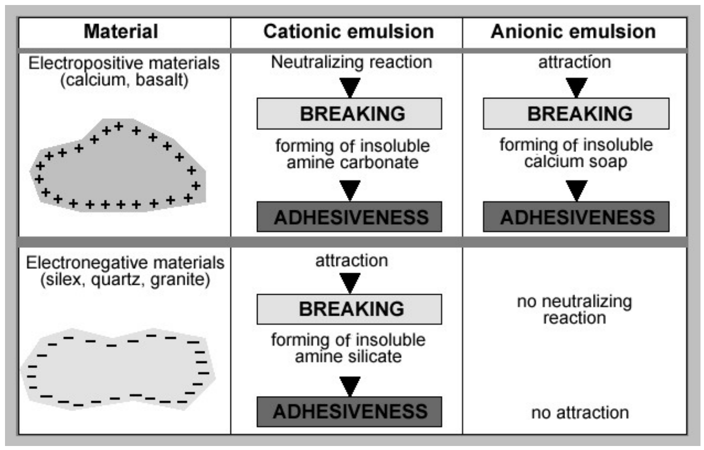


Figure 16: Material Compatibility and Reactivity of Emulsions (17)

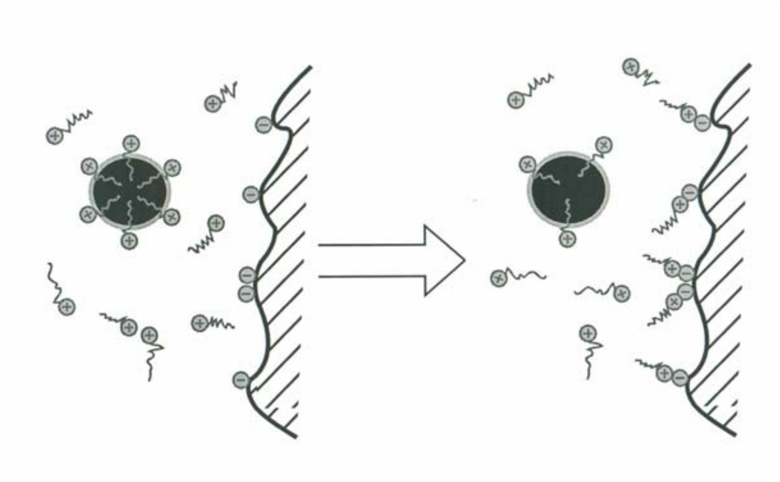


Figure 17: Cationic Emulsion Physio-Chemical Reaction with Aggregate (15)

The curing process (illustrated in Figure 18) is the same for both types of emulsion, except the reaction mechanism for cationic emulsion pushes water away from the aggregate surface. Thus, cationic emulsions tend to cure faster.

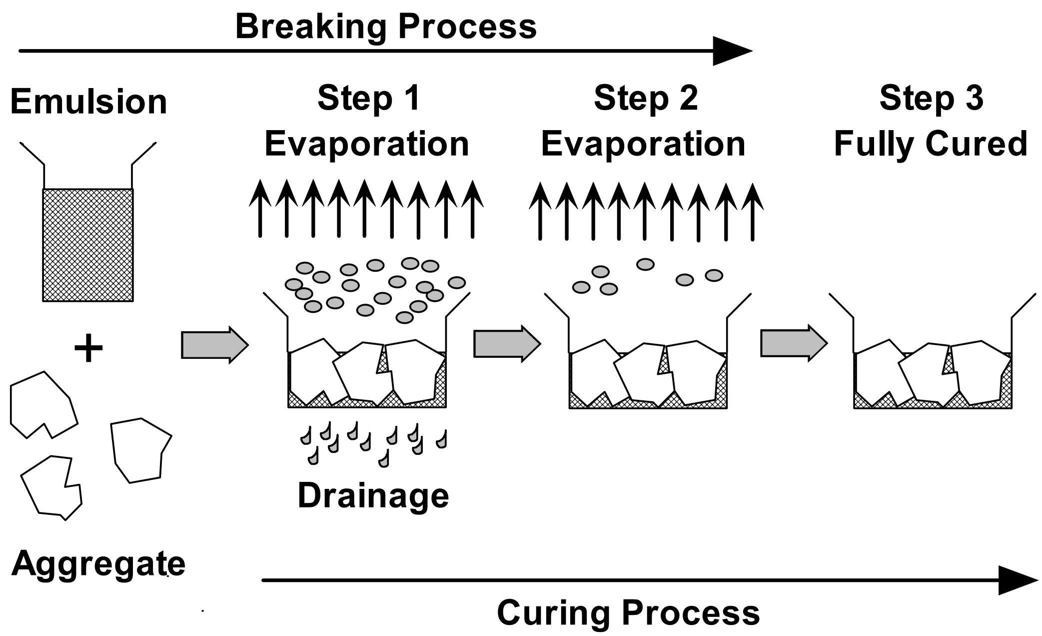


Figure 18: Emulsion Break and Cure Stages (15)

The decreased curing time for cationic emulsions has implications in the application and handling of these emulsions. These implications will be discussed in the sections on specifications and storage and handling.

4.2.5 Specifications and Testing

1. **Caltrans Specifications**: Caltrans uses several common emulsion types. These are described in detail in Standard Specifications Section 94 (9), and are briefly described below:

   - **Anionic Emulsions**: Rapid Set (RS), Medium Set (MS) and Slow Set (SS). There are subcategories that describe the base asphalt ("h" equals hard or 80/100-penetration grade or if there is no 'h" designation, it refers to the use of a softer grade- 120-150 pen grade). Numbers describe the binder content of the emulsion (1 for lower and 2 for the higher level). In anionic emulsions, these binder content designations are different for different grades; RS-1 is typically 55% minimum binder content, and RS-2 contains 65% minimum. Medium sets are 55 and 65% respectively and SS grades are only designated as SS-1 or SS-1h and are 57% minimum binder content.

   - **Cationic Emulsions**: Rapid set (CRS), Medium set (CMS) and Slow set (CSS). There are subcategories that describe the base asphalt ("h" equals hard or 80/100-penetration grade. If there is no 'h" designation, it refers to the use of a softer grade). Numbers describe the binder content of the emulsion (1 for lower and 2 for the higher level). In cationic emulsions, these binder content designations are different for different grades; CRS-1 is 60% minimum binder content, and CRS-2 65% minimum. Medium sets are 55 and 65% respectively and SS grades are only designated as CSS-1 or CSS-1h and are 57% minimum binder content.

- **Polymer Modified Emulsions**: These may be anionic or cationic. They are all rapid set and have the letter P at the start of the designation. For example PMCRS-2h is a polymer modified cationic rapid set emulsion with the hard binder. All the emulsion binder contents for this class of emulsions are 65% minimum. These emulsion types are further discussed in Chapter 4 “Chip Seals”.

- **Quickset Slurry Emulsions**: These may be anionic or cationic (QS or CQS) and have minimum binder contents of 57%. In general use are polymer modified (latex) versions of these emulsions and they have the letter “L” preceding the designation (e.g., LMCQS-1h). Such emulsions may be made with the hard binder or the softer binder. This is further discussed in Chapter 7 on Slurry Surfacings.

2. **What the Specifications Mean**: The test methods listed in the specifications (9) are designed to provide an indication of the stability, physical characteristics, and performance of the emulsion. This section presents a general overview of tests contained in the specifications.

   - Binder content is measured by distillation or evaporation. This is important to know because application rates are based on residual binder.

   - Viscosity indicates the application properties (whether the emulsion can be pumped and sprayed) and whether it will remain where it is applied without running off. The viscosity of an emulsion is a function of the binder content within the emulsion, as illustrated in Figure 19. This figure indicates that as the binder content of the emulsion increases, so does its viscosity. Emulsions with higher viscosities are more difficult to pump and spray at a given temperature than are emulsions with lower viscosities.

   - Settlement and storage stability are determined by the same test, but performed over different periods of time. They determine if an emulsion can be stored without “breaking” in the storage container. If settlement occurs during the test (as shown in Figure 20), and is not re-dispersed, this is an indication that the emulsion may flocculate and coalesce (“break”) during storage.

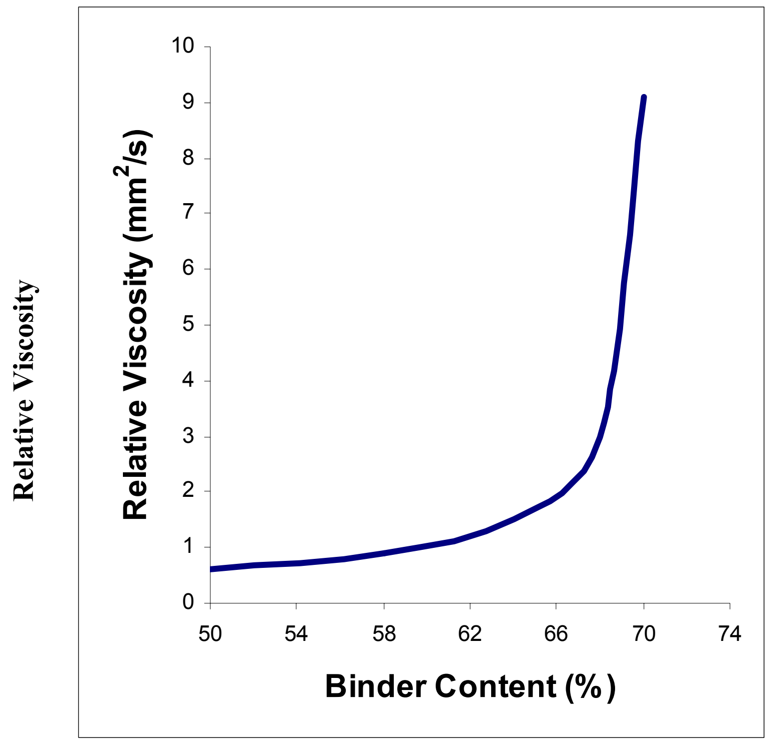
   - Demulsability is the measure of an emulsion’s resistance to breaking and gives an idea of whether the emulsion is rapid or slow setting.

   - The coating test refers to mixing characteristics with soil or aggregate.

   - The cement-mixing test is a stability test that is relevant for mixing emulsions with soils or aggregates.

   - The sieve test provides an indication of foreign matter in the emulsion that might cause problems such as clogging nozzles during spraying or clogging in-line sieves during pumping operations. It is also an indication of stability. Figure 21 illustrates the Sieve Test.

Tests on residual binder are carried out to check the base asphalt and the polymer. Penetration and ductility are conducted on the residue of both conventional and polymer modified emulsions. Torsional recovery and infrared testing are used to examine polymer content. Torsional recovery is carried out using the equipment shown in Figure 22. The recovery from a torsional load is measured and related to polymer content (the test method used is CT 332).



Binder Content %

Figure 19: Relative Viscosity Vs Binder Content (18)

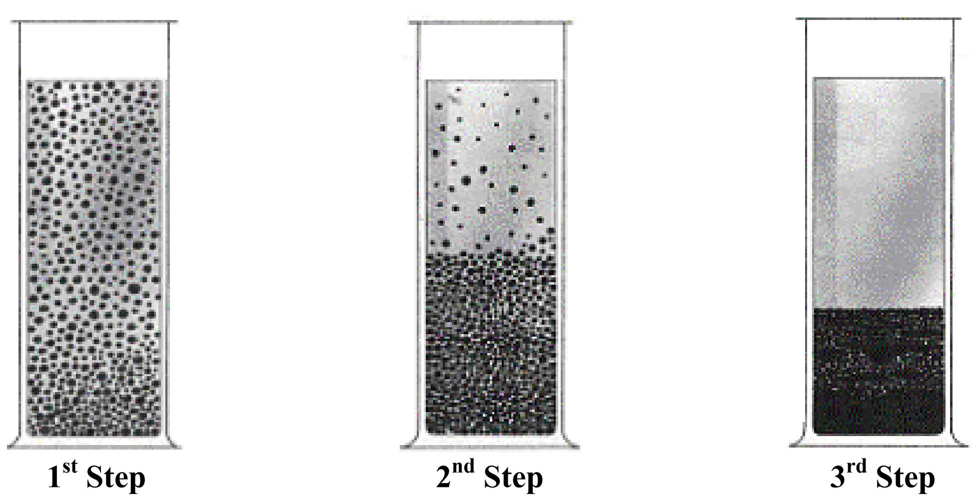


Figure 20: Settlement and Storage Stability Test (17)

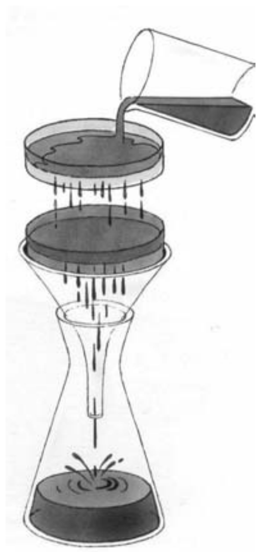


Figure 21: Sieve Test

(Note: Normally only 1 sieve is used in the AASHTO T-59 as used by CT) (17)

Figure 22: Torsional Recovery Test

4.3 CUTBACKS

4.3.1 What are Cutbacks?

A cutback is a solution of asphalt in a hydrocarbon solvent (e.g., kerosene, diesel, or naphtha). Solvents are used to reduce the asphalt's viscosity so that the cutback can be pumped and sprayed at lower temperatures [40 to 145ºC (104 to 293°F)] than that required for conventional asphalt. The solvent performs no other function in road applications. The solvent selected depends on the grade of the cutback, which in turn, is based on the expected setting rate.

During the 1970's energy crisis and in response to environmental concerns on volatile emissions (i.e., evaporation of the solvent during the application and curing processes), use of cutbacks has generally been discontinued. In California, only slow and medium cure cutbacks are still made and only slow cure cutbacks are generally specified. The main use for cutbacks is prime coats over aggregate base materials prior to placement of an asphalt-wearing course in new construction.

4.3.2 Manufacturing

Because cutbacks are solutions of asphalt and solvent, they are easily manufactured. This can be done on site by circulation in a tank. In refinery applications, inline blending or emulsion colloid mills have been used to manufacture cutbacks.

4.3.3 Specifications and Testing

The Caltrans cutback specifications are found in the Standard Specifications Section 93, and they are referred to as "Liquid Asphalts" (9).

- Slow curing (SC): these contain a heavy oil solvent. Caltrans has four designations SC-70, SC-250, SC-800, and SC-3000. The number refers to kinematic viscosity of the cutback.

- Medium Cure (MC): these are made with a kerosene type solvent and have the same viscosity designations as SC grades.

The main specifications relate to safety as measured by flash point and water content, viscosity and boiling range of the solvent, application and cure rate, residue percentage for residual application rate, and residue tests to ensure the correct base asphalt grade had been used. The main effect of increasing the viscosity is to increase the application temperature requirements. This is covered in the Standard Specifications Section 93.

4.4 POLYMER MODIFIED BINDERS (PMB'S) & PERFORMANCE BASED ASPHALTS (PBA'S)

4.4.1 What are Polymers and Polymer Modified Binders?

Polymers are large molecules that enhance the properties of virgin asphalt. Depending on the basic polymer units or monomers used, a wide range of properties can be achieved. It is possible to categorize polymers in a number of ways, but for engineering purposes they are conveniently described as having glassy (stiffness) or rubbery (elastomeric) properties. Often this is termed plastomeric or elastomeric. However, this is very dependant on conditions such as temperature, rate of loading and strain level (19). As the demands of a modern road system have, in some areas, exceeded the capacity of conventional bituminous materials, polymer additives are a means by which pavement performance may be enhanced.

The use of a polymer has no value if it does not substantially improve the life cycle cost of the material in which it is used or solve a specific problem. The selection of polymer modification should almost always be based on improved performance related to cost. Although there are a substantial number of polymers in use today for a variety of products, only a relative few are commonly used in asphalt mixtures (21). Examples of polymers commonly used in asphalt mixtures include:

- Styrene Butadiene Copolymer (radial and linear) (SBS)
- Polyethylene (PE)
- Styrene Butadiene Rubber (SBR)
- Polybutadiene (PB)
- Ethylene Vinyl Acetate (EVA)
- Ehtylene Methyl Acrylate (EMA)
- Atactic Polypropylene (PP)
- Epoxies and Urethanes
- Tire Rubber (Crumb)

4.4.2 How Polymer Modified Binders are Manufactured

Many types of manufacturing configurations exist to make polymer-modified asphalts. Manufacturing may be done at high or low shear, on site, or in a factory. The main stages of manufacturing require the following procedures:

- Metering of polymer, asphalt, and additives.
- Wetting of the polymer by the asphalt/additive mix.
- Dispersion of the polymer.
- Allowance for any interaction (reaction) of the polymer with the asphalt.
- Storage and transportation.

Most of these are mechanical issues and are achieved by relatively simple techniques. Figure 23 illustrates a typical manufacturing (blending) plant.

The most important steps in the manufacturing process are dispersion and reaction. This is what determines the structure (i.e., morphology) of the final binder and hence its properties. These steps also determine the level of polymer required to achieve the desired results. Compatible systems usually have superior rheological, aging, and stability properties to those of incompatible systems at the same polymer level (19). The micrographs in Figure 24 show the structure (morphology) of SBS at 3% dispersion in a compatible (a) and incompatible (b) polymer system. The scale for both micrographs is the same.

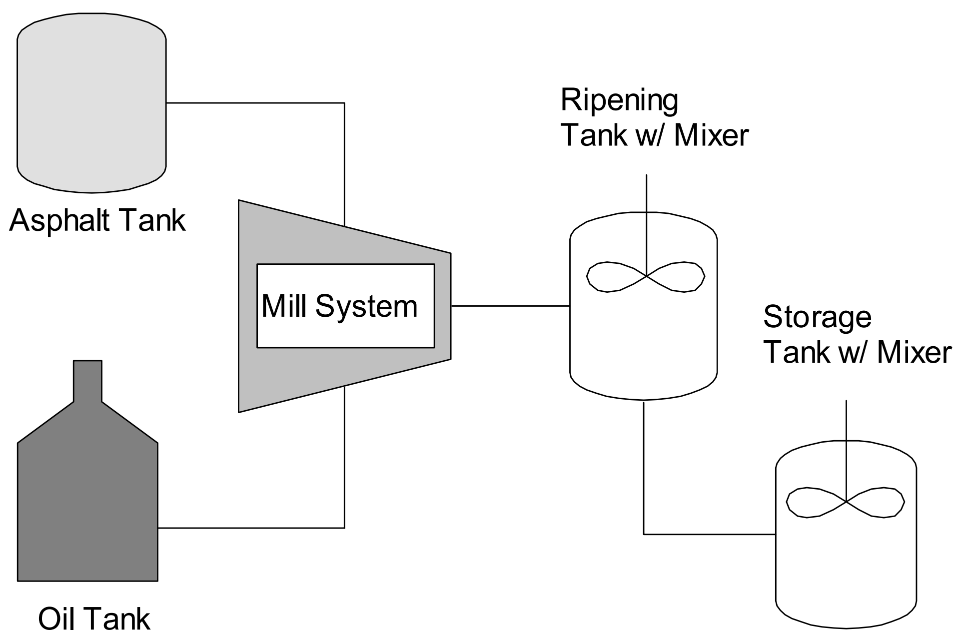
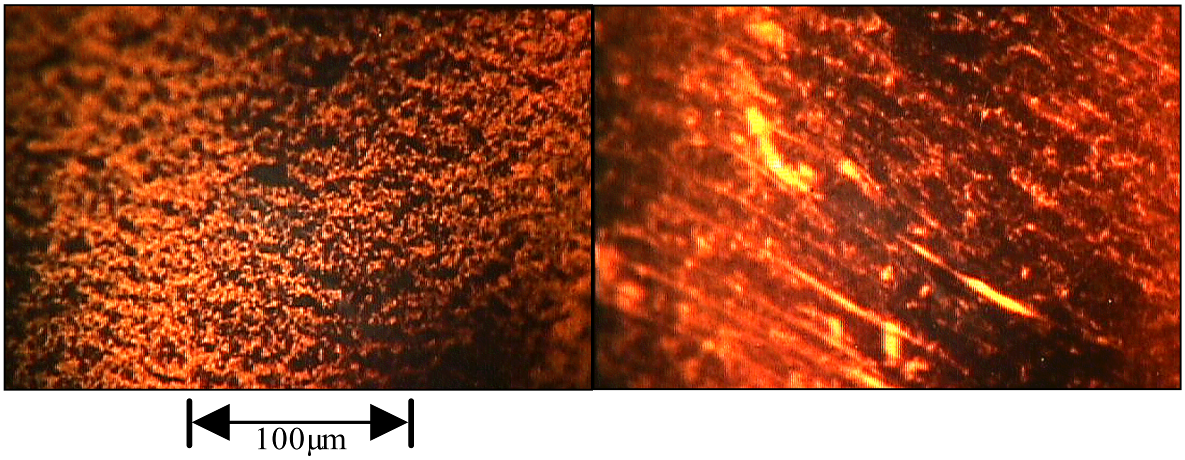


Figure 23: Typical Polymer Blending Plant (19)



(a) Compatible System **(b) Incompatible System**

Figure 24: Micrographs of Polymer Systems (19)

4.4.3 What are Performance Based Asphalts?

Caltrans was one of the originators of performance-based asphalts (PBA's) as detailed in SSP S8 M-20 (23). Some PBA's are polymer modified, notably PBA 6a, PBA 6b, and PBA 7. The PBA specification defines the performance characteristics of the binder. It also incorporates many of the standard consistency tests as well as some items that were a precursor to the Strategic Highway Research Program (SHRP) rheological parameters, such as shear susceptibility of delta and viscosity.

The different grades are suited for different climatic applications. PBA 1, the base conventional material, is similar to AR 4000. PBA 6a and PBA 6b are polymer modified asphalts and provide better high and low temperature properties than AR grades and are used in areas with hot summers and cold winters. This is achieved through the use of SBS copolymers. The main difference is the lower temperature cracking resistance, PBA 6b being superior to PBA 6a by 5 to 6°C. Both products resist rutting at very high pavement temperatures. PBA 6a is also useful in open graded mixes where the application temperatures are at the lower end of the requirements or work is being done at night. This is possible due to PBA 6a's good compaction characteristics in such mixes. PBA 7 is more heavily modified than the other materials and is suitable for high desert areas. This material has better aging resistance and may be used for this purpose in milder climates.

4.5 ASPHALT RUBBER?

4.5.1 What is Asphalt Rubber?

Scrap rubber, crumb rubber, and reclaimed rubber are all terms describing recycled rubber. The largest recycled rubber source is automobile and truck tires and is referred to as crumb rubber modified (CRM). This rubber is not a pure polymer but a blend. Most car tires in the USA are made of mainly Styrene Butadiene Rubber (SBR) or polyisoprene and carbon black. Other polymers are included in some blends, and tires are not uniformly formulated or compounded. Truck tires generally contain a higher percentage of natural rubber than car tires (up to 30% of the combined polymer content).

The variations in the CRM may affect the properties. However, in asphalt rubber binders, the particle size of the added CRM is relatively large and the chemical properties are less important than in a polymer system. Asphalt rubber binder is typically made in the field; that is, near to the job site for chip seal applications or at the hot plant site for hot mix applications.

The asphalt rubber specification is a recipe specification and is detailed in the SSP's (23). Two rubber types are specified, one is tire rubber and the other is a high natural rubber recycled material. The required rubber properties are controlled by the SSP requirements (23). Mixing temperatures are important and should be kept between 190 and 226°C (375 and 440°F). Grading is important in determining the rate of digestion and the binder's final properties. These materials are mixed into asphalt that has been modified with extender oil (high aromatic hydrocarbon) at about 2% (23).

The asphalt rubber binder improves fatigue life, resistance to rutting, and provides stone retention and crack alleviation in chip seals (25) when compared to other binders. In California, asphalt rubber gap-graded overlays may be reduced up to 50% the thickness of conventional overlays and still provide the same resistance to reflective cracking. Caltrans uses asphalt rubber binders mainly in gap graded and open graded mixes. They are also used as SAM and SAMI seals as a reflection cracking treatment. Caltrans does not currently use asphalt rubber in dense graded mixtures.

4.5.2 How is Asphalt Rubber Manufactured?

To produce asphalt rubber binder, the neat asphalt is heated to approximately 190 to 226°C (375 to 440°F) at which time the tire rubber is added via a hopper system into a pre-wet tank. The asphalt contacts and wets the CRM particles. This mix is then transferred into a reaction vessel where it "reacts" with the lighter fractions in the asphalt, mostly aromatic and napthenic oils that swell the outer areas of the particles.

A reaction is claimed to occur in which the asphalt and the rubber particle interact to form a gel coated particle (25). This reaction is similar to the process of swelling that occurs in polymer asphalt systems (22). The reaction is shown schematically in Figure 25.

How well this model reflects the actual situation and the relative effect of particle sizing is not clear but, based on polymer and asphalt chemistry, it seems adequate. It also explains why a significant change in properties occurs over time, since this type of system is not thermodynamically stable. Further, the large increase in viscosity over its early life is due to the continuation of this solvation process (28, 29).

This can be shown by examining micrographs (see Figure 26) of asphalt rubber digested with and without extender oil (relative sizing is important; all micrographs are to the same scale and the largest particles are 100μm).

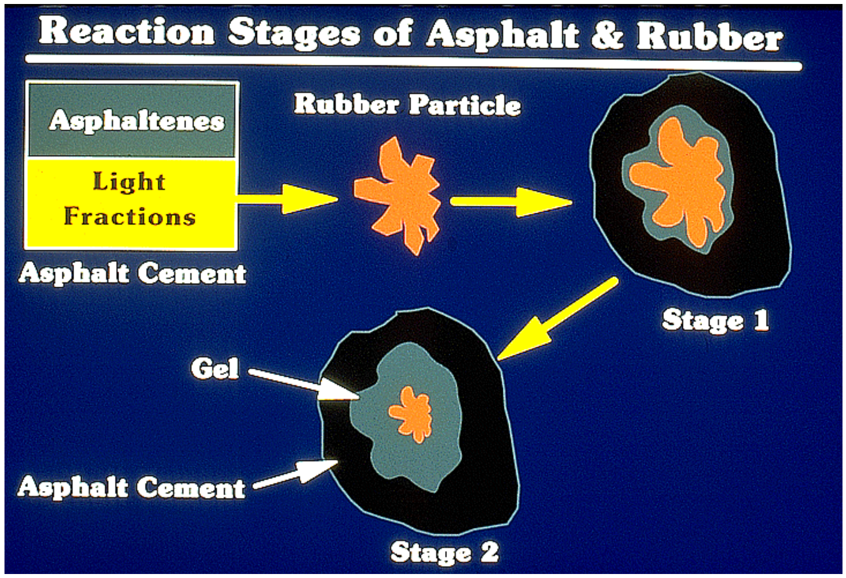
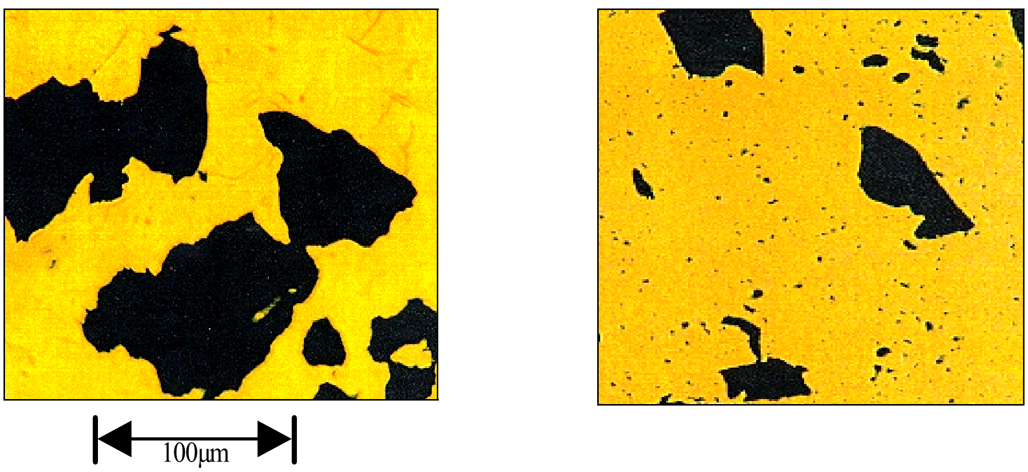


Figure 25: Asphalt Rubber "Reaction" (25)



a) Without Extender Oil **b) With Extender Oil**

Figure 26: Micrographs: Asphalt Rubber Extender Oil Effects (19)

4.6 AGGREGATES

4.6.1 What are Aggregates?

Aggregates are the major building material for pavements. The aggregate's role is to form the matrix of strength in a mix; as such their properties are critical to the success of a mix (10). Local sources are generally used but some other materials such as expanded clay (light weight aggregate) or slag may be used if they meet the required specification. Major aggregate types that may be encountered in California include (10):

- Igneous rocks: Volcanic rocks formed from molten rock. Examples are granite and basalt.
- Sedimentary rocks: Rocks formed by the laying down of layers of material that is then compressed. Examples include limestone, sandstone, and chert.
- Gravel: Formed from the breakdown of any natural rock. Usually found in rivers or waterways. River gravel is an example.
- Sands: These are formed from the deterioration of any natural rock. These often contain clay or silt and should be washed.
- Slag: This is a by-product of metallurgical processing. Slags can be from tin, steel, or copper processing. Slag is generally hard but absorbent.

There are two major categories of aggregate properties of interest in pavement applications. These are the chemical and physical properties as discussed below:

Chemical Properties: Chemical properties of aggregates identify the changes an aggregate may go through due to chemical action. Some aggregates contain substances that are soluble in water, are subject to oxidation, hydration or carbonation. The main chemical property that affects asphalt applications, however, is affinity the aggregate has for the asphalt. Asphalt must wet the surface of the aggregate and adhere to it. Failure to do so may produce the phenomena of stripping and disintegration failure of the hot mix or loss of stone in other treatment types such as slurry or chip seal. No reliable indicators exist for determination of stripping potential based on chemistry of the aggregate alone and most tests are based on testing the mixture (AASHTO T283).

Physical Properties: The most important aggregate properties are listed below:

- **Grading or Particle Size Distribution**: Grading requirements are discussed in the chapters that deal with individual treatments. Caltrans specifies grading requirements for use in HMA in the Standard Specifications Section 39. The grading is important as it determines the mixture characteristics with respect to its physical properties. For example, in HMA this includes fatigue resistance and load bearing. In open graded asphalt concrete mixtures, it will determine porosity, while in chip seals and slurry surfacing it will determine seal durability. The individual grading requirements are further discussed in the chapters on treatments 3-8. CT 202 and CT 105 measure grading. The latter test method is used if there is a difference in specific gravity of 0.2 or more between the coarse and fine portions of the aggregate or between blends of different aggregates.

- **Cleanliness or Presence of Deleterious Materials:** Dirty aggregates may cause adhesion problems in chip seal and HMA and cohesion problems in slurry surfacing. Lumps of clay may disintegrate under freeze thaw conditions or cause pockmarks in a HMA pavement. Specific testing and requirements are discussed in the chapters concerned with treatments. The Sand Equivalent test (CT 217) is used to measure this property for HMA aggregates.

- **Hardness or Abrasion Resistance:** Aggregates transmit the wheel loads to the subgrade. They must be resistant to crushing and wear to maintain this function. They must also resist crushing and degradation during stockpiling. A polished or worn aggregate will reduce skid resistance. The LA abrasion test (CT 211) is used to measure hardness and abrasion resistance.

- **Durability or Soundness:** Aggregates must be resistant to break down due to the cyclic action of wetting and drying and freeze and thaw cycles. CT 214 can be used to determine soundness.

- **Particle Shape and Surface Texture:** Aggregate particles for use in most treatments should be cubical rather than flat or elongated. This creates more interlock and internal friction in generating higher deformation resistance. In chip seals, it creates greater seal texture depth and skid resistance. The surface texture and the shape are a determinant to workability in mixes and may affect compaction. A rough fractured particle has a higher surface area and forms tougher adhesive bonds. Caltrans measures only fractured faces (CT 205).

- **Absorption Characteristics:** Aggregates may absorb asphalt; reducing the effective volumetric percentage of the binder mixtures or the effective application rate in chip seals. These changes can result in raveling of the pavement. Caltrans uses the Centrifuge Kerosene Equivalent and the Oil Ratio Test (CT 303) test to measure the absorption of aggregate.

Special aggregate requirements for specific treatments are considered in the relevant chapters.

4.6.2 How are Aggregates Manufactured?

Aggregates are manufactured in quarry operations by first blasting (if necessary) and then using a series of crushers and screens to create the desired stone sizes. Several methods of crushing may be used; which include jaw crushers (usually the primary crusher), impact crushers (these produce cubical aggregates and are generally used later in the process), attrition mills, hammer mills and gyratory cone crushers. The combination must be chosen to meet the required specifications.

5.0 STORAGE AND HANDLING

The key aspects of storing and handling any product include safety and quality. It is essential to ensure safety in handling at all times and to maintain quality so that the material remains in specification from manufacture to the intended end use.

This section covers storage and handling of:

- Conventional Asphalt
- Modified Asphalts (including asphalt rubber and MB's)
- Asphalt Emulsions
- Aggregates

5.1 CONVENTIONAL AND MODIFIED ASPHALTS

When handled properly, asphalts may be reheated or maintained at elevated temperatures without adverse effects. If asphalt is thermally abused in storage, handling or application, it may harden and compromise service properties.

5.1.1 Avoiding Problems During Storage

The main methods of avoiding potential storage problems are to ensure that equipment is properly designed, in good working condition and correct procedures are established and followed. All tanks should be designed in accordance with a recognized standard (e.g., API 650). General design considerations include tank shape, tank foundations, tank thickness, and tank access. Best management practices require a secondary containment around all tanks. Vertical tanks yield the highest asphalt to tank volume ratio of all tank configurations. Vertical tanks with a cone shaped roof are preferred, although temporary storage in horizontal tanks is acceptable. The operational tank design considerations relate to:

- **Minimizing the risk of overheating**: The tank requires accurate thermal sensors. They should be positioned in the region of the heaters and also uniformly distributed throughout the tank. The probes should be in thermal wells and removable for cleaning and calibration. Heating may be accomplished via heat transfer (oil or steam), electric coils, or direct fired. As asphalt is a good insulator, the heating rate must be controlled to prevent localized overheating, particularly when direct-fired systems are used. The heat capacity may be estimated as 0.5 and heating rate should be limited to 25°C (77°F) per hour (30).

- **Minimizing oxidation and loss of volatiles**: In order to minimize oxidation and loss of volatiles, contact with air must be minimized. This may be accomplished by designing pressure-tested, fully enclosed tanks. To avoid air entrainment, all circulation lines should re-enter the tank under the liquid level. When filling a tank, it should be filled from the bottom and the asphalt should not be allowed to freefall as this can result in entrapped air. Venting is an essential safety precaution and cannot be eliminated to reduce oxidation.

- **Maintaining asphalt homogeneity**: To maintain asphalt homogeneity and avoid temperature variation, the asphalt should be mixed on an intermittent basis. This may be done through circulation or through the use of side mixers under the liquid level. Vortex mixing entrains air and its use should be avoided. When adding fresh asphalt to a tank, circulation is necessary to stabilize temperature and combine the existing material with the fresh material.

- **Minimizing heat loss**: To conserve energy, all tanks should be insulated with fiberglass or rock wool insulation. This insulation should be at least 50 mm (2 in) thick and sheathed in aluminum or galvanized steel at least 0.7mm (0.03 in) thick. Additionally, lines should be insulated and heat traced with electric tape, steam or oil.

Safety hazards can arise from:

- **High Temperatures**: Since asphalt must be stored at high temperatures, safety issues involving burns, along with the material's contact with water, which causes rapid expansion resulting in foaming and explosive boil over, must be addressed. Burns may be avoided by always using the correct safety apparel. Additionally, ensure that all lines and surfaces are thoroughly insulated.

Due to the potentially hazardous side effects of water contacting high temperature asphalt, steps need to be taken to avoid this interaction. As water is slightly lighter than asphalt, it will move to the top of tanks. However, during transport cold water may migrate to the bottom of a tank. Water entrapment in tanks can be avoided by using watertight cone topped tanks, ensuring that tanks are watertight and hatches are sealed. Water finding gel should be used to check tanks before filling. If water is present, the asphalt should be heated through the range from 92 to 125°C (198 to 257°F) at a rate of 10 to15°C (50 to 60°F) per hour. Silicone antifoaming agent at 0.1 % can also be added. Pipes and any additives that are to be blended with the asphalt need to be checked for water.

- **Flammable or explosive atmospheres**: Asphalts normally have flash points exceeding 250°C (482°F). However, flammable atmospheres may form if contamination by light products (e.g., products created from cleaning or flushing lines) is disturbed. Ignition sources may include sparks, or static electricity. With this in mind, proper grounding is important along with the use of shielded electric motors.
- **Presence of toxic materials**: Fumes can be generated when asphalt is heated. These fumes contain particulate asphalt, hydrocarbon vapor, and sulfide gases. The latter is highly toxic and tends to build up in headspace. Proper venting is required to dispose of these fumes.

5.1.2 Recommended Storage and Handling Temperatures and Times

Asphalt and modified asphalt are stored and handled in similar ways. An exception is asphalt rubber, which is used shortly after manufacture. Allowable storage times are product specific and take into account the rate of property change, which occurs during storage. For example, an AR grade of conventional asphalt can be stored for several months, a PBA modified grade can be stored for several days, and asphalt rubber stored for only several hours.

5.2 ASPHALT EMULSIONS

Asphalt emulsions are a convenient way of handling asphalt. As water is the carrier of the asphalt and the system is chemically stabilized, emulsions may be subject to settlement or breaking prematurely. For this reason storage and handling are important issues. Over time emulsions will become coarser and undergo property changes, to avoid these problems timely use is often required. There are some simple rules for storage and handling of asphalt emulsions and they are discussed below.

5.2.1 Handling

Handling of emulsions is not difficult. By following the rules below potential problems can be avoided.

- **Pumping**: Pumps are a way of doing work on an emulsion. Pumps usually compress or shear the material they pump. This results in a compressed emulsion. If compression is too severe or occurs too often, the emulsion will become coarser by the mechanism of flocculation and coalescence and may revert back to straight asphalt. Pumps should be selected carefully. Diaphragm pumps are gentle, but require high maintenance and should only be used if essential. Centrifugal pumps are acceptable as long as the peripheral speed is not too high, less than 300rpm. Positive displacement pumps may be used, but usually 2-3 thousandths of an inch must be shimmed from the gears to provide adequate clearance and lastly old and worn pumps may be used. Always get expert advice on the appropriate pump to use.

- **Temperature**: When asphalt materials get cold, they shrink. In an emulsion, this means that the asphalt droplets get closer together. This has a number of important consequences. The material can flocculate and may coalesce; this may also cause the emulsion to settle out faster than desirable. If the material is pumped when cold the droplets are more compressed due to temperature related shrinkage. As a result, a pump that was not too tight in January may be far too tight in July. If the emulsion actually freezes, the droplets become frozen in contact and the emulsion will revert to bitumen upon thawing. For most emulsions, this happens if the emulsion gets to below 4°C (40°F). When materials get hot they expand. However, when water gets hot, its evaporation rate increases enormously. If the water evaporates, the droplets get closer together and can result in an emulsion reverting back to asphalt by the action of flocculation and coalescence. If any part of the emulsion gets hotter than 95°C (203°F) localized boiling may occur. If this happens, the droplets fuse back into asphalt. This fusing process raises a number of important aspects surrounding the heating process including the following:

    - When heating emulsions do it gently and heat according to specifications.
    - Use agitation while heating.
    - Warm pumps before use.
    - On bulk tanks in cold areas, the use of electrical heating is recommended.
    - Do not apply direct heat to emulsions with fire or a blowtorch.

5.2.2 Transport Handling

Emulsions are generally stable enough to transport. However, a common problem arises when air enters the emulsion. Air can cause the emulsion to break in the bubbles of air; CRS emulsions are particularly prone to break in this way. These larger particles can "seed" the emulsion causing settlement. Problems also arise when transport tanks are not clean. Mixing cationic and anionic emulsions can lead to breaking of the emulsion.

5.2.3 Storage

The points made for storing asphalt relate equally to the storage of an emulsion. When an emulsion is stored, it has a finite lifetime. This lifetime is determined by the formulation, handling and storage of the emulsion.

Asphalt is slightly heavier than water and as a result asphalt particles move to the bottom of the storage container. This movement is referred to as settling. If the particles pack in this way they can stick together (flocculate and coalesce) if this continues the emulsion will eventually turn back into bitumen. This settlement may be controlled to some extent by formulation. If the emulsion particles are fine enough to start with, they will settle more slowly allowing for longer storage life. Flocculation and coalescence can also occur as the result of electrical attraction between particles. If an emulsion is electrically unstable, it will flocculate and coalesce. This process may not take the emulsion entirely back to bitumen but the large particles formed as a result of this process will settle faster.

It is important to prevent settling by mixing an emulsion prior to the start of flocculation or coalescence. Once an emulsion has coarsened, remixing will not separate the larger particles again. If it has coarsened too much, pumping may break the emulsion. The only way to prevent problems is to start with a very fine emulsion and keep it properly maintained.

Tankage: While vertical tanks are preferred for plant storage, mobile storage is done with a road tanker. The road tanker increases the surface area of the emulsion exposed to air and can promote skinning. However, if properly handled, this will not become an issue for fieldwork. Specific guides for tankage include:

- Bulk tanks should be circulated at regular intervals. Circulation should be done slowly.
- The frequency of circulation will depend on the weather and how long the emulsion has spent in storage.
- Most emulsions only require circulation once a week in summer and once every five days during the winter.
- Circulation should be performed in the middle of the day, not first thing in the morning due to the colder temperatures.
- The time of circulation is based on the size of the tank; a 5000 Lt (1320 gal) tank should be circulated for 15 minutes while a 10,000 Lt (2640 gal) tank requires 20 minutes.
- Pumps must be flushed after use, but never into the emulsion tank.
- Lines and pumps should be able to be warmed before use.
- Lines should not be left part full of emulsion.

Table 3 shows the storage and application temperatures for emulsions currently in use by Caltrans (7, 15, 31).

Cleaning Procedures: For emulsions, cleanliness is very important. A sloppy operation will produce problems. When an emulsion comes in contact with air, it can begin to break. When a cationic emulsion comes into contact with metal, it can begin to break. Thus, if a pump is not properly cleaned after use, it will clog. If lines are left part full of emulsion, they will clog. The higher the performance of the emulsion, the more critical cleaning is. Cleaning should be done before storage of equipment and it should be done thoroughly. Specific guidelines include:

- Flush equipment including hoses thoroughly with WATER.
- Flush equipment and hoses with kerosene, NOT diesel, distillate or other solvent. These materials may dissolve asphalt but they are also incompatible with the emulsion and may cause the emulsion to break rather than flush it away. *NEVER FLUSH INTO THE EMULSION TANK.*
- Finish with a second flush with water.
- If a pump or line is already clogged with bitumen gentle heat may be applied at the blockage. Do not apply heat to the lines, as this will break the emulsion.
- Soak pumps with kerosene for an hour or more.
- Flush again with water after blockage is removed.

Rust, dirt, grass or other foreign material should be kept out of the emulsion. This is especially important when working with cationic emulsions as they can break by reacting with foreign materials.

Table 3: Mixing, Spraying and Storage Temperatures of Emulsions

PRODUCT	MIXING TEMPERATURE °C	SPRAYING TEMPERATURE °C	STORAGE TEMPERATURE °C
RS-1	N/A	20-60	20-60
RS-2	N/A	20-60	50-85
MS-1	10-70	20-70	20-60
MS-2	10-70	N/A	50-85
MS-2h	10-70	N/A	50-85
SS-1	10-70	10-60	10-60
SS-1h	10-70	10-60	10-60
CRS-1	N/A	20-60	10-60
CRS-2	N/A	50-85	50-85
CMS-2s	10-70	N/A	50-85
CMS-2	10-70	N/A	50-85
CMS-2h	10-70	N/A	50-85
CSS-1	10-70	20-60	10-60
CSS-1h	10-70	20-60	10-60
PMRS-2	N/A	50-85	50-85
PMRS-2h	N/A	50-85	50-85
PMCRS-2	N/A	50-85	50-85
PMCRS-2h	N/A	50-85	50-85
QS-1	10-40	N/A	10-60
QS-1h	10-40	N/A	10-60
CQS-1	10-40	N/A	10-60
CQS-1h	10-40	N/A	10-60
LMCQS-1h	10-40	N/A	10-60
MSE	10-40	N/A	10-60

The main transport requirements are to ensure that correct pumping is used, pumps should be warmed in cool climates. Clean tanks or a switch-load process should be followed. Switch loading is a process by which materials are transported in tanks that last carried a compatible material and therefore do not require the tank to be cleaned between material switching. Table 4 provides acceptable switch loading combinations. Always pump into clean tanks and always transport full containers.

Emulsions are chemical systems. In order to avoid contamination, they should never be mixed with other types of emulsions or with other chemicals.

Table 4: Acceptable Switch Load Combinations (7)

LAST PRODUCT IN TANK	PRODUCT TO BE LOADED			
	ASPHALT CEMENT	CUTBACK ASPHALT	CATIONIC EMULSION	ANIONIC EMULSION
Asphalt Cement	OK to Load	OK to Load	Empty to No Measurable Quantity	Empty to No Measurable Quantity
Cutback Asphalt	Empty to No Measurable Quantity	OK to Load	Empty to No Measurable Quantity	Empty to No Measurable Quantity
Cationic Emulsion	Empty to No Measurable Quantity	Empty to No Measurable Quantity	OK to Load	Empty to No Measurable Quantity
Anionic Emulsion	Empty to No Measurable Quantity	Empty to No Measurable Quantity	Empty to No Measurable Quantity	OK to Load
Crude Petroleum and Residual Fuel Oils	Empty to No Measurable Quantity	Empty to No Measurable Quantity	Empty to No Measurable Quantity	Empty to No Measurable Quantity
Any Product Not Listed Above	Tank Must be Cleaned	Tank Must be Cleaned	Tank Must be Cleaned	Tank Must be Cleaned

5.3 STORAGE AND HANDLING OF AGGREGATES

Aggregates must be handled and stored in a manner that avoids contamination, minimizes degradation and avoids contamination (32). Specific guidelines are as follows:

- Stockpile areas should be clean and stable to avoid contamination from the surrounding area.
- Stockpiles should be on free draining grades to avoid moisture entrapment.
- Stockpiles should be separated for different aggregate sizes to prevent inter-mingling.
- Segregation or separation of a blended aggregate is the primary concern. Segregation occurs mostly with coarse aggregates but even slurry-combined aggregate may segregate in the stockpile or on handling if it gets too dry. Segregation may be avoided by avoiding stockpiling in a cone shape. Acceptable stockpile shapes are either horizontal or radial. Making each end dump load a separate pile, each adjacent to the next, makes horizontal stockpiles. Radial stockpiles are made with a radial stacker (32).
- Degradation of the aggregate creating fines can be avoided by handling the stockpile as little as possible. In chip seal or slurry surfacing applications, re-screening may be considered.

6.0 SAMPLING BINDERS AND AGGREGATES

The following is the standard sampling requirements for testing. In the case of emulsions, sampling is a significant issue. Samples must be sent immediately for testing to ensure they are representative of the material used in the field.

Emulsions, as has been discussed, change and coarsen with storage and handling. This may result in an emulsion that is out of specification when tested despite being in specification when sampled and used. This is especially true of high binder PMCRS-2 and 2h type materials.

6.1 GENERAL SAMPLING

The following guidelines should be followed for sampling materials (32):

- Samples of emulsion and binder shall be taken in conformance with the requirements in AASHTO T 40, "Sampling Bituminous Materials," and Section 8-01 and 8-02 of the Construction Manual and California Test Method 125.
- Observe safety procedures.
- Sample binders daily using new, clean, dry 1 L Cans with Screw Lids.
- Samples are normally taken from the application lance at the rear of the distributor. Drain off sufficient material through the nozzle to ensure removal of any material lodged there.
- Samples should be taken after one-third and not more than two-thirds of the load has been removed.
- Do not submerge sample containers in solvent or wipe containers with solvent saturated cloths. Use a clean, dry cloth, only immediately after sampling, to clean containers.
- Attach a Sample Identification Form (TL-0101) to each material sample in accordance with Section 8-01 of the Construction Manual and instructions printed on the TL-0101 booklet.
- Protect the TL-0101 against moisture and stains.
- Provide the e-mail address of the RE on the TL-0101.
- Emulsions have a shelf life. It is important that all samples be sent to the Transportation Laboratory daily.
- Aggregates should be sampled according to the contractual requirements.
- Samples of aggregate shall be taken according to Section 39-3.03 "Proportioning" of the Standard Specifications.
- Samples may be taken from a conveyor belt or sampling chute.
- Field samples must be taken from the stockpile. AASHTO T 2 and Section 39 3.03 of the Standard Specifications (9) describe the method.

6.2 GENERAL TESTING DETAILS

Send samples for testing to the Transportation Laboratory:

Division of Materials Engineering and Testing Services
Flexible Pavement Materials Branch, MS #5
5900 Folsom Boulevard
Sacramento, California 95819-4612

- Samples are not to be shipped C.O.D.
- Emulsion will be tested for compliance with Section 94, "Asphaltic Emulsions", of the Standard Specifications (9).
- Aggregate samples should be tested for compliance with Section 39 "Asphalt Concrete" or Section 37 "Seal Coats" of the Standard Specifications (9) as appropriate.
- Test results are mailed to Resident Engineers. To expedite return of test results, test cards can be e-mailed to the Resident Engineers, if an e-mail address is provided on the TL-0101.

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Disclaimer

This chapter is 1 of 8 included in the Caltrans Maintenance Technical Advisory Guide (TAG). The information presented in this chapter is for educational purposes only. It does not represent a policy or specification nor does it endorse any of the products and/or processes discussed.

CHAPTER 2 FRAMEWORK FOR TREATMENT SELECTION

1.0 INTRODUCTION

There are many factors that are considered in the process of selecting an appropriate treatment for a pavement. These include pavement age, condition, traffic levels, expected future plans, as well as available funding and agency policy. At the network level, a general relationship exists between pavement condition and pavement age. For a properly constructed new pavement, the only treatments that are required are preventive maintenance (maintenance performed to delay the onset of distress). Then, as the pavement ages, it may become a candidate for routine maintenance (crack sealing or chip sealing), rehabilitation and eventually reconstruction. The purpose of this chapter is to provide guidance on treatment selection. The first step in selecting the appropriate maintenance treatment is determining, based on the life cycle and pavement condition index of the existing pavement, the most appropriate maintenance strategy for a treatment applied to a relatively new pavement differs from the strategy. The most appropriate maintenance strategy for a treatment being applied to a pavement nearing the end of its life cycle. Figure 1 illustrates the treatment strategies employed based on the condition index of the existing pavement.

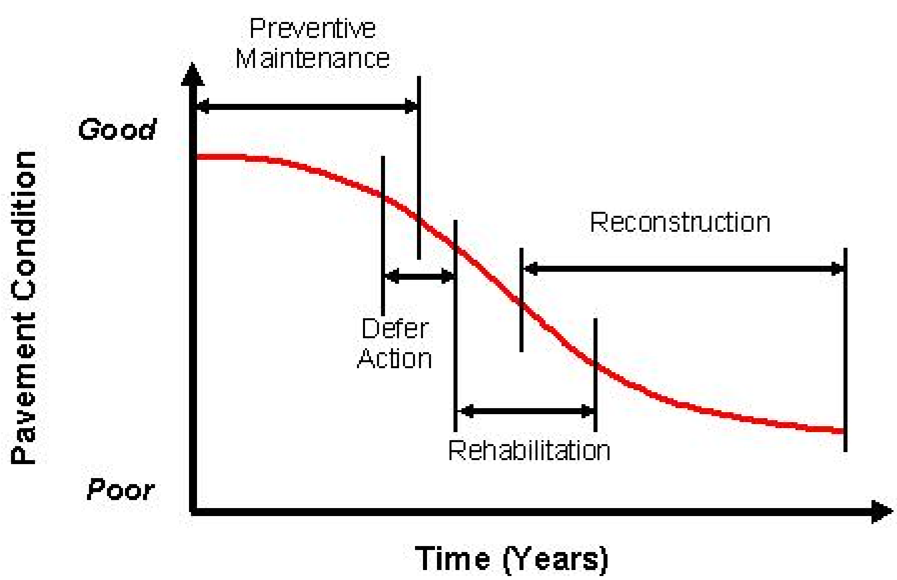

Figure 1: Treatment Strategy Based on Pavement Condition

Once an appropriate maintenance strategy has been chosen, a specific treatment is selected to address the specific distress mechanism for the pavement. The most important factors to consider when choosing a maintenance treatment include:

- Will the treatment address the distresses present? (i.e., Will it work?)
- Can the required preparation for the treatment be carried out?
- Is the treatment cost effective?
- Will the treatment be performed before the situation being addressed changes?

2.0 SELECTION PROCESS

There are three basic steps in the maintenance treatment selection process. These steps include:

- Assess the existing conditions.
- Determine the feasible treatment options.
- Analyze and compare the feasible options with each other.

2.1 ASSESS THE EXISTING CONDITIONS

The first step of the treatment selection process is to perform an evaluation of the existing conditions. This evaluation can be broken down into three processes, which include:

- Visual site inspection and/or inspection of project information from a database and/or records.
- Testing the existing pavement, as conditions require.
- Define the performance requirements for the treatment.

The Caltrans Field Distress Manual (2) or Caltrans Pavement Survey (3) may be used to identify pavement distress mechanisms. Treatment methods for the distress mechanisms are discussed in the following chapters of this document.

It is helpful to assess pavements using a pavement assessment form of some kind. A well-developed form promotes uniformity in the assessment process. The District Maintenance Engineer or other reviewer should fill out the pavement assessment form, on site, for each pavement being considered for treatment. Figure 2 illustrates an example of a pavement assessment form (2) and the type of information that should be collected.

2.2 DETERMINE THE FEASIBLE TREATMENT OPTIONS

Once the pavement condition has been quantified, test results collected and analyzed, and other available data are reviewed, feasible treatments can be identified. In this context, “feasibility” is determined by a treatment’s ability to address the functional and structural condition of the pavement while also meeting any future needs. Note that feasibility is not a function of affordability, because at this stage of the selection process the primary purpose is to determine what treatments might work. Figure 3 illustrates the Caltrans matrix for treatment options.

Distress Survey Date: ____________________ Air Temperature : Before: _____ After: _____

Surveyor: ____________________ Pavement Surface Temp: Before: _____ After: _____

Station PM/KP	Cracking																		Deformation				
	Longitudinal, a			Fatigue, b			Transverse, c			Reflective, c			Block, b			Edge, a			Rutting, d	Corrugation, b	Shoving, e	Depression, b	Overlay Bumps, c
	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H					

a = Length, meter; b = Area, square meter; c = Number and length, meter; d = Maximum depth, mm. Record plastic flow (Yes/No); e = Number and square meter
L = Low severity; M = Moderate severity; H = High severity

Figure 2: Typical Pavement Rating Form – Visual (2)

Treatment	Pavement Condition: Raveling	Oxidation	Bleeding	Rutting: <1/2"	Rutting: >1/2"	Cracking: Alligator B: 0 to 10%	Alligator B: 10 to 20%	Alligator B: 20 to 30%	Cracking: Longitudinal	Cracking: Transverse	Parameters: Climate: Desert	Climate: Valley	Climate: Coastal	Climate: Mountains	Traffic Volumes: adt<5000	Traffic Volumes: adt<5000<3000	Traffic Volumes: adt<3000	Night/Cold	Stop Points	Urban	Rural	High Snow Plow Use	Cost Per Lane Mile	Life Expectancy (years)	Life Cycle Cost ($/year)
Crack/Joint Seal																									
Emulsion	N	N	N	N	N	F	P	N	F	F	G	G	G	G	G	G	G	N	G	G	G	G	2,500	1 to 2	1,700
Modified (Rubber)	N	N	N	N		G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	2,500	2 to 3	1,000
Low Modulus (Polymer & Asphalt)																									
Fog Seal (See note 1)	F	G	N	N	N	F	P	N	P	P	G	G	G	G	F	N	N	P	F	G	G	F	4,500	1	4,500
Rejuvenator (See note 1)	G	G	N	N	N	F	N	N	N	N	G	G	G	G	G	F	N	N	N	G	G	F	4,500	2 to 4	1,500
Slurry Seals																									
Type II (See note 2)	F	G	N	N	N	F	N	N	N	N	G	G	G	F	G	G	G	P	G	G	G	P	13,000	3 to 4	3,700
Type III	G	G	N	F	N	F	P	N	N	N	G	G	G	F	G	G	G	N	G	G	G	P	13,000	3 to 4	3,700
Microsurfacing																									
Type II (See note 2)	F	G	N	G	N	F	N	N	N	N	G	G	G	G	G	G	G	F	G	G	G	F	16,000	3 to 4	4,500
Type III	G	G	N	G	G	F	P	N	N	N	G	G	G	G	G	G	G	F	G	G	G	F	16,000	3 to 4	4,500
Chip Seal																									
PME – Med. Fine	G	G	N	F	N	G	F	N	P	P	G	G	F	F	G	G	N	N	P	P	G	P	6,500	3 to 5	1,600
PME – Medium	G	G	N	F	N	G	F	N	P	P	G	G	F	F	G	N	N	N	P	P	G	F	6,500	3 to 5	1,600
PMA – Medium	G	G	N	F	N	G	F	P	P	P	G	G	G	G	G	G	N	G	P	P	G	F	12,500	4 to 5	2,800
PMA – Coarse	G	G	N	F	N	G	F	P	P	P	G	G	G	G	G	N	N	G	P	P	G	G	12,500	4 to 5	2,800
AR – Medium	G	G	N	F	N	G	G	F	P	P	G	G	G	G	G	G	N	G	P	P	G	F	20,000	4 to 6	4,000
AR – Coarse	G	G	N	F	N	G	G	F	P	P	G	G	G	G	G	N	N	G	P	P	G	G	20,000	4 to 6	4,000
PM Alternative																									
Conventional OGAC	G	G	P	P	N	G	F	N	P	P	G	G	G	G	G	G	G	P	G	G	G	O	19,500	3 to 4	5,600
PBA OGAC4	G	G	P	P	N	G	F	N	P	P	G	G	G	G	G	G	G	F	G	G	G	P	25,000	4 to 5	5,600
AR (Type O)	G	G	P	F	N	G	G	F	P	P	G	G	G	G	G	G	G	P	G	G	G	P	28,000	4 to 6	5,600
Thin Blanket ACOL																									
Conventional	G	G	P	G	G	G	G	F	P	P	G	G	G	G	G	G	G	G	G	G	G	G	20,000	3 to 5	5,000
PBA	G	G	P	G	G	G	G	G	F	F	G	G	G	G	G	G	G	G	G	G	G	G	25,000	3 to 6	5,600
R (Type G)	G	G	P	G	F	G	G	G	G	G	G	G	G	G	G	G	G	F	G	G	G	G	30,000	5 to 8	4,600
Digouts	P	P	G	N	G	N	N	G	P	P	G	G	G	G	G	G	G	G	G	G	G	G	19,000	5 to 8	2,900

G – Good Performance
F – Fair Performance
P – Poor Performance
N – Not Recommended

Note: 1. Generally used on shoulders, low volume roads, and parking areas. Should not be placed on traveled way by contract until further notice.
2. Generally used on shoulders, parking areas, and locations where a less aggressive surface texture is desired.

Figure 3: Caltrans Maintenance Treatment Matrix (5)

Once the feasible options have been determined, the limitations of each of the options should be taken into account in relation to its suitability vs. the other feasible options. Treatment limitations are imposed by such factors as deflection, pavement, curvature, roughness and permeability. The most inexpensive option that satisfies the maintenance requirements within its limitations should be considered first. At this point, a life cycle analysis or other cost effectiveness measure should be made as discussed in the next section.

2.3 ANALYZE AND COMPARE THE FEASIBLE TREATMENT OPTIONS

It is likely that there will be several treatments that are identified as feasible. In comparing these different treatments, thought should be given to the treatment placement cost, the life of the treatment and whether or not the treatment extends the life of the pavement. Additional factors to consider when analyzing and comparing treatment options are: the cost effectiveness, traffic level, construction limitations, and any factors, such as weather, curing times or local issues that affect a specific treatment. The most desirable treatment is the one that provides the greatest benefit (whether that benefit is measured in terms of improvement in condition, extension of pavement life, or even, more simply, the life of the treatment) for the lowest life cycle costs. At this point a life cycle or other cost effectiveness measure should be made.

Reconstruction and maintenance costs rise as a pavement ages. However, if maintenance and/ or rehabilitation (M&R) is carried out too early the costs are prohibitively high. There is an optimum time at which maintenance can be performed to provide the maximum cost effectiveness. Figure 4 shows a typical cost effectiveness relationship with respect to timing of treatment applications.

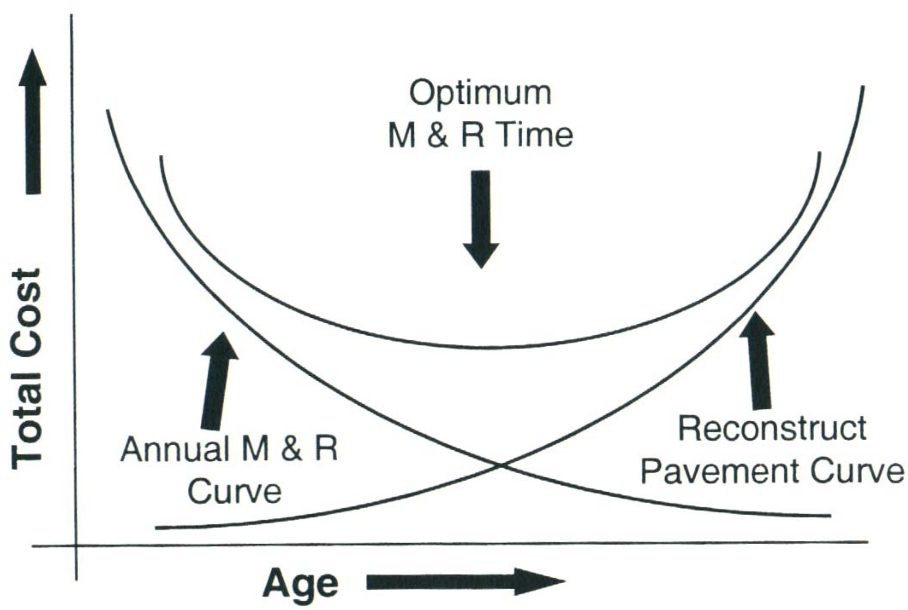

Figure 4: Treatment Timing versus Costs (6)

2.3.1 Cost Effectiveness

Caltrans calculates cost effectiveness using the Caltrans Pavement Condition Report (3) system. However, for an initial assessment a more simplified approach may be employed (5). This simplified approach is useful as costs and actual bid prices fluctuate. One simplified approach that can be used is the equivalent annual cost (EAC). In this method an equivalent annual cost is calculated using the following equation (5):

EAC = Unit Cost of Treatment / Expected Life of Treatment……………………..(9.1)

At this stage the treatment that meets the performance requirements with the lowest EAC may be selected. Other, more complex, methods exist (7) and may be used to calculate whole of life costing.

2.3.2 Choosing from the Maintenance Treatment Matrix

The main issues to consider when selecting between accepted treatments listed in the Caltrans treatment selection matrix are:

- Performance and Constructability
- Customer Satisfaction

Performance and constructability factors include the expected life of a treatment, seasonal effects on a treatment, existing pavement conditions, the existing pavement structure and the EAC calculated for the treatment. The contractor's experience, materials availability and weather limitations should also be taken into account. Each of these items is rated on a scale of 1 to 5. The District Maintenance Engineer or local supervisor should assign the ratings based on their individual experience. The ratings are based on the fact that a treatment is suitable when it is properly applied; however, project limitations such as climate conditions and material limitations may prohibit proper procedures from being followed. In situations where new products or material sources are being introduced, a risk factor should be considered, and a lower rating given to these materials. Similarly, if a contractor is unfamiliar with the new product or new material a lower rating should be given, despite the technical properties of a new product.

Customer satisfaction factors are social factors and include: traffic disruption, skid resistance achieved and noise level. Aesthetic factors such as dust and general appearance are also included. This allows a feasible option to be evaluated on factors other than cost and performance. The most cost effective and long lasting treatment may not be the right treatment for the right pavement at the right time under some conditions.

The rating factor is the weight, based on overall importance to the job success, assigned to a specific treatment's attribute; the higher the rating the more significant the attribute's impact on the job's success. The sum of all rating factors must equal 1.0. Figure 5 illustrates a blank ratings evaluation worksheet while Figure 6 shows an example of a worksheet comparing a chip seal and a microsurfacing for a particular job. Based on the results of the worksheet (Figure 6), a microsurfacing treatment (Total Score of 3.55) would be chosen over the chip seal (Total Score of 2.90) for this job. This process should be repeated for all potential treatments that meet the feasibility requirements.

RATING FACTOR			SCORING FACTOR CHIP	SCORING FACTOR MICRO		RATING FACTOR		TOTAL SCORE CHIP	TOTAL SCORE MICRO
PERFORMANCE EVALUATION ATTRIBUTES									
	%	Expected Life			×		=		
	%	Seasonal Effects			×		=		
	%	Pavement Structure Influence			×		=		
	%	Influence of Existing Pavement Condition			×		=		
CONSTRUCTABILITY ATTRIBUTES									
	%	Cost Effectiveness (EAC)			×		=		
	%	Availability of Quality Contractors			×		=		
	%	Availability of Quality Materials			×		=		
	%	Weather Limits			×		=		
CUSTOMER SATISFACTION ATTRIBUTES									
	%	Traffic Disruption			×		=		
	%	Noise			×		=		
	%	Surface Friction			×		=		
100	%					*Total*			

RATING FACTOR: PERCENT OF IMPACT ON TREATMENT DECISION (total must = 100%)
SCORING FACTOR: 5 = Very important
4 = Important
3 = Some importance
2 = Little importance
1 = Not important

Figure 5: Rating Evaluation Work Sheet (6)

NOTE: Ratings may vary from one district to another.

RATING FACTOR			SCORING FACTOR CHIP	SCORING FACTOR MICRO		RATING FACTOR		TOTAL SCORE CHIP	TOTAL SCORE MICRO
PERFORMANCE EVALUATION ATTRIBUTES									
15	%	Expected Life	3	4	×	0.15	=	0.45	0.60
10	%	Seasonal Effects	2	3	×	0.10	=	0.20	0.30
5	%	Pavement Structure Influence	3	3	×	0.05	=	0.15	0.15
5	%	Influence of Existing Pavement Condition	4	2	×	0.05	=	0.20	0.10
CONSTRUCTABILITY ATTRIBUTES									
10	%	Cost Effectiveness (EAC)	5	4	×	0.10	=	0.50	0.40
5	%	Availability of Quality Contractors	4	3	×	0.05	=	0.20	0.15
10	%	Availability of Quality Materials	3	2	×	0.10	=	0.30	0.20
5	%	Weather Limits	3	4	×	0.05	=	0.15	0.20
CUSTOMER SATISFACTION ATTRIBUTES									
20	%	Traffic Disruption	1	5	×	0.20	=	0.20	1.00
5	%	Noise	1	4	×	0.05	=	0.05	0.15
10	%	Surface Friction	5	3	×	0.10	=	0.50	0.30
100	%					*Total*		*2.90*	*3.55*

RATING FACTOR: PERCENT OF IMPACT ON TREATMENT DECISION (total must = 100%)
SCORING FACTOR: 5 = Very important
4 = Important
3 = Some importance
2 = Little importance
1 = Not important

Figure 6: Example Ratings Evaluation Worksheet

Chip Seal Vs. Microsurfacing (6)

3.0 REFERENCES

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Disclaimer
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CHAPTER 3 CRACK SEALING, CRACK FILLING & JOINT SEALING OF FLEXIBLE & RIGID PAVEMENTS

1.0 INTRODUCTION

Cracking in pavements occurs when a stress is built up in a surface layer that exceeds the tensile or shear strength of the pavement causing a fissure or crack to open. Crack sealing and crack filling are methods which can be used to repair these cracks in pavement surfaces. The cause of the crack and its activity play a dominant role in determining the success of crack sealing or filling operations.

This chapter addresses crack sealing and filling techniques associated with flexible hot mix asphalt (HMA) pavements and joint and crack sealing of rigid portland cement concrete (PCC) pavement systems. The reader is advised to pay close attention to the type of pavement system being addressed, as treatment techniques can vary.

1.1 TYPES OF CRACKS

Cracking may be associated with various distress mechanisms. Crack types include: fatigue cracks, longitudinal cracks, transverse cracks, block cracks, reflective cracks, edge cracks, slippage cracks, and joints in PCC pavements (1). Each crack type is discussed below:

1.1.1 Flexible (AC) Pavements

Fatigue Cracking: These cracks form a pattern similar to an alligator's skin as illustrated in Figure 1. They are the result of repetitive traffic loads or high deflections often due to wet bases or sub grades. This type of cracking can also lead to potholes and pavement disintegration. Neither crack sealing or filling can treat this type of failure. Alligator cracking can be preceded by longitudinal cracking in the wheel paths. Caltrans refers to longitudinal cracking in the wheel path as Alligator A and multiple interconnected cracks in the wheel path as Alligator B cracking. Alligator C cracking is multiple interconnected cracking across the entire roadway.

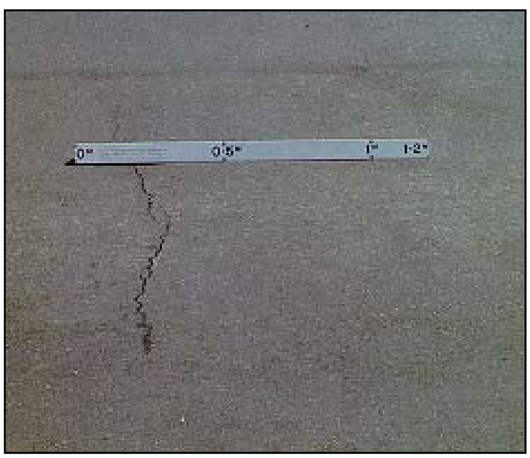
Longitudinal Cracks: These cracks run longitudinally along the pavement, as shown in Figure 2, and are caused by thermal stress and/or traffic loadings. They occur frequently at joints between adjacent travel lanes or between a travel lane and the shoulder, where hot mix density is lower and voids are higher. Longitudinal cracking may be associated with raveling and poor adhesion or stripping. These cracks can be effectively treated with crack sealants.

Figure 1: Fatigue Cracking

Figure 2: Longitudinal Cracking

Transverse Cracks: These cracks occur perpendicular to the centerline of the pavement, or laydown direction, as shown in Figure 3. Transverse cracks are generally caused by thermally induced shrinkage at low temperatures. When the tensile stress due to shrinkage exceeds the tensile strength of the HMA pavement surface, cracks occur. These cracks can be effectively treated with crack sealants.

Block Cracking: These cracks form regular blocks (Figure 4) and are the result of age hardening of the asphalt coupled with shrinkage during cold weather. They can be effectively treated with crack sealants.



(Direction of Travel →)
Figure 3: Transverse Cracking

Figure 4: Block Cracking

Reflection Cracking: Reflection cracks are caused by cracks, or other discontinuities, in an underlying pavement surface that propagate up through an overlay due to movement at the crack. They exhibit any of the crack patterns mentioned and must be treated according to the original distress mechanism. Figure 5 illustrates reflection cracking in asphalt concrete over portland cement concrete

Edge Cracking: These are crescent-shaped or fairly continuous cracks intersecting the pavement edge and are located within 0.6 m (2 ft) of the pavement edge, adjacent to an unpaved shoulder. They include longitudinal cracks outside of the wheel path and within 0.6 m (2 ft) of the pavement edge (2). Figure 6 illustrates edge cracking. Edge cracks are caused by overloading at the edge of the pavement, shear failure or erosion in the shoulder. This type of cracking cannot always be effectively treated with crack sealants.

Slippage Cracks: These cracks produce a characteristic crescent shape, as shown in Figure 7, and are caused when the top layer of the asphalt shears, often due to high deflections and a poor bond between the layers. This type of cracking cannot be effectively treated with crack sealants.

Figure 5: Reflection Cracking

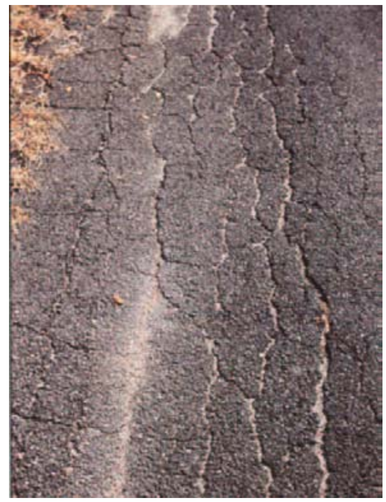


Figure 6: Edge Cracking

Figure 7: Slippage Cracking

1.1.2 Rigid (PCC) Pavements

Joints: Joints in rigid pavements are designed and constructed to permit expansion and contraction of rigid pavements so as to prevent cracking of the slabs between the joints. Typically they are constructed by sawing the concrete shortly after placement of the concrete. Joints may be transverse or longitudinal and are normally sealed during construction and resealed as needed throughout the life of the pavement. Joints are generally straight with vertical cut faces.

Cracks: Cracks in rigid pavements are generally load associated, or due to excessive thermal movement that is not adequately controlled by the joint system. Cracks may be transverse, longitudinal, or angled, especially at slab corners.

1.2 PROJECT SELECTION

Crack sealing and or crack filling may be an option for either surface preparation or surface sealing of a cracked PCC or HMA pavement. Projects are selected on the following criteria:

- The base should be sound.
- Cracks are only sealed or filled when greater than 3mm (0.1 inches) or up to 25mm (1 inch).

1.3 PROJECT PLANNING

Ideally, crack-sealing treatments should be applied when the crack width is at its midpoint to widest, usually in the spring, fall, or winter (i.e., during moderately cold weather conditions). Weather conditions during the time planned for installation need to be appropriate, not too cold or wet. Since non-working cracks do not change in width significantly with temperature, application of crack filling treatments can proceed at any time of the year when weather conditions are appropriate. Traffic passing over a hot applied sealed or filled crack is usually not an issue; however, traffic control during the application of the treatment should be in force long enough to allow for adequate curing of the product and prevent tracking. Sand is typically needed for cold applied systems to prevent tracking. Planning considerations will vary according to the treatment method chosen, for example cold pour materials require different handling than hot pour. Provision must be made to preheat the hot pour before work may commence but cold pour may be used immediately.

1.4 WHETHER TO SEAL OR FILL

The first question to be answered is whether to seal or fill a crack. Cracks may open and close horizontally with temperature and moisture changes and may undergo vertical movements as the result of load applications. Figures 8 and 9 illustrate these mechanisms of crack movement.

In order to determine whether to seal or fill a crack, it must be established whether the crack is working or non-working and whether the crack undergoes horizontal or vertical movement. The total horizontal movement of a crack over the period of one year is the primary determining factor of whether a crack is a working or non-working crack. The Caltrans criteria for a working crack is ≥ 6 mm (1/4 in) of horizontal movement annually (1); FHWA requires only 3 mm (1/8 in) (4). Vertical movement is not usually considered (4). Additionally, the width of the crack plays a role in deciding whether it is a working or non-working crack. Crack sealing is usually triggered when the crack width exceeds 6 mm (1/4 in). Also, the type of the crack can provide an indication of whether it is a working crack or not. Working cracks can be transverse or longitudinal to the pavement, but are most often transverse. Working cracks with limited edge deterioration should be sealed, rather than filled.

When the criteria for working cracks is not met, or when cracks are closely spaced and have little movement, crack filling is less expensive (4). The criteria for deciding whether to seal or fill a crack are listed in Table 1.

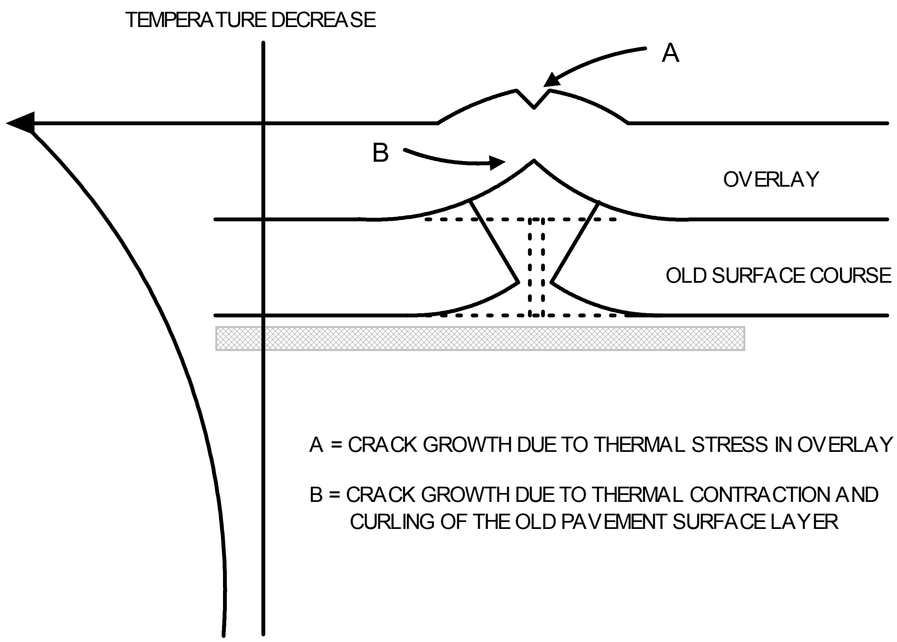


Figure 8: Thermal Effects on Crack Growth (3)

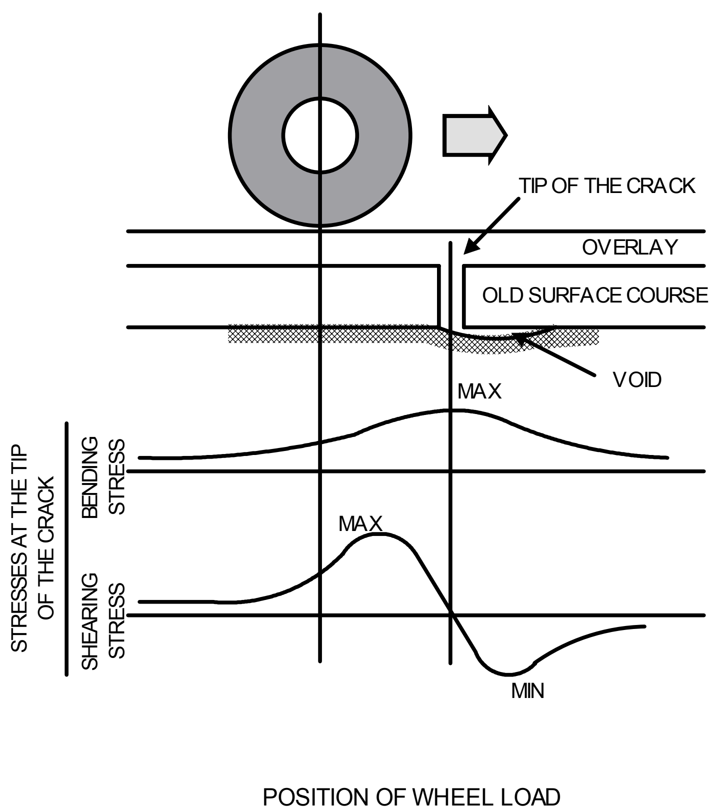


Figure 9: Traffic Load Effects on Crack Growth (3)

Table 1: FHWA Criteria for Crack Sealing or Filling (4)

CRACK CHARACTERISTICS	CRACK TREATMENT ACTIVITY	
	CRACK SEALING	CRACK FILLING
Width	3-25 (mm)	3-25 (mm)
Edge Deterioration	Minimal to None (<25% of crack length)	Moderate to None (<50% of crack length)
Annual Horizontal Movement	≥ 3mm	< 3mm
Type of Crack	Transverse Thermal Cracks Transverse Reflective Cracks Longitudinal Reflective Cracks Longitudinal Cold Joint Cracks	Longitudinal Reflective Cracks Longitudinal Cold Joint Cracks Longitudinal Edge Cracks Distantly Spaced Block Cracks

1.4.1 Crack Sealing

Crack sealing and filling prevent the intrusion of water and incompressible materials into cracks. The methods vary in the amount of crack preparation required and the types of sealant materials that are used.

Crack sealing is the placement of materials into working cracks. Crack sealing requires thorough crack preparation and often requires the use of specialized high quality materials placed either into or above working cracks to prevent the intrusion of water and incompressible materials. Crack sealing is generally considered to be a longer-term treatment than crack filling.

Due to the moving nature of working cracks a suitable crack sealant must be capable of:

- Remaining adhered to the walls of the crack,
- Elongating to the maximum opening of the crack and recovering to the original dimensions without rupture,
- Expanding and contracting over a range of service temperatures without rupture or delamination from the crack walls, and
- Resisting abrasion and damage caused by traffic.

Section 2.1 discusses material requirements in further detail.

1.4.2 Crack Filling

Crack filling is the placement of materials into nonworking or low movement cracks to reduce infiltration of water and incompressible materials into the crack. Filling typically involves less crack preparation than sealing and performance requirements may be lower for the filler materials. Filling is often considered a short-term treatment to help hold the pavement together between major maintenance operations or until a scheduled rehabilitation activity.

Crack filling is for active or non-active cracks created by ageing of the binder. Such cracks are not completely inactive and require some flexible characteristics. A suitable filler material must be capable of:

- Remaining attached to the walls of the crack,
- Possessing some elasticity, and
- Resisting abrasion and damage caused by traffic.

Section 2.1 discusses material requirements in further detail.

1.5 TREATMENT PERFORMANCE

The performance life of a treatment is affected based on the amount of crack preparation and the type of material used (4). It has been found that depending on the amount of preparation and material selection, crack sealants can provide up to 9 years of service and fillers up to 8 years of service (4). In California, overbanded treatments have contributed to poor ride, ride noise and poor surface appearance and are not recommended for use unless it has been squeegeed flush to the surface of the road. It should not be placed more than 12.5mm (1/2 inch) wider than the width of the crack (on both sides of the crack).

Emulsions or asphalt materials placed in a flush configuration in unrouted cracks (see Section 2.4) can provide 2 to 4 years of service while hot applied rubber and fiber modified asphalt fillers placed in flush or overbanded configurations (Section 2.4) can provide 6 to 8 years of service (4).

Several methods exist for evaluating a treatment's performance. One method is based on determining a treatment's effectiveness. Treatment effectiveness is the success of the treatment measured as a percentage of the total treatment that has not failed (4). In order to determine the condition of a treatment, visual inspections of the treated areas are required. Inspections for treatment failure should be carried out once per year (4).

1.5.1 Treatment Failures

Treatment failures can be attributed to improper treatment selection, improper material selection, poor workmanship, and improper application or lack of post-treatments. Common treatment failures include:

- **Adhesion loss:** The sealant does not adhere to the sides or bottom of the crack.
- **Cohesion loss:** The sealant fails in tension by tearing.
- **Potholes:** The crack is not completely sealed, allowing water into the pavement. Continued deterioration leads to pumping and pothole formation.
- **Spalls:** The edges of the crack break away as a result of poor routing or sawing.
- **Pull-on:** The sealant is pulled out of the crack by tire action.

1.5.2 Treatment Effectiveness

The firs step in determining a treatment's effectiveness is establishing how much of the treatment has failed in relation to the total length of treatment applied (% failure). Once the amount of treatment failure is determined, the treatment's effectiveness can be calculated using the following expression (4).

Effectiveness = 100 - % failure…………….…………………………(2.1)
Where: % Failure = 100 X [Length of Failed Treatment / Total Length of Treatment]

By routinely monitoring treated areas, a graphical representation of a treatments' effectiveness can be generated like the one shown in Figure 10. From this figure, the projected life of the treatment used on this cracked area can be projected as the time at which the effectiveness has dropped to 50% (as defined above). Graphs like these can be used to determine when additional treatments may become necessary (4).

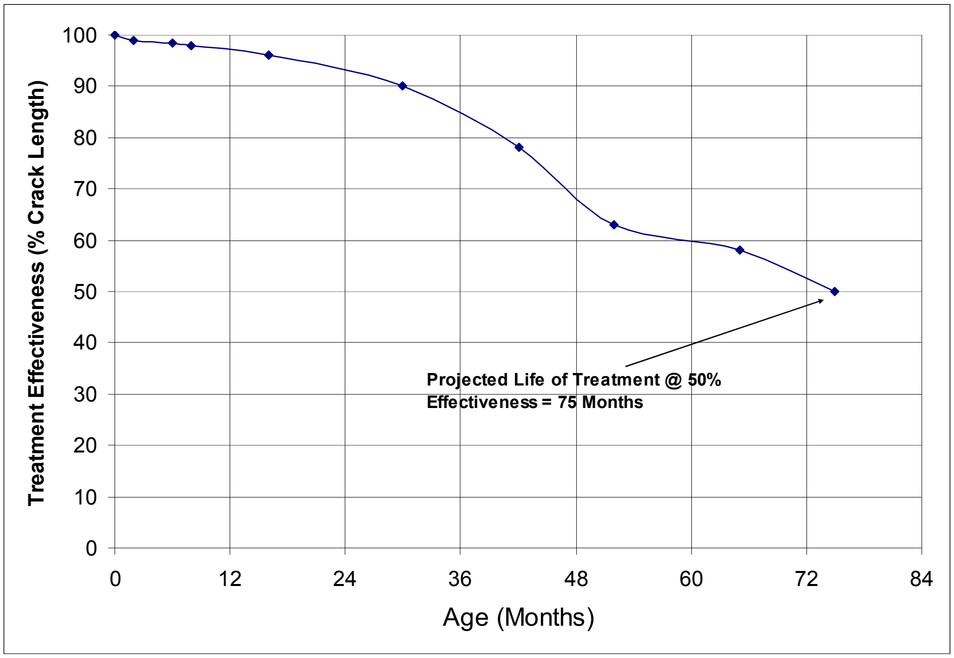


Figure 10: Treatment Effectiveness (4)

1.5.3 Cost Effectiveness

The cost effectiveness of a treatment can be determined readily once the treatment effectiveness has been determined. Cost effectiveness is the total cost of a treatment divided by its effectiveness. Cost effectiveness may be converted into an annual cost by dividing the cost effectiveness by the number of years required to reach 50% effectiveness.

2.0 MATERIALS

Crack sealing and filling material specifications for Caltrans fall under SSP 37-400 (7), 41-200 (8), 51-740 (9) and Standard Specifications Section 94 (10). The materials and methods discussed below apply to HMA pavements unless specified otherwise.

2.1 MATERIALS

2.1.1 Materials for Crack Sealing

Crack sealing materials are designed to adhere to the walls of the crack, stretch with the movement of the crack over the range of conditions and loads associated with the crack location, and resist abrasion and damage caused by traffic. For sealing working cracks, the preferred sealant is usually elastomeric. This means the sealant has a low modulus of elasticity and will stretch easily and to high elongations (usually around 10 times its non strained dimensions) without fracture. Such sealants also recover over time to close to their original dimensions. The sealants are usually applied at elevated temperatures due to their high viscosity at ambient temperatures and they set or cure by cooling and reforming into complex structures. This is called thermoplastic. Thermoset is sometimes used to describe these materials, however this is incorrect. A thermoset is a material that undergoes a chemical cross-linking when heated. This structure is retained as it cools and is not reversible by reheating. Thermoplastics form physical structures on cooling but this process is reversible with reheating. Hot application ensures good adhesive bond to the crack walls. In California most of the hot pour materials are rubber-modified asphalt. These materials have excellent abrasion resistance and are useful for trafficked surfaces.

Cold pour materials for crack sealing in California are usually silicone based and often used prior to paving. These materials cure either by exposure to moisture in the air or by mixing a hardening agent with the base silicone. These materials often have poor abrasion resistance and should not be used in trafficked areas. Other materials such as epoxies and polyurethanes are almost always cured by addition of a second chemical.

2.1.2 Materials for Crack Filling

For crack filling applications, the cracks are basically inactive (non-working). Crack filling materials are designed to adhere to the walls of the crack, and resist abrasion and damage caused by traffic.

Crack filling materials may be hot applied rubber or polymer asphalts, or cold applied emulsion-based products. The emulsion products assist with forming a good adhesive bond with the crack wall and additives such as Styrene Butadiene Rubber (SBR) latex ensure that the material can endure some degree of movement. In some cases, hot applied fiber modified asphalt binders may be used.

Table 2 lists Caltrans and AASHTO specifications for various crack sealants and fillers. In addition, it provides approximate costs and service lives of these materials.

Table 2: Crack Sealer and Filler Specifications

Material	Specifications (CT/ AASHTO)	Application Type	Approx. Costs ($/kg)	Approx. Life (Years)
Asphalt Emulsion	CT section 94/ M140, M208	Filling	0.15-0.30	2-4
Asphalt Cements	CT section 94/ M20, M226	Filling	0.03-0.15	2-4
Fiber Modified Asphalt	No Specification	Filling	0.35-0.60	6-8
Polymer Modified Emulsion (PME)	CT section 94/ M140, M208	Filling (minor sealing)	0.80-1.20	3-5
Asphalt Rubber (AR)	CT SSP 37-400	Sealing	0.45-0.60	6-8
Specialty AR Low Modulus	CT SSP 37-400	Sealing	0.75-1.40	5-9
Silicone	CT SSP 41-200, SSP 51-740	Sealing	5.75-6.75	4-6

2.2 STORAGE AND HANDLING OF MATERIALS

Chapter 1 of this manual identifies procedures for material storage and handling. In all cases, the manufacturer's recommendations for storage and handling should be closely followed.

Hot pour materials require very high temperatures, typically between 188 to 200°C (370 to 390°F) (4). These materials may degrade or cross link when exposed to excessive temperatures for long periods of time. For this reason, the manufacturer's recommendations must be followed exactly.

2.3 MATERIAL PLACEMENT METHODS

Once a suitable seal or fill material has been selected, as set forth in Caltrans Standard Special Provisions SSP 37-400 (7), the appropriate placement method must be determined. Placement methods vary according to the nature of the distress. When selecting the placement method, one should consider the method's applicability to: 1) the type of distress, 2) the dimensions of the crack channel, 3) the type of crack channel (cut or uncut), and 4) the finish requirements. Each method carries its own set of job equipment and preparation requirements. Placement methods include:

- Flush Fill
- Overband
- Reservoir
- Combination: Reservoir w/Band-Aid
- Combination: Sand Fill w/ Recessed Finish
- Backer Rod

2.3.1 Flush Fill Method

In the flush fill method, fill material is forced into an existing uncut crack. Once filled, the crack is struck off flush with the pavement. Figure 11 illustrates the flush fill method.

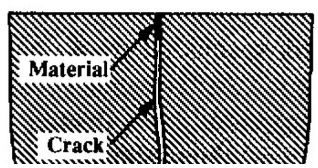
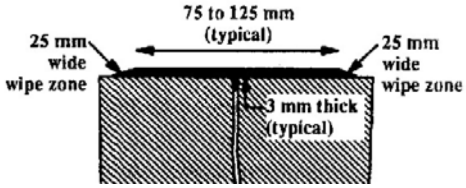


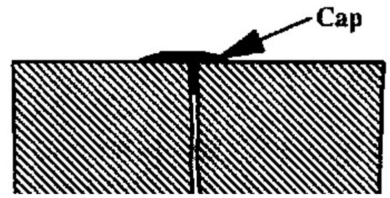
Figure 11: Flush Fill Method (4)

2.3.2 Overband Method

In the overband method, fill material is forced into and placed over an uncut crack. If the fill material is squeegeed flat, it is referred to as a 'Band-Aid'; if not; it is referred to as capped. Overbanding and capping should not be done if silicone has been chosen as the fill material. This is due to silicone's poor abrasion resistance. Figure 12 illustrates the overband method with both finishing options.



a) Simple Band-Aid



b) Capped

Figure 12: Overband Method (4)

Caltrans does not recommend this practice and advises that all crack sealing and filling be squeegeed if material is left above the surface. Overbanding can create a rough ride and/or excess road noise and causes problems when placing subsequent overlays.

2.3.3 Reservoir Method

In the reservoir method, the crack is cut or routed to form a reservoir that is filled with a sealant. The sealant may be left flush or slightly below the surface of the reservoir. The depth and width of the reservoir varies according to job requirements. Saw depths will be greatest when working with very active cracks and cracks in PCC pavements. Crack cutting will often depend on the number of cracks and whether the cutter can follow the shape of the crack. Typical reservoir widths range from 12 to 25 mm (0.5 to 1.0 in), and even up to 38 mm (1.5 in) in very cold climates. Reservoir depth ranges from 12 to 25 mm (0.5 to 1.0 in). Reservoir use is appropriate for pavements in good condition, without extensive cracking amounts. Crack cutting units, when operated by trained, experienced personnel, can follow meandering random cracks. Figure 13 illustrates the reservoir method.

2.3.4 Combination Method: Reservoir with Band-Aid

This combination method involves the formation of a 'Band-Aid' over the top of a cut reservoir. Figure 14 illustrates the combination method. Like the overband method, the combination method should not be used with materials that are prone to pickup due to traffic or materials with poor wearing characteristics (4). The combination method can be used on heavily trafficked roads, but care must be taken to squeegee excess material off the surface.

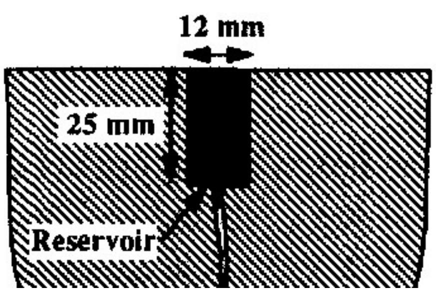


Figure 13: Reservoir Fill Method with Flush Finish (4)

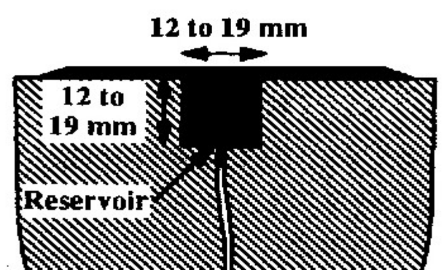


Figure 14: Combination Fill Method (4)

2.3.5 Combination Method: Sand Fill with Recessed Finish

Thermal cracking can develop over time and penetrate the full depth of asphalt pavement in a roadway. As thermal cracks progress down through the asphalt layers, they typically continue to widen and it is not unusual for such cracks to be 12 to 25 mm (0.5 to 1 in) or wider and exceed 102 mm (4 in) in depth. If these types of cracks are sealed or filled full depth, the large volumes of filler or sealer tend to soften and migrate under loads in hot weather, and begin to pull out under traffic. If an overlay is applied, the heat of the new mat will draw the filler and sealer materials up through the overlay. In areas with heavy sealer or filler applications, fat spots, flushing, and shoving in the overlay can occur. These symptoms can only be remedied by changes in construction procedures or the removal and replacement of the affected materials.

Sealant application should not exceed 25 mm (1 in) in depth. For full depth wide cracks, backer rod can be used to limit sealant depth. Another method that can be used is to partially fill the crack with sand. Blow out any debris with air, fill the crack with clean sand to a point approximately 19 to 25 mm (0.75 to 1 in) below the adjacent pavement surface, and tamp lightly as needed with a steel rod or piece of rebar to reduce any large voids in the sand. Then apply the crack sealer over the top of the sand and along the crack faces, the surface of the sealant should be cupped slightly below the adjacent pavement surface. This recessed finish allows some movement of the crack and sealer material without creating an undesirable hump on the surface. This fills and seals the deep wide crack while limiting the impact on subsequent paving operations. Figure 15 illustrates this combination method.

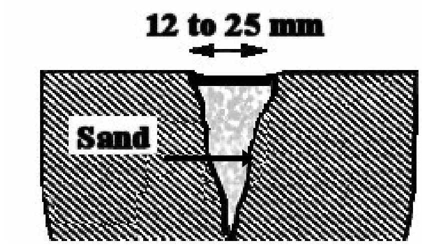
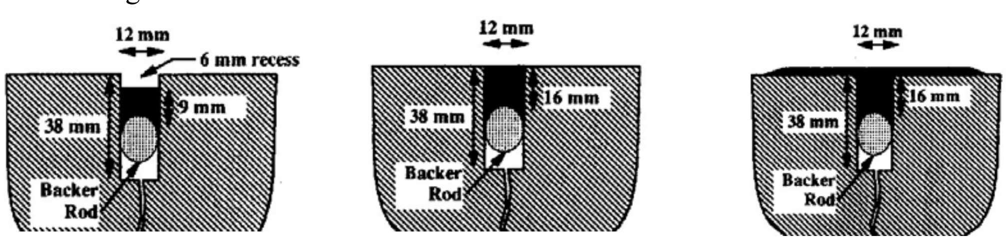


Figure 15: Combination: Sand Fill with Recessed Finish

2.3.6 Backer Rod (PCC Pavements)

Joint sealing applications for PCC pavements may require the incorporation of a backer rod or bond breaker. The backer rod, typically polyethylene foam, is placed within a crack or joint to prevent the sealant from sticking to the reservoir bottom and to restrict the sealant depth to the upper portion of the joint. A backer rod is also incorporated in very large cracks or joints and when silicone is being used. Currently, Caltrans does not use self-leveling silicones. A backer rod is only used if it is cost effective and the cracks are relatively straight like those occurring in PCC joints. Figure 16 shows three typical backer rod configurations.



a) Recessed Finish **b) Flushed Finish** **c) Capped Finish**

Figure 16: Three Common Backer Rod Configurations (4)

2.4 SELECTING THE APPROPRIATE PLACEMENT METHOD

The appropriate placement method should be based on the governing considerations of the project. Governing project considerations include:

- Type and extent of the sealing or filling operation,
- Traffic conditions,
- Crack characteristics,
- Material requirements,
- Desired performance (expectations),
- Aesthetics, and
- Cost.

Table 3 outlines method placement issues in relation to governing project considerations.

Table 3: Placement Method Considerations (4)

Project Consideration	Method Applicability
Type and Extent of Operation	Most filling operations, and some sealing operations, omit crack cutting operation. However, many northern States have found crack cutting necessary and desirable for cracks exhibiting significant movements.
Traffic	Overband configurations experience wear and, subsequently, high tensile stresses directly above the crack edges, leading to adhesive edge separations. Thus, overband configurations should be avoided for sealing cracks on heavily trafficked roads.
Crack Characteristics	Overband configurations are appropriate for cracks having a considerable amount of edge deterioration (> 10 percent of crack length); because the overband simultaneously fills and covers the deteriorated segments in the same pass. Reservoir methods without overbanding should not be used on cracks with edge deterioration.
Material Type	Materials such as emulsion, asphalt cement, and silicone must be placed unexposed to traffic due to serious tracking or abrasion problems.
Desired Performance	For long-term sealant performance flush reservoir, and recessed band-aid configurations provide the longest life.*
Aesthetics	Overband and combination configurations detract from the general appearance of the pavement.
Cost	Omission of crack cutting operation reduces equipment and labor costs but may decrease treatment longevity. Combination configurations require significantly more material than reservoir configurations, resulting in higher costs. The placement method impacts the type of material to use as well so costs may be higher for specialty materials (see Table 2).

** Ride Quality is an important consideration*

3.0 CONSTRUCTION

3.1 SAFETY AND CONTROL

The Resident Engineer (RE) can examine and approve the contractor's traffic control plan prepared in accordance with the Caltrans Safety Manual (11) and the Caltrans Code of Safe Operating Practices (12). The signs and devices used must match the traffic control plan. The work zone must conform to Caltrans practice and requirements set forth in the Caltrans Safety Manual and the Caltrans Code of Safe Operating Practices. All workers must have all required safety equipment and clothing. Signage shall be removed when it no longer applies.

3.2 EQUIPMENT REQUIREMENTS

Equipment requirements vary according to the treatment method chosen. Equipment may be required for:

- Routing or Sawing,
- Crack Cleaning and Drying,
- Backer Rod Placement (PCC Pavements),
- Application of Sealer or Filler,
- Finishing Method, and
- Trafficking and Subsequent Treatments.

Equipment requirements are covered in more detail in Sections 3.4 through 3.7 of this chapter.

3.3 CLIMATIC CONDITIONS

Crack sealing treatments should be placed when the cracks are at their midpoint to maximum point of expansion. This is not always practical since cracks are at their maximum point of expansion during the coldest months. Most crack fillers and sealants have limitations to their ability to wet and form films at low temperatures. This is due to either a high viscosity or the fact that they are emulsified. Additionally, winter climates make working conditions difficult and in some regions impossible. Bearing these considerations in mind, the fall is typically the best time for application. At this time air temperature are typically between 7°C and 18°C (45 to 65°F) in most parts of California. Under these conditions, cracks are usually at or near their mid-point of movement, which helps to ensure that the crack sealant or filler will not be extended or compressed too much when temperatures increase or decrease, respectively, following application of the sealant or filler. In addition, application during the fall (i.e., at moderate temperatures) ensures that temperatures have not dropped to a point where sealants will have difficulty wetting the crack walls or forming continuous films. In colder climate areas, spring and fall work conditions are required to allow workers to properly prepare the pavement surface and install products.

3.4 PREPARATION

Site preparation requirements vary according to the sealing or filling method and materials chosen for the project. The following paragraphs describe site preparation in further detail.

3.4.1 Routing or Sawing

When routing or sawing is incorporated, cracks need to be cleaned and dried prior to application of the filler or sealant. When pavements are cracked extensively, routing or sawing of cracks may not be appropriate. Crack cutting becomes especially important in climates where crack movement is very high. Crack cutting allows more filler to be used and provides better control of the crack channel shape. Secondary cracks along the primary crack are not usually routed. Routing is generally not used in HMA or PCC pavements in California. Crack cutting and routing equipment includes vertical spindle routers, rotary impact routers, and random crack saws. Damage to the pavement should be kept to a minimum by clean cutting. The use of carbide bits improves the quality of cutting and typically produces clean reservoir cuts. Figure 17 illustrates a rotary impact router in use.

Figure 17: Crack Routing Operation

3.4.2 Cleaning and Drying

Debris left in a crack, resulting from sawing, routing, or pavement use will affect the adhesion of the sealant or filler. Debris also contaminates the sealing or filling material and reduces cohesion. Reduced adhesion or cohesion normally results in early failures. To avoid these contamination-related failures, sawed or routed cracks must be cleaned prior to being treated. Several cleaning methods can be used, including:

- Air blasting,
- Hot air blasting,
- Sand blasting, and
- Wire brushing.

Air blasting involves directing a concentrated stream of air into the crack or joint to blow it clean. Air blasting equipment is effective and efficient for cleaning cracks. Air blasting is not efficient for drying cracks. Should a crack require drying, hot air blasting should be used. Air pressure should be a minimum of 670 kPa (97 psi) with a flow of 0.07 m^3/s (2.5 ft^3/s). Air blasting equipment must be equipped with moisture and oil traps.

Hot air blasting is done using a hot compressed air heat lance. While cleaning and drying the crack, hot air blasting also promotes enhanced bonding associated with the crack edges being warmed. Care must be taken to ensure that the pavement is not overheated or heated for excessive periods of time as this will result in unnecessary hardening of the asphalt binder in the pavement adjacent to the crack.

Sand blasting involves directing a stream of sand entrained in compressed air into the crack. The abrasive nature of the sand cleans the crack or joint. Sandblasting, which is used for cleaning cracks in PCC pavements by many states, is an effective treatment. However, sandblasting is messy and typically requires a two-phase operation. The first operation is cleaning the joint surface; the second cleans the sand from the joint and its surroundings. On new PCC pavements, sand blasting is required to clean the surface prior to applying the sealant.

Wire brushing or brooming involves the use of a wire broom stock or stiff standard broom to brush out the crack or joint. Wire brushing can be an effective cleaning method. Wire brushing may be done manually or using power driven brushes. Figure 18 illustrates the manual crack cleaning method using a broom

3.4.3 Backer Rod (PCC Pavements)

Installation of a backer rod should be performed once a joint or crack channel has been cleaned. Installation of the backer rod into the channel is accomplished either by manual means or through the use of a specialized three-wheel tool. Two wheels ride on either side of the crack while the third rolls the backer rod into the crack channel. Figure 19 illustrates a backer rod installed in a crack channel.

3.4.4 Application of Sealer or Filler

The material selected will in part, determine the application method. Typically, asphalt emulsions are applied directly to the cracks. Hot applied rubber modified sealants, especially asphalt rubber, have excellent adhesion and do not require the application of a thin sand coating (blotter coat) prior to trafficking. Emulsions must be blotter coated prior to being trafficked. Emulsions may be applied via gravity feed devices, such as pour pots, or via pressure hoses. Some emulsions may require heating to achieve appropriate application viscosity. Hot applied rubberized sealants need to be agitated and heated and maintained at the correct temperature throughout their application. For polymer and rubber modified materials, control of temperature is important in preventing degradation. For hot applied fiber filled materials, the fiber may settle; therefore, agitation is required. For such materials indirect oil heating is recommended. Required capacity of sealant or filler application equipment is determined by the job size. Preheating the material before use is advisable to ensure productivity is optimized. Figure 20 illustrates a hot pressure feed sealing operation and a gravity fed pour pot.

The application rate of a sealant or filler plays an important role in the quality of a crack sealing or filling project. Problems associated with over applied sealer or filler material include fat spots, localized tenderness, and flushing when treated areas are overlaid with hot mix.

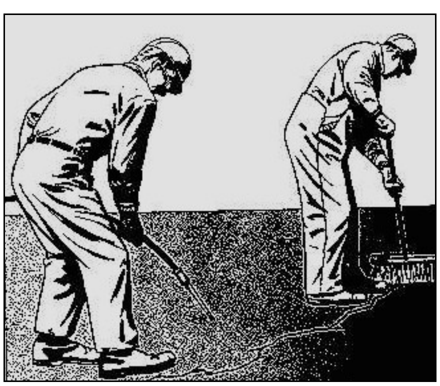


Figure 18: Manual Crack Cleaning

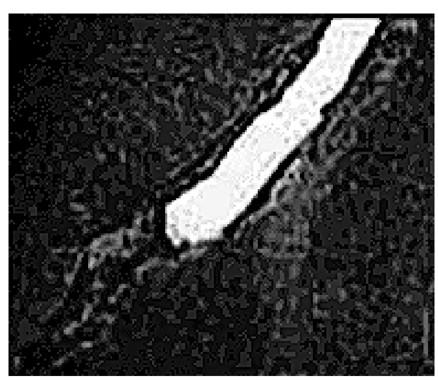


Figure 19: Backer Rod Installed Into Crack Channel

a) Hot Pressure Fed

b) Pour Pot

Figure 20: Application Techniques and Equipment

3.5 FINISHING

Finishing techniques will vary depending on the application and type of material chosen. Flush finishes and overbanding methods require the use of a squeegee. In some cases, a preformed plate on a hand lance assists in making the required flush result. Figure 21 shows three typical flat finishing techniques. As stated earlier, all sealant left on the surface shall be squeegeed to prevent a rough ride and is the only method recommended by Caltrans.

a) Squeegee

b) Flat Plate Use

c) Over Banding

Figure 21: Typical Flat Finishing Techniques

Blotter coats of clean sand are usually used with emulsion crack filling to prevent pick-up of an overband. A blotter coat is often used to prevent pick-up upon re-opening to traffic. To ensure a high quality blotter coat, only clean and dry sand should be used. Figure 22 illustrates the brooming of a blotter coat over a treated crack. This practice is not recommended by Caltrans as it leaves broom marks and voids in the sealant.

Figure 22: Brooming Blotter Coat Over a Treated Crack

3.6 TRAFFICKING AND SUBSEQUENT TREATMENTS

Sealants and fillers undergo a curing cycle depending on the type of material used. Emulsions cure by water loss and reduce in volume. This process usually takes several days and creates a concave surface in the crack. Generally, cracks filled with these materials should not be overlaid for at least a year. Trafficking should not be allowed until after the emulsion has set sufficiently so that tires passing over the sealant/filler won't pick it up. Caltrans normally sands the sealer prior to opening to traffic.

Hot applied materials are thermoplastic; they set when they cool provided no diluents, such as solvents, are used in their formulation. These materials produce a non-tacky finish once the material reaches ambient temperature. A blotter coat can assist in this process. In addition, hot applied sealants require a three to four month cure time prior to being covered with a blanket or seal. Hot applied materials should not be placed over cold mix patches. This hot applied material will pick up, pulling the patch out.

Silicone, along with two-part systems (used in PCC pavements), cure by cross-linking either due to ambient moisture or a two-part chemical reaction. When using these materials the manufacturers' recommendations must be followed. Overbanding and capping must not performed when using these materials and they should be applied such that they do not receive direct traffic. Sanding the fresh crack seal reduces safety concerns (slick pavements) and improves the surface appearance (aesthetics). Excess sand must be swept away before opening the road to traffic. Cold applied sealants require a one year cure time prior to being covered with a blanket or seal.

3.7 JOB REVIEW - QUALITY ISSUES

Quality issues are typically related to the poor choice of sealing and filling methods and poor workmanship. Common examples of poor sealing and filling methods include excessive use of sealant and multiple uses of treatments over several years. One common example of poor workmanship includes over-filling without proper finishing. Figures 23 through 25 illustrate these commonly addressed quality issues. These practices directly impact traffic safety, smoothness and appearance for users.

Figure 23: Excessive Sealant

Figure 24: Multiple Treatments

Figure 25: Poor Workmanship – Raised, Bumpy Sealing

4.0 TROUBLESHOOTING

This section provides information to assist the maintenance personnel with troubleshooting problems with crack sealing and crack filling projects. Appendix A discusses some field considerations to assist the development of successful jobs.

4.1 TROUBLE SHOOTING GUIDE

The troubleshooting guide presented in Table 4 associates common problems to their potential causes. For example, a sealant separating from the sides of a crack may be caused by application to a wet crack surface, dirty crack surface, poor material finishing technique, application of cold sealant, insufficient material, rain during the application, or application during cold weather. Appendix A lists field considerations to ensure a successful outcome.

Table 4: Trouble Shooting Crack Sealing and Filling Projects

	PROBLEM						
	ALL SEALS			EMULSION SEALS ONLY			
CAUSE	Tacky Picks Up	Re-Cracks Quickly	Bumpy Surface	Separation From Crack Sides	Emulsion Sealer Not Breaking	Emulsion Sealer Breaks Too Fast	Emulsion Sealer Washes Off
Crack Wet					●		●
Sealant Not Cured	●			●		●	
Crack Dirty	●	●		●		●	
Insufficient Sanding	●			●		●	
Poor Finish, Wrong Tools	●	●	●	●		●	
Sealant Too Cold		●	●				
Sealant Too Hot	●			●			
Application Too High	●		●	●			
Application Too Low		●	●				
Sealant Degraded Due to Overheating	●	●	●	●	●	●	●
Rain During Application					●		●
Cold Weather		●			●		
Hot Weather	●		●	●		●	

In addition to the troubleshooting guide, Table 5 lists some commonly encountered problems and their recommended solutions.

Table 5: Common Problems and Related Solutions

Problem	Solution
TRACKING	▪ Reduce the amount of sealant or filler being applied. ▪ For hot applied materials, allow to cool or use sand or other blotter. ▪ Allow sufficient time for emulsions to cure or use a sufficient amount of sand for a blotter coat. ▪ Ensure the sealer/filler is appropriate for the climate in which it is being placed.
PICK OUT OF SEALER	▪ Ensure cracks are clean and dry. ▪ Increase temperature of application. ▪ Use the correct sealant for the climate. ▪ Allow longer cure time before trafficking.
BUMPS	▪ Check squeegee and ensure it is leaving the correct flush finish. ▪ Have squeegee follow more closely to the application. ▪ Decrease the viscosity of the sealer. ▪ Change the rubber on the squeegee.

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APPENDIX A

SUGGESTED FIELD CONSIDERATIONS

The following field considerations are a guide to the important aspects of performing a crack sealing or crack filling project. The various tables list items that should be considered in order to promote a successful job outcome. As thoroughly as possible, the answers to these questions should be determined before, during, and after construction. The staff to do this work will vary by job type and size. Some topics may need attention from several staff members. The field supervisor should be acquainted with its contents. The intention of the tables is not to form a report, but to bring attention to important aspects and components of the project process. Some information is product specific and contained in the relevant standard specifications, special standard provisions, or special provisions.

PRELIMINARY CONSIDERATIONS	
PROJECT REVIEW	▪ Is the project a good candidate for crack sealing or filling? ▪ What type of cracking exists? How severe is it? How much is there? ▪ Are there base failures along the project? ▪ How much bleeding or flushing exists? ▪ Is the pavement raveling or oxidized? ▪ What is the traffic level? ▪ Is the base sound and well drained? ▪ Would a membrane (SAM, SAMI) treatment be a better solution? ▪ Review project for bid/plan quantities.
DOCUMENT REVIEW	▪ Crack activity (movement) information. ▪ Application specifications. ▪ Construction manual. ▪ Special provisions. ▪ Traffic control plan.
DETERMINING APPLICATION TYPE	▪ What type of application is being used? ▪ Are agency guidelines and requirements being followed? ▪ Are the cracks being sawn or routed? ▪ Is a bond beaker being used?
MATERIAL CHECKS	▪ Has a crack survey been done? ▪ Has the amount of filler/sealer material required been calculated for the number and length of cracks being treated? ▪ Has the sealer or filler been produced by an approved source? (if required) ▪ What is the application temperature and the safe heating temperature? ▪ What special handling requirements are needed: heating rate, allowable storage time at high temperatures, cold application? ▪ Has the sealer or filler to be used been sampled and submitted for testing? ▪ Is a blotter coat required? Is clean, dry sand available?

PRE-SEAL INSPECTION CONSIDERATIONS	
SURFACE PREPARATION	▪ Do the cracks need to be sawn or routed? ▪ Are secondary cracks to be sawn or routed? ▪ Have the cracks been cleaned? ▪ Have oily residues been scrubbed from the pavement? ▪ Has the surface been cleaned, dried, and broomed?
WEATHER REQUIREMENTS	▪ Air and surface temperatures have been checked at the coolest location on the project? ▪ Air and surface temperatures meet agency and sealant/filler manufacturer requirements. ▪ Application should not begin if rain is likely. ▪ Application should not begin if freezing temperatures are expected.
TRAFFIC CONTROL	▪ The signs and devices used match the traffic control plan. ▪ The work zone complies with Caltrans traffic control policies as described in the Caltrans Safety Manual (9). ▪ Flaggers do not hold the traffic for extended periods of time. ▪ Unsafe conditions, if any, are reported to a supervisor. ▪ Signs are removed or covered when they no longer apply.
EQUIPMENT INSPECTION AND CONSIDERATIONS	
SAWING/ ROUTING UNIT	▪ Is a saw or router to be used? ▪ Is the unit fully functional? ▪ Are the cutting bits sharp to avoid spalling or cracking? ▪ Are the cutting bits the correct size? ▪ Is all equipment free of leaks? (Hydraulic oil, diesel, motor oil etc.)
SEALING UNIT	▪ Is the sealing unit functional? ▪ Are the moisture and oil filters on the compressor clean and functioning? ▪ Does the unit have temperature control (for hot applied sealants)? Is the temperature controller working properly and is the measuring device calibrated? ▪ Does the sealing unit provide adequate pressure to deliver material to the crack at an appropriate rate? ▪ Is a pour pot being used? ▪ Is a kettle applicator being used? Is the kettle being kept at least partially full at all times? ▪ Is the applicator unit re-circulating during idle periods? ▪ What method is being used to ensure that the crack sealant or filler is flush with the pavement surface? ▪ Is all equipment free of leaks? (Hydraulic oil, diesel, motor oil etc.)

PROJECT INSPECTION CONSIDERATIONS	
CRACK SEALING OR FILLING APPLICATION	▪ Does the operator have safety gear appropriate for the job? ▪ Have the cracks been mapped? ▪ Does the cutting/routing follow the crack as closely as possible? ▪ Are cut dimensions satisfactory? ▪ Are the cracks dry at the time of sealing? ▪ Is there a backer rod? Is it properly installed; straight, not twisted or damaged? ▪ Is the backer rod placed to the specified depth? ▪ Is the backer rod compressed correctly in the crack channel? ▪ The sealing operation must follow directly behind the cutting/cleaning/drying operations? ▪ Sealant flows evenly with no surging? Vat to be kept at least part full at all times. ▪ Is the sealant at the correct application temperature? ▪ Check sealant temperature at nozzle using high temperature thermometer or infrared thermometer. ▪ Is the squeegee shape correct and not worn, clean and free of carbon or filler build up, operated at the correct distance from the crack, and centered on the crack? ▪ Sealant is even and consistent and has not been reheated more than the allowable number of times and for the recommended periods of time? ▪ Are there excessive bubbles in the material caused by water? ▪ Confirm that crack channel is filled from the bottom up and not overfilled. ▪ Does the application have an even and uniform finish, flush with the pavement surface? ▪ Reapply sealant to any areas that are under filled. ▪ The application is stopped as soon as any problems are detected. ▪ Check bond by peeling the filler or sealant. ▪ Do not traffic until the sealant or filler does not track under traffic.
CLEAN UP	▪ All material spills are cleaned up. ▪ All loose sand is removed from the traveled way.

Disclaimer
This chapter is 1 of 8 included in the Caltrans Maintenance Technical Advisory Guide (TAG). The information presented in this chapter is for educational purposes only. It does not represent a policy or specification nor does it endorse any of the products and/or processes discussed.

CHAPTER 4: PATCHING AND EDGE REPAIR

1.0 DESCRIPTION

Patching, one of the most expensive of the maintenance procedures for hot-mix asphalt (HMA) pavements, (per unit of measure, i.e. cost/ton, cost/in^2, cost/yd^2) and is often done in preparation for other forms of corrective maintenance, pavement preservation, or pre-treatment prior to an overlay. Patching restores the pavement surface to a state where other preservation treatments can be used with a good chance of success.

The primary methods of patching include the replacement of materials that have been lost due to localized pavement distress or disintegration, the complete removal (dig out) and replacement of continuous segments of failed pavement, or the application of a thin layer of HMA material over segments of pavement that exhibit more surface-related distress/distortion. Once patched, the distressed area is repaired or strengthened so that it can carry a significant traffic level with improved performance and lower rates of deterioration.

Patching may be temporary, semi-permanent, or permanent treatments. The appropriate method to be used depends on the traffic level, the time of the year during which the repair is carried out, the time until scheduled rehabilitation, and the availability of equipment and personnel.

Patching is best carried out during clear moderate weather. However, emergency repairs may require patching be performed during poor winter weather conditions. In these instances, the durability of the patch is likely to be poor and the patch should be considered to be temporary. Accordingly, it is a good strategy to plan for a more semi-permanent repair of these areas when moderate weather conditions prevail.

This chapter is divided into pothole patching, material dig out and replacement, edge repair, and surface reinstatement. The procedures and materials associated with each method are addressed in a similar fashion.

1.1 PATCHING

Patching is a process in which the material in a highly distressed area is either removed and replaced or additional material is added to cover up the distressed area. Merely filling a hole will not prevent the development of distress adjacent to or within the patch in many instances. Maximum performance is achieved when the boundaries of the distressed area are appropriately marked and cut, the failed material is removed, the remaining (underlying) material is recompacted, the hole is properly prepared, and new material is added and compacted to a level similar to that for a new pavement.

The primary methods used to perform pothole patching are:

- Temporary
- Semi-Permanent
- Injection Patching (Not yet widely used in California)

The primary materials used for pothole patching are:

- Hot-mix asphalt (HMA) - preferred
- Cold-mix asphalt – temporary fix only
- Aggregate / asphalt emulsion combinations (i.e., injection patching)
- Special patching mixtures

1.2 DIG OUTS

Dig outs are used when the pavement has failed in localized areas too such an extent that even the underlying support materials have disintegrated, become infiltrated with fine-grained materials, or otherwise lost their load-carrying capacity. Unlike typical patching, dig outs require the removal and replacement of much (if not all) of the underlying base/sub base materials. Due to the thorough nature of this method, it has sometimes been referred to as spot reconstruction.

The main steps associated with dig outs are:

- Marking and cutting of the boundaries.
- Breakup and removal of the pavement surface and affected base/sub base layers.
- Placement and compaction of new base/sub base layers.
- Application of tack coat along the edges of the repair area.
- Placement and compaction of new asphalt surface.

The main materials used for dig outs are:

- Hot-mix asphalt (HMA) - preferred
- Cold-mix asphalt – emergency fix only
- Granular base course – for remote areas or low volume roads

1.3 PAVEMENT EDGE REPAIRS

Edge repairs are used when the pavement has failed along the edges due to the action of traffic and the loss of edge support that occurs due to the presence of water, aggressive-growth vegetation, and wind from either traffic or the atmosphere. The main materials and methods used in edge repairs are the same as those associated with patching and dig outs.

1.4 SURFACE REINSTATEMENT

The main method used for surface reinstatement is skin patching. Skin patching does not require a dig out. Typically, either a thin layer of HMA or a cold mix blanket can be applied to the existing surface or a coat of spray binder (emulsion) is applied and covered with a layer of aggregate. Aggregate is either washed sand or fine aggregate [3 to 5 mm (0.1 to 0.2 in)] compatible with the emulsion being used. HMA skin patches are rolled with a light or hand roller, while spray-on patching is rolled using the maintenance truck wheels.

2.0 PROJECT SELECTION

2.1 POTHOLES

Potholes are a form of disintegration of the pavement that may be associated with poorly compacted material, raveling, cracking, base failure or aging of the pavement. Potholes often appear after rain or during thaw periods when pavements are weaker. The generally accepted mechanisms for pothole formation are as follows:

- Raveling, stripping, or cracking in the pavement surface.
- Water penetrates the surface layers of the pavement, softening the underlying pavement layers, which increases deflections. Figure 1 illustrates how water can penetrate a pavement.
- Ice formation and heaving in the pavement occurs in some climatic areas. Figure 2 illustrates heaving due to a freeze-thaw cycle in a cold climate.
- Fines from the underlying pavement layers are lost, reducing overall structural strength and support for the pavement surface. Figure 3 illustrates the resulting cavity when the fines are lost due to migration or pumping.
- Once a hole is formed, it will continue to grow until it is repaired. Figure 4 illustrates the role traffic plays in enlarging a pothole.

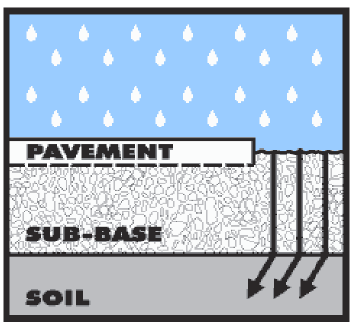


Figure 1: Water Penetration of Pavement (1)

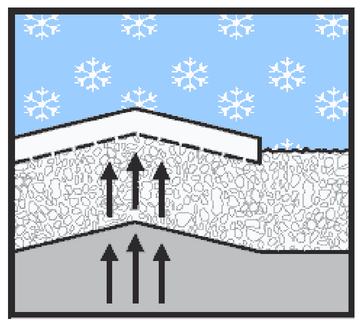


Figure 2: Heaving Effects Caused by the Freeze/Thaw Cycle (1)

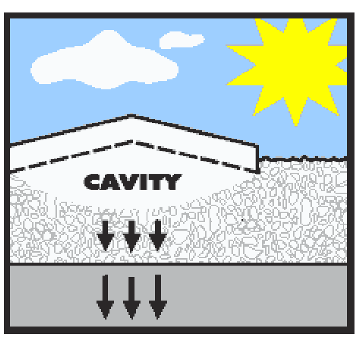


Figure 3: Loss of Fines Results in a Void Under the Pavement (1)

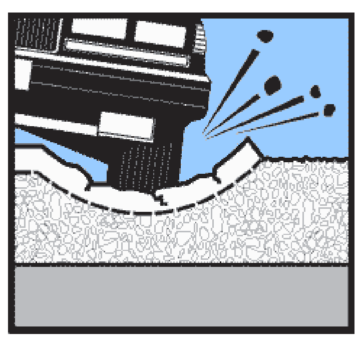


Figure 4: Once Formed, Traffic Enlarges Potholes (1)

2.2 EDGE FAILURE

Edge failures occur when the edge of a pavement breaks up. This failure is caused by traffic loading at the edge of the pavement (usually due to a horizontal geometry problem) and/or the infiltration of water at the edges of the pavement or shoulder. Although edge failures are usually out of the primary wheel paths, their presence can accelerate the normal deterioration of the pavement in the traveled way.

2.3 COSTS AND PERFORMANCE

The main costs associated with patching include:

- Labor
- Materials
- Equipment
- Traffic Delays

Cost effectiveness is determined by the patch survival rate. To determine the patch survival rate, repairs should be monitored for at least one year. Monitoring consists of checking for the presence of repairs and noting the survival or failure of each pavement section. Figure 5 shows typical survival rate curves, where A, B and C represent three separate patch locations. The area under the curve represents the patch survival rate.

Dig outs are generally carried out using larger equipment and are the most expensive method of patching. The effectiveness of dig outs is determined in the same manner as described for patching above.

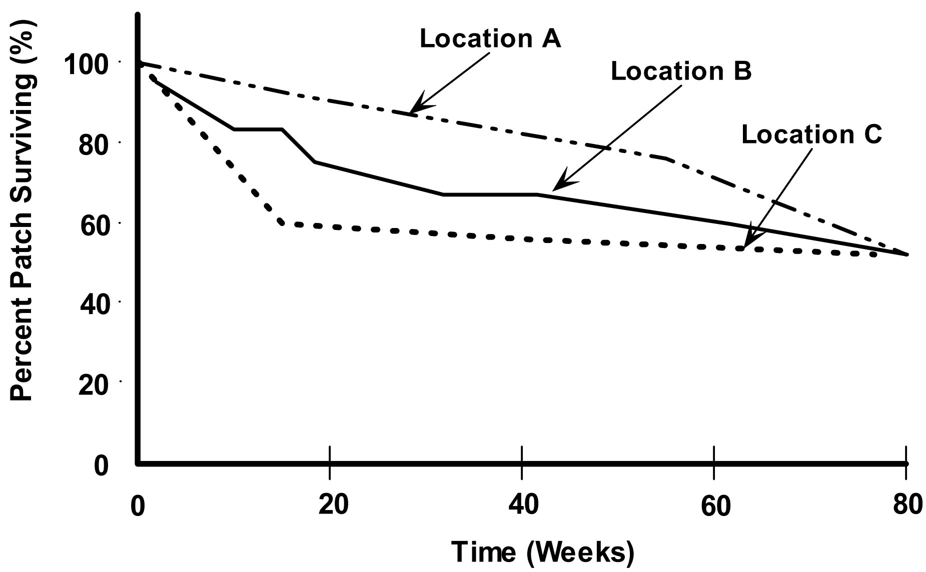


Figure 5: Typical Survival Rate Curves (2)

2.4 DESIGN AND SPECIFICATION

Patching design and specification is based on procedures of application and the use of appropriate materials. The materials should be tested according to the related specifications. Generally HMA materials are specified based on Caltrans Dense-Graded Asphalt Concrete (DGAC) specifications as presented in Standard Specifications Section 39 (3). However, the mix type used may vary according to traffic conditions.

Caltrans also uses cold-mixes for patching. These are generally proprietary products and should be handled according to the manufacturer's specifications.

3.0 CONSTRUCTION PROCEDURES

3.1 POTHOLE PATCHING

Construction procedures for pothole patching vary according to the method and materials selected. The three primary patching techniques along with edge sealing technique are described below. Appendix A, "Suggested Field Considerations", at the end of this chapter, provides a series of tables to guide project personnel through the important aspects of performing a patching or edge repair project.

3.1.1 Throw and Roll

The "throw and roll" method is often used for temporary patches. This is only appropriate when weather conditions are too poor for a semi-permanent patch to be placed or the road is due to be rehabilitated soon. It is the most inexpensive and least labor-intensive method for patching a pothole and includes the following steps. Figure 6 illustrates a typical throw and roll application.

- Patching material is placed into the hole, with or without cleaning and/or drying of the hole.
- The material is compacted using the maintenance truck tires.
- The finished patch should have 3 to 6 mm (1/8 to ¼ in) of crown to help avoid water ponding.
- Clean up is generally not required.

Figure 6: Throw and Roll Patching

3.1.2 Semi-Permanent Patches

Semi-permanent patching is considered to be an effective patching method (second only to complete removal and replacement of the failed area). The following steps describe how this form of patching is carried out:

- Mark the boundaries of the distressed area, taking care to encompass a slightly larger area than that reflected by the distress. The repair boundaries should be as rectangular as possible and take into consideration the dimensions of the equipment that will be used for removal of the old material and compaction of the new material.

- Cut the boundaries of the patch square using either a diamond saw or pneumatic hammer with a spade bit. In the case of the latter, care should be taken not to damage the HMA surface layer in the sound pavement.

- Remove water and debris from the hole. Figure 7 illustrates a hole that has been dewatered and cleaned of debris. Depending on the size of the pothole, this may be accomplished manually with a pick and shovel or with various combinations of power equipment, i.e., a pneumatic hammer and shovel, backhoe, or front-end loader. Cold milling equipment can also be very effective for this operation.

- Square up the sides of the hole until the edges of the hole are sound pavement. This step is usually very simple if the boundaries of the repair area were cut with a diamond saw or established with cold milling equipment. It is usually only required when manual techniques of material removal are employed. Figure 8 illustrates a hole that has been extended to sound pavement and firm supporting material. It is suggested that the depth of the patch be 50% thicker than the thickness of the failed layer.

- Apply a tack coat of asphalt emulsion to the sides and bottom of the hole at a rate of approximately 1 liter/m^2 (0.2 gal/yd^2) of slow or rapid setting emulsion. The tack coat should either be sprayed or brushed on the edges of the repair, never poured. Figure 9 illustrates the tack coat application.

- Place the patch material in the hole. If the patch is placed manually, use a shovel (*not a rake*) to place the HMA material taking care to avoid segregation. The hole should be overfilled by 20 to 25 percent of its depth to provide adequate material for compaction. An asphalt rake should be used to feather or blend the patch edges.

- Compact the patch material with a hand device or a small vibratory roller. It is preferable to use compaction equipment whose surface is smaller than the size of the patch. It is very difficult to achieve satisfactory compaction with equipment that bridges the repair area. Figure 10 illustrates the compaction of the patch material.

- The finished patch should have a 3 to 6 mm (0.1 to 0.2 in) crown. This allows for further compaction by traffic and helps prevent standing water in the patch area. Figure 11 illustrates the finished patch.

- The patched area should be seamed with crack sealant and fog sealed.

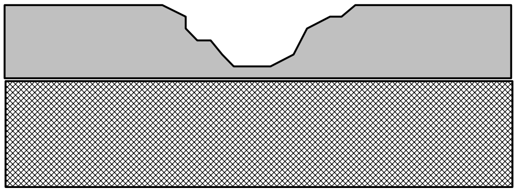


Figure 7: Dewatered and Cleaned Pothole (4)

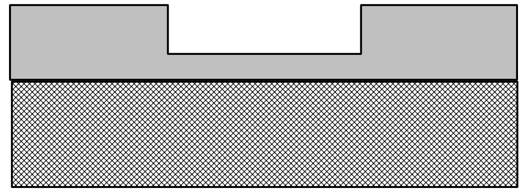


Figure 8: Surface and Base of Pothole Prepared for Treatment (4)

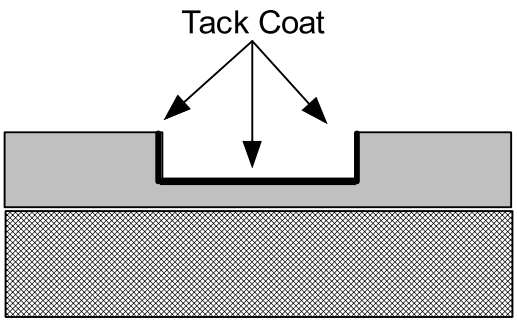


Figure 9: Tack Coat Applied to All Sides of Hole (4)

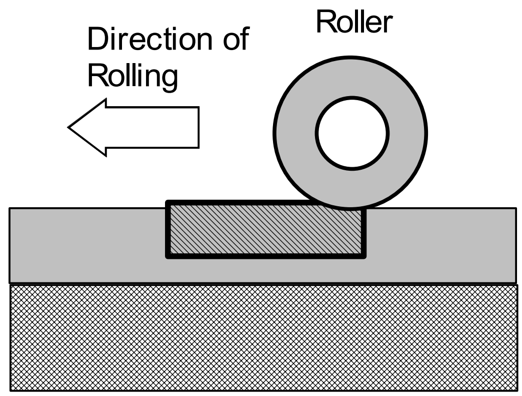


Figure 10: Patch Material Placed and Compaction in Progress (4)

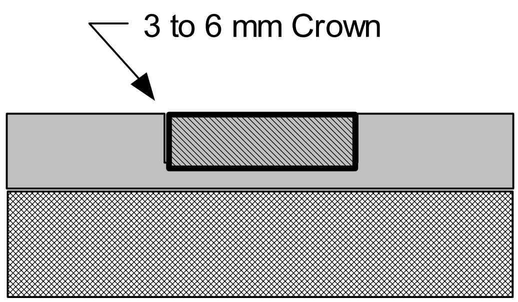


Figure 11: Finished Patch with a 3 to 6 mm Crown (4)

3.1.3 Injection Patching

Injection patching is a rapid and effective method of patching that requires specialized equipment. This method, not currently used by Caltrans, is used for lower trafficked roads and is an alternative to the throw and roll method. These patches are temporary, but generally have a longer life than throw and roll patches (5). The steps for injection patching are described below:

- Prepare the site for patching by blowing debris and water from the hole with the application nozzle. Figure 12 illustrates site preparation.
- Spray a tack coat of emulsion on the sides and bottom of the hole at a rate of approximately 1 liter/m^2 (0.2 gal/yd^2). Figure 13 illustrates the application of a tack coat.

- Blow asphalt/aggregate mixture into the hole, filling the hole to the top. Figure 14 illustrates filling the prepared hole.
- Finish with a layer of dry aggregate. Figure 15 illustrates the application of a finish coat to minimize pick up. Note: It is not necessary to roll a pothole patched using this method. This is one advantage to the injection method.

Figure 12: Site Preparation

Figure 13: Application of Tack Coat

Figure 14: Filling the Prepared Hole

Figure 15: Application of Finish Coat

3.1.4 Edge Sealing

To improve the durability of a patch, the edge of the patch should be sealed to prevent the intrusion of water and other debris. Edge sealing refers to the application of asphaltic material along the edges of a patch. Once set, this ensures that water cannot penetrate the patch seam. Sealing materials may be rubberized to allow for differential movement between the existing pavement material and the new patch material. Figure 16 illustrates a finished edge seal application.

Figure 16: Edge Seal Application

3.2 DIG OUTS AND EDGE REPAIRS

When the edge of the pavement has broken away or the base has failed due to severe alligator cracking, the complete removal (dig out) of failed asphalt and base materials is typically required. Dig out selection is important, as areas that fail due to alligator cracking will produce reflective cracks through new surface treatments if the distressed pavement is not replaced. When in doubt, a dig out should be performed.

3.2.1 Dig Outs

The typical dig out construction process is as follows:

- Mark the boundaries of the distressed area to be replaced. Strive for rectangular areas taking into consideration the dimensions of the equipment that will be used for removal of the failed material and compaction of the new material.
- Cut out the perimeter of the area with a diamond saw or cold milling machine.
- Break up and remove the failed pavement to the subgrade material using appropriate combinations of pneumatic hammers, backhoes, front-end loaders, and cold milling equipment.
- Clean and dry the dig out area.
- Place and compact new (virgin) base course material using appropriate combinations of front-end loaders and roller compaction equipment. The finished base course surface should typically be 25 mm (1 in) below the original base course surface. This provides for a thicker and more stable patch.
- Apply a tack coat of emulsion at a rate of approximately 1 liter/m^2 (0.2 gal/yd^2) to the sides of the repair area. Tack may also be placed along the bottom of the repair area if local experience indicates good performance. Place the patch material in the prepared dig out area.
- Generally larger aggregates 12 to 19 mm (1/2 to ¾ in) are used for dig outs because of their thickness. Place the patch material in the prepared dig out area. *Note: HMA is typically used as the patch material (AR-4000 with 9mm aggregate. AR-8000 should be used if the area has a history of pushing or shoving.).*
- The patch material is typically placed in lifts if the depth of the repair is greater than 100 mm (4 in). The thickness of any lift should not exceed 100 mm (4 in). The final lift should be made using enough material that 3 to 4 roller passes are required to roll the patch flush with the old pavement.

- Compact each lift using equipment similar to that typically used in hot-mix asphalt compaction operations. The width of the compaction equipment should be narrow enough to fit within the repair area. Equipment that bridges the repair area is less likely to achieve adequate compaction of the HMA material (Note: Caltrans allows wheel rolling in all lifts except the top lift).
- The finished patched area should have a crown of 3 to 6 mm (1/8 to ¼ in).

Figure 17 illustrates a completed dig out project. Before the new pavement is open to traffic, it is recommended that the edges are seamed with crack sealant and the entire patch is fog sealed.

Figure 17: Dig Out Project

3.2.2 Edge Repair

The basic construction steps associated with a repair along the edge of the pavement depend upon the severity and depth of the deterioration. If the distress is confined mainly to the HMA surface, then the steps associated with a regular patching operation should be employed. If, on the other hand, the deterioration extends well below the surface, then the steps associated with a dig out are more appropriate. In both cases, the intent is to provide improved lateral support along the pavement's edge. Accordingly, extra precautions should be taken for achieving adequate compaction and maintaining good drainage at that interface with the shoulder.

3.3 SKIN PATCHING (SURFACE REINSTATEMENT)

Choosing the appropriate skin patching method depends largely on what materials are available. Table 1 summarizes three typical approaches.

4.0 TROUBLESHOOTING

This section provides information to assist maintenance personnel with troubleshooting problems with patching and edge repair projects. Table 2 outlines common problems and related solutions.

Table 1: Approaches for Surface Reinstatement

METHOD A: HMA APPLICATION
• The area to be patched is cleaned of debris. • A diluted tack coat emulsion is applied at a rate of approximately 0.5 l/m^2 (0.1 g/yd^2) • The HMA is laid over the surface and spread. The HMA should be spread to a minimum of twice the thickness of the largest aggregate size. • The HMA is then compacted using a pneumatic tired roller and possibly a steel wheel finish roller. A vibratory roller is not recommended because of the possibility of crushing aggregate in thin lifts.
METHOD B: EMULSION SEAL COAT
• The area to be patched is cleaned of debris. • A tack coat emulsion is applied at a rate of approximately 1 l/m^2 (0.2 g/yd^2). • A layer of sand or fine aggregate, typically 3 to 5 mm (0.1 to 0.2 in) in depth, is applied. • The patched area is then rolled with a pneumatic tired roller.
METHOD C: COLD MIX
• The area to be patched is cleaned of debris. • A light tack coat of diluted emulsion is applied at a rate of approximately 0.5 l/m^2 (0.1 g/yd^2). • Spread mix over area to be repaired to a depth of 25mm (1 in). • Compact mix using a pneumatic tire roller (or haul trucks) and finish with a steel wheel roller. • Follow up before winter with a fog seal.

Table 2: Common Patching Problems and Related Solutions

PROBLEM	SOLUTION
PATCHING MATERIAL PICKS OUT	• Ensure the hole is cleaned properly and not too wet. • Ensure sufficient tack coat is applied. • Use a self-setting cold-mix when holes cannot be dried properly. • Ensure the patch is solid before trafficking. • Dust patch surface with sand or small aggregate. • Wait for better weather. • Do not use cutback based cold-mix (unless a temporary repair is being done). • For HMA patches, allow to cool before traffic is allowed over the patch. • Ensure required compaction is achieved.
FLUSH SURFACE	• Reduce asphalt or emulsion content in the mix. • Reduce tack coat application. • Allow longer time before trafficking. • Ensure the gradation of the aggregate is appropriate.
UNEVEN SURFACE	• Ensure cold-mix is workable. • Ensure HMA is at the right temperature for placement and compaction. • Ensure adequate compaction is achieved.
LOSS OF COVER ROCK IN SEAL COAT PATCHES	• Ensure surface is clean. • Ensure correct emulsion content is sprayed. • Ensure aggregate is spread while the emulsion is still brown. • Ensure emulsion is broken before traffic is allowed. • Allow longer cure time before traffic.
TRAFFIC COMPACTS MIX TO BELOW EDGE OF HOLE	• Ensure finished hole is overfilled 3 to 6 mm (0.1 to 0.2 in). • Ensure adequate compaction is achieved. • Ensure mix is workable at application temperatures. • Allow longer time before trafficking.

5.0 REFERENCES

1. "Birth of a Pothole", http://www.dot.state.mn.us/information/potholes/michdot/michdotpotholes.html.

2. Federal Highway Administration, U.S. Department of Transportation, "Materials and Procedures for Repair of Potholes in Asphalt- Surface Pavements", FHWA-RD-99-168, Washington, DC, 1999.

3. California Department of Transportation, "Standard Specifications", Section 39, Sacramento, CA, 1999.

4. Asphalt Emulsion Manufacturers Association, "A Basic Asphalt Emulsion Manual", Annapolis, MD, 1998.

5. Strategic Highway Research Program, "Distress Identification Manual for the Long-Term Pavement Performance Project", SHRP-P-338, Washington, DC, 1993.

6. Asphalt Institute, "Pavement Maintenance Techniques", Manual Series MS-3, Lexington, KY, 1995.

7. The Asphalt Institute, "A Basic Asphalt Emulsion Manual", Manual Series No. 19, Lexington, KY, 1999.

APPENDIX A

SUGGESTED FIELD CONSIDERATIONS FOR PATCHING & EDGE REPAIR

The following field considerations are a guide through the important aspects of performing a patching or edge repair project. The various tables contain items that should be considered in order to promote a successful job outcome. Thorough answers to these questions should be determined, as required, before, during, and after construction. The appropriate staff to do this will vary by job type and size. Some topics may need attention from several staff members. The contractor or maintenance field supervisor should be acquainted with its contents. The intent of the tables is not to form a report, but to bring attention to important aspects and components of the project process. Some information is product specific and contained in the relevant standard specifications, standard special provisions, or special provisions.

PRELIMINARY RESPONSIBILITIES	
PROJECT REVIEW	▪ What is the extent of the potholes? ▪ What caused them? ▪ Is base failure extensive? ▪ Are pothole patches or dig outs required? ▪ Will a surface treatment be needed after the repair? ▪ What is the traffic level? ▪ Is the majority of the base sound and well drained? ▪ What time of year will repairs be performed? ▪ Is a temporary or permanent patch required? ▪ Will the patch require an edge seal? ▪ Review project for quantities of materials required.
DOCUMENT REVIEW	▪ Material specifications. ▪ Dig out / patching methods. ▪ Required special provisions. ▪ Construction manual. ▪ Traffic control plan (TCP).
MATERIAL CHECKS	
EMULSION INJECTION OR COLD-MIX PATCHING	▪ Are the materials compatible with the job requirements? ▪ Is the emulsion produced by an approved source? ▪ Has the delivered emulsion been sampled and submitted for testing? ▪ Does the aggregate meet all specifications and is clean and free of deleterious materials (sand equivalent)? ▪ Is the aggregate damp, but not wet? ▪ Is the emulsion warm to the touch but not hot? ▪ Is the tack emulsion suitable for the climatic conditions? ▪ Is the cold-mix within specifications? ▪ Is the cold-mix workable at the required temperatures?

MATERIAL CHECKS	
SPECIAL COLD-MIX PATCHING	▪ Are materials compatible with the job requirements? ▪ Are the materials within specification? ▪ Is the tack emulsion within specification?
HMA PATCHING	▪ Are the materials compatible with the job requirements? ▪ Is the tack emulsion produced by an approved source? ▪ Has the delivered emulsion been sampled and submitted for testing? ▪ Is the HMA made to specification? ▪ Is the HMA workable in the climatic conditions used?
DIG OUTS AND EDGE REPAIRS	▪ Are the materials compatible with requirements? ▪ Is the emulsion produced by an approved source? ▪ Has the delivered emulsion been sampled and submitted for testing? ▪ Is the mix used for reinstatement within specification? ▪ Is the base course material within specification?
SKIN PATCHING	▪ Are the materials compatible with requirements? ▪ Is the emulsion produced by an approved source? ▪ Has the delivered emulsion been sampled and submitted for testing? ▪ Is the aggregate clean, dry, and properly graded? ▪ Is the base course material within specification?
PRE-SEAL INSPECTION RESPONSIBILITIES	
SURFACE PREPARATION	▪ Are the edges of potholes or dig outs straight and free of debris? ▪ Has the existing surface been inspected for drainage problems? ▪ For dig outs, has all failed material been removed?
EQUIPMENT INSPECTIONS	
INJECTION PATCHING MACHINE	▪ Is the machine fully functional? ▪ Is the equipment free of leaks (hydraulic oil, diesel, motor oil, etc)? ▪ Does the aggregate flow freely? ▪ Does the emulsion flow freely? ▪ Is the compressor working properly?
DIG OUT COLD PLANERS	▪ Is the machine fully functional? ▪ Are the cutting tips sharp and do they make a clean cut without spalling the edges? ▪ Is the equipment free of leaks (hydraulic oil, diesel, motor oil etc)?

EQUIPMENT INSPECTIONS	
POTHOLE PATCHERS – HMA/COLD-MIX	▪ Is the equipment free of leaks (hydraulic oil, diesel, motor oil etc)? ▪ Are heating systems working and able to accurately control mixing temperature? ▪ Are all conveyors working? ▪ Are the hoses for applying tack coat working properly? Is the tack coat being applied at the correct rate?
SKIN PATCHING	▪ Is the equipment free of leaks (hydraulic oil, diesel, motor oil etc)? ▪ Are the heating systems working and accurately controlling the mix temperature? ▪ Can the hand spray line or boot truck spray be properly controlled? ▪ Is aggregate spreading being properly controlled?
COMPACTION DEVICES	▪ Is the equipment free of leaks (hydraulic oil, diesel, motor oil etc)? ▪ Are tandem or other rollers in working order and meet specification requirements? ▪ Are compaction measurement devices (such as nuclear gages) in working order?
WEATHER REQUIREMENTS	▪ Have the air and surface temperatures been checked at the coolest location on the project and do they meet agency requirements. ▪ Application of patching does not begin if rain or snow is likely. ▪ Emulsion type applications should not start if freezing temperatures are expected.
TRAFFIC CONTROL	▪ The signs and devices used match the traffic control plan. ▪ The work zone complies with Caltrans requirements. ▪ Flaggers do not hold the traffic for extended periods of time. ▪ Signs are removed or covered when they no long apply.

PROJECT INSPECTION RESPONSIBILITIES	
INJECTION PATCHING	▪ Does the operator have the correct safety equipment? ▪ Is the weather going to be fair and above freezing for at least 48 hours after patching? ▪ Is the aggregate and emulsion within specification? ▪ Is there enough emulsion and aggregate available? Is the aggregate clean and dry and within specification? ▪ Are the holes to be patched in a stable pavement? Are they dry? ▪ Do the holes have vertical and clean sides? ▪ Is the tack coat applied evenly and only 1 mm (0.04 in) thick? ▪ Does the aggregate flow evenly into the hole? ▪ Does the emulsion evenly coat the aggregate? ▪ Is the hole finished with a layer of aggregate? ▪ Does the mixture show signs of curing (turn black) within the first 10 minutes? ▪ Is the application is stopped as soon as any problems are detected? ▪ Does the application of the patching material appear uniform? ▪ Does the surface have an even and uniform texture? ▪ Check application rate based on amounts of aggregate and emulsion used. ▪ What is the time between spreading and opening to traffic? ▪ Adjust work time, emulsion level, or mixture temperature to allow opening to traffic.
COLD-MIX PATCHING: THROW AND GO	▪ Does the operator have the correct safety equipment? ▪ Is the weather going to be fair and above freezing for at least 48 hours after patching? ▪ Is the mix and tack emulsion within specification? ▪ Is there enough emulsion and mixture available? Is the mixture workable at the temperatures of application? ▪ Are the holes to be patched in a stable pavement? Are they dry? Is there debris in the hole? ▪ Is the tack coat sprayed evenly and no more than 1 mm thick? ▪ Does the mix fill the holes evenly? ▪ Are multiple lifts required, hole depth > 100 mm (4 in)? ▪ Finished patches should be slightly crowned to allow for secondary compaction produced by traffic. ▪ Does the mixture compact satisfactorily? ▪ Is the surface finish even and uniform? ▪ Do tires pick up the final surface? If so, dust with aggregate or sand.

PROJECT INSPECTION RESPONSIBILITIES	
COLD-MIX PATCHING: DIG OUTS AND EDGE REPAIRS	▪ Does the operator have the correct safety equipment? ▪ Is the weather going to be fair and above freezing for at least 48 hours after patching? ▪ Is the mix and tack emulsion within specification? ▪ Is there enough emulsion and mixture available? Is the mixture workable at the temperatures anticipated during application? ▪ Are the holes to be patched in clean, dry, and in a stable pavement? ▪ For edge repairs, is the pavement edge clean and not spalled? ▪ Is the tack coat sprayed evenly and no more than 1 mm (0.04 in) thick? ▪ Does the mix fill the holes evenly? ▪ Are multiple lifts required, hole depth > 100mm (4 in)? ▪ Finished patches should be slightly crowned to allow for secondary compaction produced by traffic. ▪ Does the mixture compact satisfactorily? ▪ Do the rollers allow a good surface profile? ▪ Is the surface finish even and uniform? ▪ Do tires pick up the final surface? If so, dust with aggregate or sand.
HMA PATCHING: THROW AND GO	▪ Does the operator have the correct safety equipment? ▪ Is the weather going to be fair and above freezing for at least 48 hours after patching? ▪ Is the mix and tack emulsion within specification? ▪ Is there enough emulsion and mixture available? Is the mixture workable at the temperatures of application? ▪ Are the holes to be patched in clean, dry, condition? Are they in a stable pavement? ▪ Is the tack coat sprayed evenly and no more than 1 mm (0.04 in) thick? ▪ Does the mix fill the holes evenly? ▪ Are multiple lifts required, hole depth > 100 mm (4 in)? ▪ Finished patches should be slightly crowned to allow for secondary traffic compaction. ▪ Does the mixture compact satisfactorily? ▪ Is the surface finish even and uniform? ▪ Do tires pick up the final surface? If so, dust with aggregate or sand.

PROJECT INSPECTION RESPONSIBILITIES	
HMA PATCHING: DIG OUTS AND EDGE REPAIRS	▪ Does the operator have the correct safety equipment? ▪ Is the weather going to be fair and above freezing for at least 48 hours after patching? ▪ Is the mix and tack emulsion within specification? ▪ Is there enough emulsion and mixture available? Is the mixture workable at the temperatures of application? Is the mix hot enough? ▪ Where a pothole-patching machine is being used does it keep the mix hot without degrading it? ▪ Are the holes to be patched in clean, dry condition? Are they in a stable pavement? ▪ For edge repairs and dig outs are the edges straight and not spalled? ▪ Is the tack coat sprayed evenly and no more than 1 mm thick? ▪ Does the mix fill the holes evenly? ▪ Are multiple lifts required, hole depth > 100 mm (4 in)? ▪ Finished patches should be slightly crowned to allow for secondary compaction produced by traffic. ▪ Does the mixture compact satisfactorily? ▪ Is the surface finish even and uniform? ▪ Do tires pick up the final surface? If so, dust with aggregate or sand.
SKIN PATCHING	▪ Does the operator have the correct safety equipment? ▪ Is the weather going to be fair and above freezing for at least 48 hours after patching? ▪ Is the emulsion within specification? ▪ Is the aggregate clean and dry and within specification? ▪ Is there enough emulsion and aggregate available? ▪ Are the holes to be patched in clean, dry condition? Are they in a stable pavement? ▪ Is the emulsion sprayed evenly and no more than 1 to 2 mm (0.04 to 0.08 in) thick? ▪ Is the aggregate spread evenly over the road surface? ▪ Is the surface finish even and uniform? ▪ Do tires pick up the final surface? If so, dust with aggregate or sand.
ROLLING: (WHEN REQUIRED)	▪ Is the patch stable before rolling begins? ▪ Is the entire surface rolled only once? ▪ Do the rollers travel slowly—8 kph (5 mph) maximum. Do they pick up or tear the mat? ▪ Joints and overlaps may require extra passes in parking lot work especially.

PROJECT INSPECTION RESPONSIBILITIES	
CRACK SEALING	▪ Crack seal all seams ▪ Fog seal patch surface
OPENING THE PATCHING TO TRAFFIC	▪ The traffic travels slowly—40 kph (25 mph) or less—over the fresh patches. ▪ Reduced speed limit signs should be used when pilot cars are not used. ▪ Remove all construction related signs when opening to normal traffic.
CLEAN UP	▪ All loose patching material should be removed from the travel way. ▪ Remove binder application or spills from all areas including curbs, sidewalks and radius applications.

Disclaimer

This chapter is 1 of 8 included in the Caltrans Maintenance Technical Advisory Guide (TAG). The information presented in this chapter is for educational purposes only. It does not represent a policy or specification nor does it endorse any of the products and/or processes discussed.

CHAPTER 5 CHIP SEALS

1.0 INTRODUCTION

Chip sealing is the application of a bituminous binder immediately followed by the application of an aggregate. The aggregate is then rolled to embed it into the binder. Multiple layers may be placed and various binder and aggregate types can be used to address specific distress modes or traffic situations.

1.1 TYPES OF CHIP SEAL

There are many different types of chip seals in use by agencies, but only treatments currently being used by Caltrans are discussed in detail in this manual. However, additional treatments not currently in use are also described to promote a broader understanding of other methods. Types of chip seal treatments include:

- **Single Chip Seal**: A single chip seal is an application of binder followed by an aggregate. This is used as a pavement preservation treatment and provides a new skid resistant wearing surface, arrests raveling, and seals minor cracks. Figure 1 illustrates a single chip seal application.

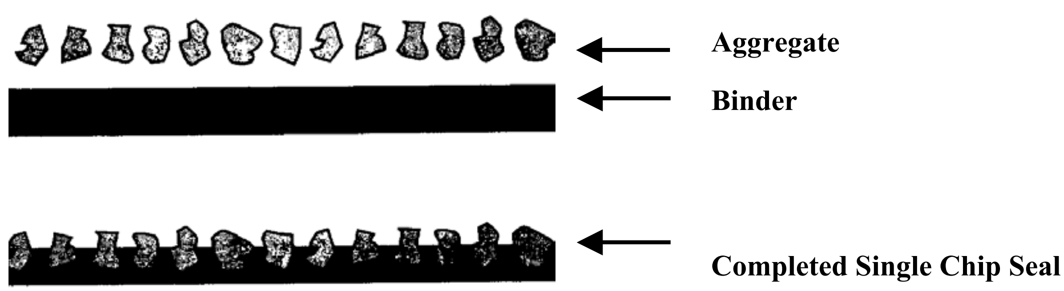


Figure 1: Single Chip Seal

- **Multiple Chip Seal:** A multiple chip seal (or armor coat) is a built-up seal coat consisting of multiple applications of binder and aggregate. As an example, a double chip seal consists of a spray application of binder, spreading a layer of aggregate, rolling the aggregate for embedment, applying an additional application of binder, spreading another layer of aggregate (approximately half the average least dimension of the base coat aggregate), and rolling once more. Sweeping should be done between applications. This process may be repeated, as necessary, to build up a pavement's edges. Multiple chip seals are used where a harder wearing and longer lasting surface treatment is needed. **Caltrans does not use multiple chip seals at this time**. Figure 2 illustrates a multiple chip seal application.

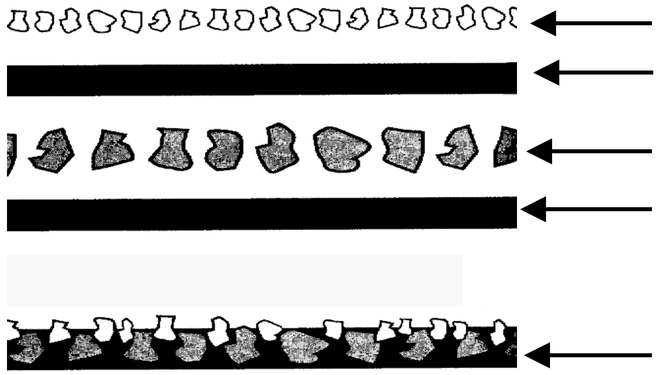


Figure 2: Multiple Chip Seal

- **Stress Absorbing Membrane (SAM) Seal:** A SAM is a single chip seal in which a modified binder (normally asphalt rubber) is applied, followed by a layer of aggregate, and rolling. Binder applications are much higher than those used for conventional chip seals. Generally a SAM has been referred to as being used with AR binders.
- **Stress Absorbing Membrane Inter-layer (SAMI):** A SAMI is a membrane seal that is used to retard the rate of reflection cracking in new overlays. It consists of an application of modified binder followed by a layer of aggregate, spread and rolled. An overlay is then placed over the membrane. If necessary, traffic may be allowed to operate on the SAMI prior to construction of the overlay.

1.2 BINDER TYPES

Binder type varies according to the type of chip seal being used. Binder types include:

- **Asphalt Emulsion:** Polymer-modified emulsions (PME), such as PMCRS-2h, as included in the Standard Specifications, Section 94 (1).
- **Performance-Based Asphalt (PBA) Cements:** Hot applied modified binders that can be placed at cooler temperatures than emulsion binders and can be placed at night. Examples include PBA 6 and PBA 6a binders (2).
- **Asphalt Rubber Binder:** Binders modified with high levels of crumbed tire rubber and a high natural rubber content material. These binders are sprayed hot and require hot chips pre-coated with asphalt. Hot applied AR binders can be placed at cooler temperatures than emulsion binders and can be placed at night.
- **Rejuvenating Emulsion:** These are emulsions modified with rejuvenating oils (and sometimes polymers) that are used to penetrate and soften existing asphalt pavements.

Table 1 lists common binder types and their suitable applications.

Table 1: Binder Type and Suitable Applications

BINDER TYPE	SINGLE	MULTIPLE	SAND	SAM/ SAMI
Asphalt Emulsions	Yes	Yes	Yes	No
PBA	Yes	Yes	Yes	No
Asphalt Rubber	Yes	Yes	Yes	Yes
Rejuvenating Emulsions	Yes	Yes	Yes	No

2.0 PROJECT SELECTION

The general selection of preventive maintenance treatments was covered in Chapter 2. The selection of a pavement for a chip seal project is based on the structural soundness of a pavement and the types of distress that are present. The ability of a treatment to address the current condition of a project is paramount in selecting an appropriate treatment. The main criteria addressed by the varying chip seal types are:

- **Conventional chip seals** are used on structurally sound pavements with minimal cracking.
- **Polymer-Modified Emulsion (PME) chip seals** are used to correct raveling and pavement oxidation.
- **Rubberized chip seals** cure quickly, restore skid resistance on worn surfaces and resist reflection cracking.
- **Special binders** such as asphalt rubber and PBA may be used to address specific distress modes.
- **Distresses such as cracking, flushing, and base failures** cannot be addressed with conventional or hot applied chip seals.
- **Deformation, rutting and shoving** cannot be addressed with chip seals of any kind.

Table 2 lists appropriate binder/chip seal combinations for addressing various distress mechanisms. Generally, chip seals are not used on roads with AADT > 40,000.

The main advantages associated with chip seals include:

- **Improved Skid Resistance**: Chip seals provide good skid resistance.
- **Cost Effective Treatments:** Chip seals are typically cost effective when properly placed on the right type of pavement.
- **Good Durability:** Chip seals wear well and can have long service lives.
- **Ease of Construction:** Chip seals are typically constructed rapidly and cause less disruption to the traveling public than do other treatments that take longer.

Table 2: Binder/Chip Seal Combinations for Addressing Specific Distress Mechanisms

Binder/ Chip Seal Combination	Raveling	Aged Pavements	Bleeding/Flushing	Load Associated Cracks	Water Proofing	Climate Associated Cracks	Heavy Traffic Volumes	Stone Retention	Improve Skid Resistance
PME/Single	Yes	Yes	No	No	Yes	No	Yes	Yes	Yes
PME/Double	Yes	Yes	No	No	Yes	No	Yes	Yes	Yes
PME/Sand	Yes	Yes	No	No	Yes	No	No (light)	Yes	No
PBA/Single	Yes	Yes	No	No	Yes	No	Yes	Yes	Yes
PBA/Double	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
PBA/Sand	Yes	Yes	No	No	Yes	No	No	Yes	No
AR/SAM	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
Rejuvenating Emulsion	Yes	Yes	No	No	Yes	No	Yes	Yes	Yes

The main disadvantages associated with chip seals include:

- **Cure Time:** PME seals take several hours (depending on the climatic conditions) to reach a stage where they can tolerate unrestricted traffic.
- **Flying Chips:** Chip seals must be swept to remove excess stone to avoid broken windshields and vehicle damage.
- **Noise Considerations:** Chip seals can be noisy to travel on.
- **Weather Considerations:** Cold applied chip seals must be constructed during warm, dry weather and during the daytime only. Hot applied chip seals may be applied in cooler conditions and at night.
- **Performance**: Chip Seals create a rougher surface and are generally not used for parking lots. Chip seals do not improve ride quality.

Other limitations of chip seals include:

- **PME Seals:** These are not normally suitable for intersections or high stress areas.
- **PBA Seals:** These cure quickly, but are not suitable for very high stress areas due to their low initial shear strength.

3.0 DESIGN AND SPECIFICATION

3.1 MATERIAL SPECIFICATIONS

3.1.1 Binders

Binders are selected based on their performance characteristics. They need to provide good adhesion and or stickiness. Polymer Modified emulsion binders usually contain latex additives, although other elastomeric polymers are often used. The purpose of the polymer is to improve stone retention during the early life of the treatment and to increase the softening point of the binder after cure (i.e., the temperature at which the binder changes phase from being primarily solid to being primarily fluid). The general-purpose base binder is an 85/100-penetration grade asphalt cement. This base binder mostly controls low temperature properties. For cold climates, a softer base asphalt (e.g. an 120/150 penetration grade) may be warranted. For hot climates, a harder base binder (e.g., a 40/50 penetration grade) might be considered.

PBA's are, by definition, performance-based. This means that they may contain a range of materials to enhance certain characteristics. PBA-6 and PBA-6a usually contain elastomeric polymers, which increase the binder's softening point and improves its crack resistance. Asphalt rubber binders contain high levels of crumbed tire rubber and high natural rubber materials, which increases the softening point of the binder, improves stone retention, and produces good resistance to reflection cracking. In general, the base binder largely determines the low temperature properties; softer bases should be used in lower temperature areas. Selection of a particular binder type should also take into consideration climatic conditions, traffic levels, and types of loads associated with the project (e.g., consideration of snow plow use, AADT, and percent trucks).

Emulsion specifications are included in Section 94 of the Standard Specifications (2) and related SSP's as discussed in Chapter 1 of this guide.

3.1.2 Aggregates

For chip seals, the best performance is obtained when the aggregate has the following characteristics:

- Single-sized, if possible.
- Clean.
- Free of clay.
- Cubical (limited flat particles).
- Crushed faces.
- Compatible with the selected binder type.
- Aggregates must be damp for emulsion use, but must be dry for use with hot binders.

The specifications for aggregates used in chip seals are included in Section 37-1.02 of the Standard Specifications.

3.2 CHIP SEAL DESIGN

Properly designed chip seals have proven to be cost effective in sealing pavements and providing a new riding surface with enhanced frictional characteristics. Many countries have developed rational chip seal design methods and, as a result, have used chip seals on major highways. Caltrans does not currently employ a formal design process for Chip Seals. The methods currently used are based on experience and do not address adjustments for the factors identified below. This section is included for information purposes only and to provide a foundation for an improved design process.

The basics of chip seal design are straightforward, as the binder application rate and the aggregate application rate are the only variables of major importance to consider. However, to correctly calculate these rates requires an understanding of the materials and the surface on which they are to be applied. Additional factors to consider include traffic, climate, and existing surface condition. The determination of the proper binder and aggregate application rates is discussed in greater detail in the following two sections. The design of multiple seal coats is also briefly described. However, sand seals and sandwich seals are designed strictly from experience and are not included in this discussion of design procedures.

3.2.1 Binder Application

In chip seal design, the residual binder application rate is the most important factor affecting seal performance. Enough binder must be present to hold the aggregate in place, but not so much that the binder fills, or is forced by traffic action to cover the aggregate. The proper amount of binder ensures that the desired surface texture is maintained. Chip seal design is not like hot mix asphalt design, in that film thickness is not as applicable a concept. Binder application rates are determined based on the average least dimension of the aggregate, as well as other aggregate properties such as shape, density, absorption and grading. The optimum binder content also depends on how much binder flows into existing voids in the pavement, and how much binder is already present at or near the pavement surface.

The McLeod method is the most common design method for chip seals (6); however it is not used by Caltrans. This method assumes that 70% of the voids in the aggregate must be filled (i.e., 70% embedment). In some states, this is adequate and has been adopted as the standard; however, modifications can be made for varying project conditions.

A more detailed discussion on this design method can be found in “A General Method of Design for Seal Coats and Surface Treatments” by N.W. McLeod. The McLeod method also assumes the use of a cubical, single-sized aggregate. This may not always be the case (e.g., California specifications specify graded aggregates). The main modification for graded aggregates is determining a median aggregate size (50% passing). The aggregate shape must also be examined; this is done by measuring the flakiness index (3). The average least dimension (ALD) can then be determined using the following equation (3):

$$H = [M / 1.139285 + (0.011506)*FI] \qquad (4.1)$$

where: *H = Average Least Dimension, or (ALD)*
M = Median Particle Size
FI = Flakiness Index

ASTM C29 is used to measure the loose unit weight. This approximates the voids in the loose aggregate when it is dropped onto the pavement. The voids in this state are 50% for cubical, single-size aggregate and lower for graded aggregate. It is assumed that once rolled a cubical aggregate will reduce its unit weight to a point where the voids content is 30% and finally to 20% once trafficked. These assumptions are adjusted when using graded aggregates. Figures 2 through 4 illustrate the average least dimension (ALD) concept, along with the effects of flakiness and changes in voids based on compaction.

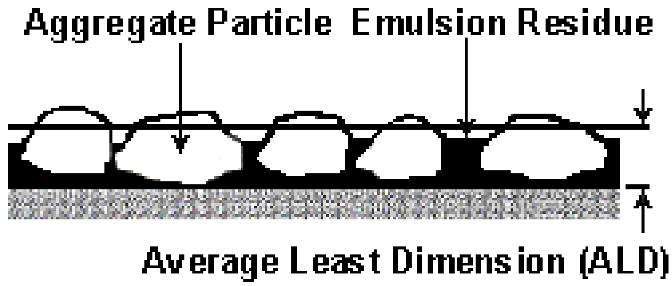


Figure 2: Illustration of ALD (4)

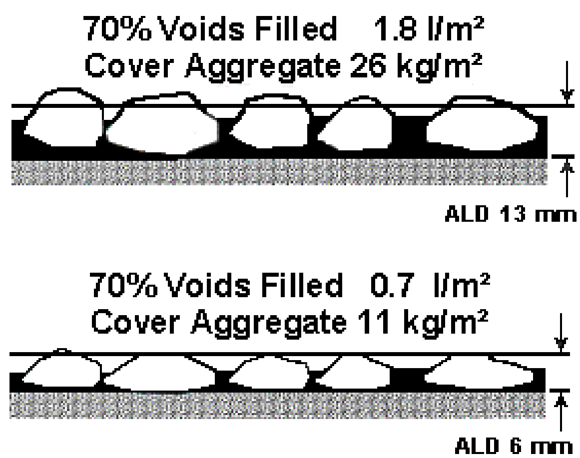


Figure 3: Illustration of Flakiness of Aggregates (4)

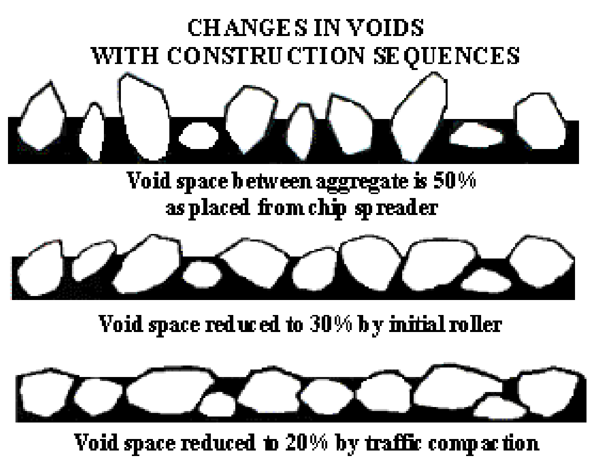


Figure 4: Effects of Compaction on Voids in Cubical Aggregate (4)

The voids in loose aggregate may be calculated using the following equation (3):

$$V = 1 – W / 1000*G \quad (4.2)$$

where: *V = Voids in the Aggregate*
W = Loose Unit Weight of the Aggregate (in ASTM use 29kg/m^3)
G = Bulk Specific Gravity of the Aggregate (usually determined from local information or measured)

Most design methods calculate the specific requirements for each job by considering the required corrections in addition to the basic application rate (the rate designed to result in 70 percent embedment). One method for estimating the binder content is as follows (3):

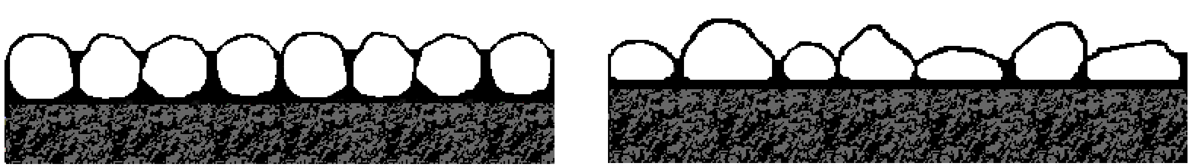
B = [0.40(H) × T × V + S + A + P] / R……………………..(4.3)

where:
B = Binder Content (l/m^2)
H = ALD (m) – (See Page 5.7)
T = Traffic Factor – (See Table 3)
V = Voids in Loose Aggregate (%) – (See Equation 4.2)
S = Surface Condition Factor (l/m^2) – (See Table 5)
A = Aggregate Absorption (l/m^2) – (See CTM 303)
P = Surface Hardness Correction for Soft Pavement (L/m^2) – (See Table 6)
R = Percent Binder in the Emulsion (%) – (See Manufacturer)

For projects in areas maintained by snowplows, the binder content is calculated using both the median particle size and the ALD. The average of these two results is used as the starting application rate in these areas.

Corrections to the basic application rate for the aggregate address variables that affect the level to which it becomes embedded in the binder. The corrections are ultimately applied to the calculation of the binder application rate. These variables include:

- **Aggregate Characteristics:** Important aggregate characteristics include absorption and shape. Corrections for absorption are based on experience and the characteristics of the local aggregates. Chip shape effects are variable: rounded chips leave greater voids and do not interlock and are not recommended. This type of chip also requires additional binder. Non-uniform sized aggregates produce uneven surfaces. Figure 5 illustrates both rounded and non-uniform chip applications.



a) Rounded **b) Non-Uniform**

Figure 5: Aggregate Shape Characteristics (5)

- **Traffic Volume:** This factor accounts for the role that traffic volumes play in achieving the ultimate embedment of 80 percent (20 percent void space). The traffic factor is lower for higher traffic volumes and higher for lower traffic volumes. Table 3 lists the application rate correction factors associated with varying traffic levels.

Table 3: Traffic Factors (3, 6)

VEHICLES/DAY	0-100	101-500	501-1000	1001-2000	>2000
Correction Factor	0.85	0.75	0.70	0.65	0.60

- **Loss of Aggregate Due to Traffic (Traffic Whip-Off):** A traffic whip-off correction accounts for the effects of traffic operations on removing aggregates from newly chip sealed roads. Reasonable values for losses are 5% for low volume roads and residential streets and 10% for high-speed roads and highways. Table 4 lists road types and associated whip-off correction factors.

Table 4: Road Type and Associated Aggregate Loss (Whip-Off) Factor (3)

ROAD TYPE	PERCENT WASTAGE (%)	WHIP-OFF FACTOR (E)
Rural & Residential	5	1.05
Higher Volume Roads	10	1.10
State Highways	15	1.15

- **Existing Pavement Condition:** Existing pavement conditions play a very important role in determining the optimum binder content. A smooth surface will require less binder than will a rough or porous surface. Table 5 details the correction factors associated with various existing pavement conditions.

Table 5: Correction Factors Associated with Existing Road Conditions (3)

EXISTING PAVEMENT	CORRECTION (l/m^2)
Black, flushed asphalt	-0.04 to -0.27 (Depending on severity)
Smooth, non-porous or smooth	0.00
Slightly porous and oxidized or matte	+0.14
Slightly pocked, porous, and oxidized	+0.27
Badly pocked, porous, and oxidized	+0.40

- **Embedment:** Aggregates may be punched or embedded into soft pavement surfaces by roller compaction and traffic. Table 6 provides corrections based on surface hardness and related traffic volume using a Ball Penetrometer test (7).

Table 6: Binder Content Correction Based on Surface Hardness and Related Traffic Volume (7)

SURFACE HARDNESS	TRAFFIC VOLUME (AADT PER LANE)				
	150 -300	300 -625	625 -1250	1250 -2500	>2500
Hard (Ball Value 1 – 2)	Nil	Nil	Nil	-0.1 l/m^2	-0.2 l/m^2
Medium (Ball Value 3 – 4)	Nil	Nil	-0.1 l/m^2	-0.2 l/m^2	-0.3 l/m^2*
Soft (Ball Value 5 – 8)	-0.1 l/m^2	-0.1 l/m^2	-0.2 l/m^2	-0.3 l/m^2	-0.4 l/m^2*

**Where embedment allowances of 0.3 l/m^2 or more are indicated, consideration should be given to alternative treatments such as multiple chip seal (armor-coating) with higher quality materials rolled into the surface, or the use of a primer seal/ prime and seal with a small aggregate in order to provide a platform on which a larger aggregate seal may be placed.*

3.2.2 Aggregate Application

Calculation of the design aggregate application rate is based on determining the amount of aggregate needed to create an even, single coat of chips on the pavement surface. Though not used by Caltrans, the amount of cover aggregate required can be determined using the following equation (3):

$$C = (1 - 0.4V) \times H \times G \times E \qquad (4.4)$$

where:

C = Cover Aggregate (kg/m²)
V = Voids in Loose Aggregate (%)
H = ALD (mm) – (See Page 5.7)
G = Bulk Specific Gravity – (See CT 206 & CT 208)
E = Wastage Factor (%)

Equation 4.1 is used to calculate H (average least dimension) and Equation 4.2 is used to calculate V (voids in loose aggregate). The bulk specific gravity of coarse and fine aggregates, G, can be determined using CT 206 and CT 208, respectively. The wastage factor (E) is to account for whip-off and handling and is normally estimated by the designer based on experience with local conditions. While other design methods are available, Equation 4.4 provides a good starting point and covers most situations. It requires that the user consider the attributes of the surface being sealed and the conditions to which it will be subjected, which are both very important.

The design of multiple coat seals is based on the same concepts as the single chip seal. First, a design is performed for each layer as if it were the only layer in the system. Next, the following three additional rules are applied as follows: 1) the maximum nominal top size of each succeeding layer of cover aggregate should be no more than half the size of the previous layer's aggregate; 2) no allowance is made for wastage; and 3) except for the first application, no correction is made for the underlying surface texture. The amounts of binder determined for each layer of aggregate are added together to calculate the total binder requirement. For two-layer chip seals, 40% of the total binder requirement is applied for the first layer of aggregate and the remaining 60% is applied for the second layer.

3.2.3 Application Rate for Polymer Modified and Asphalt Rubber Modified Seals

For asphalt rubber (e.g., SAMI's), typical binder application rates of 2.2 to 2.5 l/m^2 (0.55 to 0.65 gal/yd^2) are used. For asphalt rubber seals, the binder application rate is significantly higher compared with the base application level calculated for unmodified binder. The higher binder rates are possible due to the higher viscosity of these binders. Application of cover aggregate should be the same in a SAM or SAMI to avoid damage to the membrane due to pick-up by the construction equipment or when the membrane is opened to traffic.

Caltrans practices for these materials are summarized in their standard specifications, Section 37-1.05.

4.0 CONSTRUCTION

4.1 CONSTRUCTION PROCESS

The sequence of construction events is as follows:

1. Project Preparation
2. Surface Preparation
3. Binder Application
4. Aggregate Spreading
5. Rolling
6. Sweeping (Brooming)

Figure 6 illustrates the construction process from binder application through final sweeping. Details of the construction process are provided in the following sections.

4.2 PREPARATION

Preparation of the surface is critical to the performance of the chip seal. Areas of the pavement exhibiting structural failures (such as potholes and deteriorated patches) should be addressed by the removal or patching and sealing of the failed area. Avoid the use of cold mix for patching prior to applying the chip seal. Finally, the prepared surface must be clean, dry and free of any loose material before applying the binder. Preparation for a chip seal project typically includes:

- Milling of the surface (if there is extensive loose material or areas of bleeding that must be removed).
- Crack sealing or filling of cracks that are likely to reflect through the chip seal (see Chapter 3).
- Patching any deteriorated areas or dig outs where required (see Chapter 4).
- Cleaning or brooming any loose material from the pavement surface, such as areas of raveling.
- Removing pavement markers and delineators.

If the patched areas are generally more porous than the rest of the pavement, a tack coat prior to sealing may be required. Known shaded areas that seldom get sunlight (i.e. under bridge decks) may need a tack coat as well to prevent rock loss.

a) Binder Application

b) Spreading of Aggregate

c) Rolling

d) Sweeping

Figure 6: Construction Process for Chip Seals

4.2.1 Materials

A work site needs to contain a facility for storing aggregate and binder. Generally, binders are trucked directly from the manufacturer and off loaded for use. However, situations arise when distance and weather create the need for off site storage. The site should be chosen well in advance of project start-up. The aggregate stockpile should ideally be placed on a sloped and paved surface, but at least on a sloped surfaced to promote drainage of the stockpile. It should also ideally be protected from contamination with foreign material. Once stockpiled, the aggregate should not be moved until it is to be transported to the road being chip sealed. Following project completion, any remaining aggregate must be removed from the stockpile site and the site restored to its original condition before being used as a stockpile site. The methods for storing and handling binders and aggregates, for chip seals, is the same as those for terminal storage as outlined in Chapter 1 (Introduction) of this guide.

4.2.2 Weather Conditions

On the actual day when chip seals are constructed the weather should be clear and warm. In general, pavement surface temperatures should be 10°C (55°F) and rising, and the humidity should be 50% or lower. Wind may cause the emulsion spray to be diverted and compromise uniformity of application rate. A gentle breeze will assist in accelerating cure times. Any rainfall immediately before, during or after the construction of the PME chip seal will contribute to failure of the treatment. Thus, placement of chip seals should be avoided during such conditions. The actual requirements vary for different binder types and are included in the Caltrans specifications.

4.2.3 Traffic Control

The Resident Engineer (RE) examines and approves the contractor's traffic control plan prepared in accordance with the Caltrans Safety Manual (8) and the Caltrans Code of Safe Operating Practices (9). The signs and devices used must match the traffic control plan. The work zone must conform to Caltrans practice and requirements set forth in the Caltrans Safety Manual and the Caltrans Code of Safe Operating Practices. All workers must have all required safety equipment and clothing.

After chipping, pilot cars should be used for between 2 and 24 hours to ensure that traffic speed is limited to approximately 30 kph (20 mph).

4.3 JOINTS

Chip seal passes should begin and end on felt paper or equal. This ensures that the transverse joints are clean and sharp. Longitudinal joints may be made with an overlap. In this process a wet edge (i.e., one without an application of aggregate) of 75 to 100 mm (3 to 4 in) is left (not in a wheel path) and the next run overlaps this wet edge. The chip distributor then covers the whole run to the pavement's edge. Figure 7 illustrates the layout of felt paper at the end of a project lane.

4.4 SPRAYING EQUIPMENT

The spray distributor is the most important piece of equipment in the chip seal process. Its function is to uniformly apply the binder over the surface at the designed rate. Typically, spray distributors (boot trucks) are truck mounted as shown in Figure 8, but trailer units have also been used. A distributor should have a heating, circulation, and pumping system, along with a spray bar, and all necessary controls to guarantee proper application.

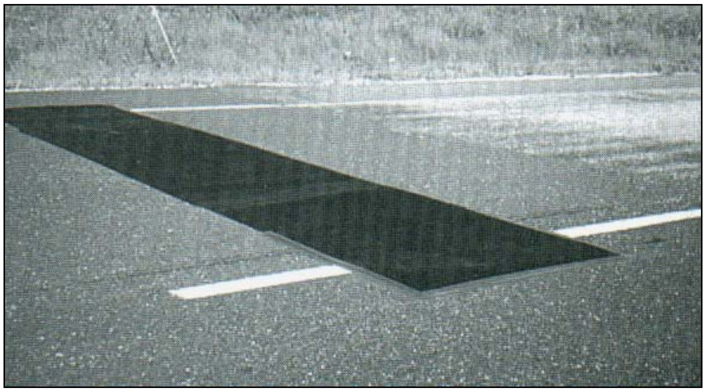


Figure 7: Start and Stop Passes on Roofing Felt (Transverse Joints)

Figure 8: Spray Distributor

4.4.1 Distributor Preparation

The steps associated with preparing the distributor include:

a) Calibrate the distributor by spraying a pre-weighed area of carpet (backed with a waterproof layer) and subtracting the initial weight from that of the sprayed carpet, then dividing the difference by the area of the carpet. Although this is the responsibility of the contractor, the inspector should verify that the distributor is spraying the binder at the correct application rate. See CT 339 for calibration procedures.
b) Blow the spray nozzles to ensure there are no blockages and checking the nozzle angles (see Figure 9) to ensure they spray at an angle 15 to 30 degrees from the spray bar axis. Often, the outer-most nozzles will be turned in to give a sharp edge with no over spray.
c) Check the distributor bar's height. The height is usually set so that a double or triple overlap is obtained as illustrated in Figure 10.
d) Check the distributor bar's transverse alignment to ensure it is closely perpendicular to the centerline of the pavement
e) Check the binder temperature to ensure it is in the appropriate range for proper application. Chip seal emulsion should be between 40 and 85 °C (104 and 185°F) (6).
f) Ensure an adequate supply of binder is available.

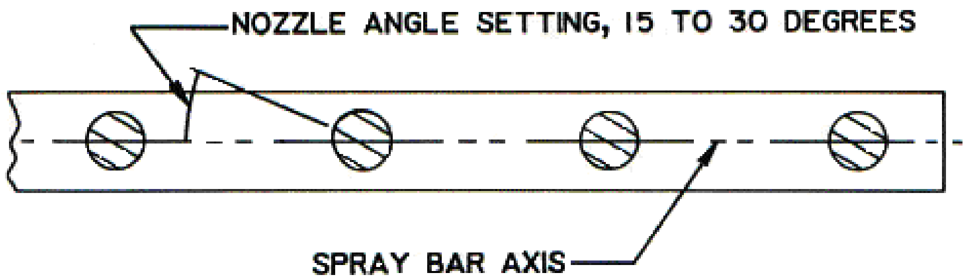


Figure 9: Spray Bar with Nozzle Arrangement (6)

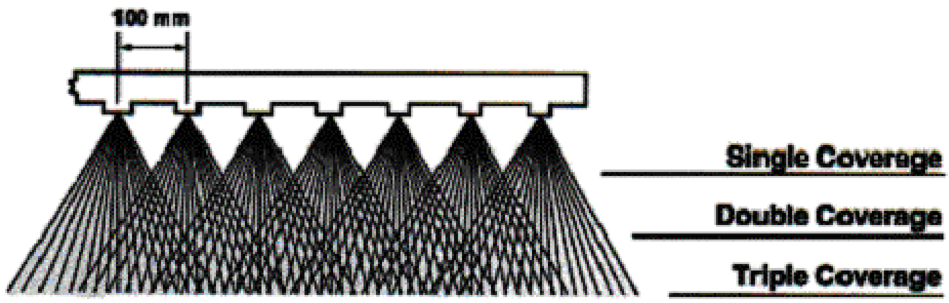


Figure 10: Spray Bar Height Arrangements (6)

Visual checks should be made throughout the spraying process to ensure that the spray bars are clean and are spraying even fans. There should be no streaking of binder visible on the surface. If streaking occurs, the operation should be stopped to recheck proper functioning of the spray bar as well as proper binder temperature. The inspector should check application rates frequently. The application rate can be checked using the calibration method mentioned above or using the alternative method outlined in Appendix A of this chapter. The method above is recommended for equipment calibration while the alternative method is appropriate for quick spot-checking during construction.

4.4.2 Chip Spreader

Chip spreaders must be able to spread an even coating of aggregate one layer thick over the entire sprayed surface. Figure 11 shows a typical chip spreader.

Figure 11: Chip Spreader

Prior to applying aggregate on a project, the following steps should be taken:

a) Calibrate the spreader by spreading chips over a pre-weighed area of carpet and subtracting the initial weight from that of the carpet with chips spread onto it, then dividing the difference by the area of the carpet. Although this is the responsibility of the contractor, the inspector should verify that the spreader is applying the aggregate at the correct application rate.
b) Ensure all gates in the spreader open correctly.
c) Ensure the spreader applies the aggregate is an even, single-layer thickness.
d) Ensure that the spreader is not leaving piles of aggregate and is not spreading too thick a layer. Too thick a layer of aggregate can result in the aggregate being crushed under rollers or by traffic, compromising the seal. Too thick a layer of aggregate can also result in the lever and wedge effect illustrated in Figure 12, which also compromises the seal.
e) Ensure an adequate supply of aggregate is available prior to applying the binder.
f) Ensure proper moisture content of aggregate for PME chip seals.

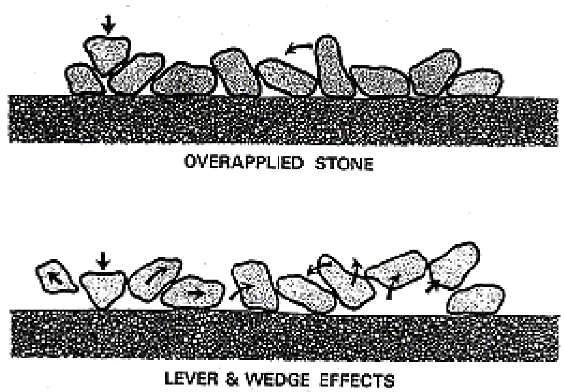


Figure 12: Lever and Wedge Effect (5)

4.4.3 Chip Spreading Process

The application of aggregate should follow the binder application by no more than 90 seconds in order to obtain the best possible aggregate retention. A good visual check is that the spreader should be no more than 30 m (100 ft) behind the distributor truck. The first chip spreading pass is usually done against traffic to allow good centerline match up. The direction for spreading is chosen mostly to minimize truck movements on the fresh oil.

Visual checks of the spreading include checking that the aggregate does not roll or bounce when applied. The flow of aggregate should also be checked. If a wave of binder forms in front of the blanket of aggregate, the binder application may be too heavy. The scalping screen should also be checked for build up of clay or other contaminants. If such contamination is heavy, it may be necessary to re-screen the stockpile. The spread pattern should be even without ripples or streaks. If ripples or streams occur, the spreading gates may need to be lowered and the machine slowed down.

4.5 HAUL TRUCKS

Haul trucks are responsible for providing a continuous supply of binder to the site and aggregate to the spreader. Haul trucks should be in good mechanical condition. Leaking haul trucks can compromise the seal binder. Single axle trucks carry between 4,500 and 6,350 kg (5 and 7 tons) and trucks with tandem axles between 9,000 and 12,700 kg (11 and 14 tons). For this reason, trucks with tandem axles are the preferred. The increased capacity requires fewer hook ups resulting in less chance for spillage and a more efficient operation.

Tires on the trucks should be examined for binder pick up. If pick up occurs, it may severely damage the mat. Tires should be cleaned and sanded. Trucks should not drive on the new surface unnecessarily and should never brake sharply. When driving on the fresh mat, wheel paths should be staggered to assist in embedding the aggregate uniformly. When pulling away from the spreader, trucks should move smoothly and slowly to prevent wheel spin and mat damage. Trucks shall not be allowed to lose or dump chips when pulling away from the chip spreader. No sharp turning movements or high speeds should be allowed on a newly constructed chip seal.

4.6 ROLLING

The function of the roller is to embed the aggregate into the binder and orient it into an interlocking mosaic. This is initially accomplished with pneumatic rollers as shown in Figure 13; compaction applied by traffic finish the process. Rolling should be expedited in hotter weather to ensure proper embedment of the aggregate. Steel rollers are not normally recommended because they can crush the aggregate.

Figure 13: Pneumatic (Rubber Tired) Roller

The important variables when rolling chip seals are:

- Contact pressure
- Number of passes and pattern
- Speed
- Smoothness of tires
- Adequate number of rollers

Contact pressure depends on the vehicle weight, the number of tires, tire size and rating, and the tire inflation pressure. Rollers that can be ballasted are very useful in assuring sufficient contact pressure. The ballasted weight should be 4500 to 5400 kg (4 to 6 tons), with a corresponding tire pressure of 600 kPa (87 psi). Tires must have a smooth tread, should not vary more than 50 kPa (7 psi) in pressure, and should not wobble during operation.

Rollers should follow aggregate spreading by no more than 150 m (500 ft) and should not be operated at more than 10 kph (6 mph). The rolling pattern will depend on the number of rollers used. A minimum of two rollers should be used to cover the full width of the chip spreader. When two rollers are used, three passes are sufficient; one forward, one in reverse, and the final pass extending into the next section.

4.7 BROOMING

Brooming is required before, after, and sometimes during the chip seal operation. Before applying the chip seal the pavement must be swept clean of dust and debris. During a multi-coat sealing operation excess aggregate shall need to be broomed off between coats. After the chip seal has been constructed, excess aggregate must be broomed off to minimize whip-off by traffic.

Brooming is done using rotary brooms with nylon or steel bristles or with vacuum mobile pickup brooms. The broom should not be worn, and should not be operated in such a manner that removes embedded aggregate. Figure 14 illustrates a typical brooming operation.

Mobile pickup brooms are usually capable of picking up aggregate and storing it. Sometimes so-called “kick brooms” are used. These brooms move the aggregate into a windrow so that is can be collected, but they often generate dust and may sweep aggregate into watercourses or gutters. Figure 15 illustrates a typical kick broom.

Brooming can generally be done within 2 to 4 hours after sealing. Hot applied chip seals can be swept within 30 minutes while conventional chip seals can be swept in 2 to 4 hours. A flush coat shall be applied after brooming to eliminate further rock loss and improve durability prior to opening the pavement to uncontrolled traffic.

Figure 14: Brooming Process, Shown on a Shoulder Seal

Figure 15: Kick Broom

5.0 FIELD TESTING

Most tests of constructed chip seals are empirical and provide the user an indication of what extra adjustments must be made on the job site. Though not used by Caltrans, the Ball Penetrometer Test (7) and the Sand Patch Test (ASTM E965) are useful methods for checking the original pavement and the final seal. In the Ball Penetrometer Test, a ball is hammered on the pavement surface using a Marshall hammer a predetermined number of times. The amount of ball penetration into the existing surface is an indicator of the pavement's hardness with typical values ranging from 0 to 0.5 mm. The Sand Patch Test gives surface texture information for classifying surface type or examining seals with typical texture depths ranging from 1 mm to 2.5 mm depending on the aggregate size. Figure 16 illustrates a technician performing the Ball Penetrometer Test and the Sand Patch Test.

a) Ball Penetrometer Test

b) Sand Patch Test

Figure 16: Field Test Methods

6.0 TROUBLESHOOTING

This section provides information to assist maintenance personnel in troubleshooting problems with chip seals. The guide, along with a related table on problems and solutions, address common problems encountered during the course of chip seal projects.

6.1 TROUBLESHOOTING GUIDE

The troubleshooting guide presented in Table 7 associates common problems to their potential causes. In California, the most common problem is flushing.

In addition to the troubleshooting guide, Table 8 lists some commonly encountered problems and some recommended solutions.

Table 7: Troubleshooting Chip Seal Problems (Hot/Emulsion/Asphalt Rubber)

CAUSE	PROBLEM										
	Excessive Loss of Aggregate	Crushing of Aggregates	Pickup of Binder	Adhesion Problems	Raveling of Aggregates	Streaking of Binder	Transverse Patches	Flushing	Failure in Shade	Polishing of Aggregate	Poor Mosaic of Finished Mat
Poor Traffic Control	●		●		●				●		●
Poor Equipment	●		●		●		●	●	●		●
Spray Temperature	●		●		●	●	●		●		●
Vehicle Speeds	●				●	●	●	●	●		●
Distributor Nozzles	●				●	●		●	●		
Climatic Conditions											
Cold Surfaces	●			●	●				●		●
Wet	●			●	●				●		●
Windy	●			●	●				●		●
Binder											
Wrong Binder	●		●	●	●	●		●	●		●
Too Little Binder	●			●	●				●		●
Too Much Binder	●		●					●			●
Aggregate											
Too Little	●		●					●			●
Too Much	●	●		●	●		●		●		●
Wet	●			●	●			●	●		●
Dirty	●			●	●				●		●
Quality	●	●		●	●				●	●	
Wrong Size	●				●			●	●	●	●
Precoat											
Too Little	●			●	●				●		
Too Heavy	●				●						

Table 8: Common Problems and Related Solutions

PROBLEM	SOLUTION
Streaking or drill marks in the emulsion	▪ Ensure emulsion is at correct application temperature. ▪ Ensure the viscosity of the emulsion is not too high. ▪ Ensure all the nozzles are at the same angle. ▪ Ensure the spray bar is not too high or too low. ▪ Ensure the spray bar pressure is not too high or too low. ▪ Ensure nozzles are not plugged.
Exposed emulsion after chip application	▪ Ensure the chip spreader gate is not clogged or malfunctioning. ▪ Ensure the chip spreader is covering all the binder
Excessive chips/Many chips with small amounts of emulsion	▪ Ensure the chip spreader gate is not malfunctioning or chipper head is not overloaded. ▪ Lower the chip application rate.
Uneven chip application	▪ Re-calibrate the chip spreader; ensure all spreader gates are set the same.
Emulsion on the top of chips	▪ Ensure the chip spreader is not operating too fast. ▪ Ensure trucks, rollers, and pilot cars are operating correctly at low speeds.
Chips being dislodged	▪ Ensure the emulsion application is not too light. ▪ Ensure the chips are not dirty or dusty. ▪ Ensure the traffic or equipment speeds are not too high. ▪ Ensure brooming does not occur before the emulsion is properly set.
Emulsion bleeding or flushing	▪ Ensure the emulsion application is not too high. ▪ Ensure the aggregate application is not too low.
After brooming, loss of chip at centerlines	▪ Check centerline procedure. ▪ Check binder application rate.
Excessive splattering of the emulsion	▪ Lower the spray pressure.

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APPENDIX A

SUGGESTED FIELD CONSIDERATIONS FOR CHIP SEALS

The following field considerations are a guide through the important aspects of performing a chip seal project. The various tables list items that should be considered in order to promote a successful job outcome. The answers to these questions should be carefully evaluated before, during and after construction. The appropriate staff to do this will vary by job type and size, and some topics may need attention from several staff. The field supervisor should be acquainted with its contents. Responses to the questions in these tables are not meant to form a report, but rather to call attention to important aspects and components of the chip seal project process. Some information is product-specific and contained in the relevant standard specifications, standard special provisions, or special provisions.

PRELIMINARY RESPONSIBILITIES	
PROJECT REVIEW	▪ Is the project a good candidate for a chip seal? ▪ How much rutting is present? ▪ How much and what type of cracking exists? ▪ Is crack sealing needed? ▪ How much bleeding or flushing exists? ▪ Review project for bid/plan quantities.
DOCUMENT REVIEW	▪ Bid specifications. ▪ Special provisions. ▪ Construction manual. ▪ Traffic control plan (TCP).
MATERIALS CHECKS	▪ The type of binder to be used is compatible with the chips? ▪ The binder is from an approved source (if required)? ▪ The binder and aggregate have been sampled and submitted for testing (if required)? ▪ All chips are close to the same size? ▪ The chips are clean and free of excess fines? ▪ The chips used with emulsions are in a surface-damp condition? ▪ Is the emulsion temperature within application temperature specification?
SURFACE PREPARATION	▪ Is the surface clean and dry? ▪ Have all pavement distresses been repaired and sealed? ▪ Has the existing surface been inspected for drainage problems? ▪ Have pavement markers been removed and temporary markers placed?

EQUIPMENT INSPECTIONS	
BROOM	▪ The bristles are the proper length? ▪ The broom can be adjusted vertically to avoid excess pressure? ▪ Are water misters operable?
DISTRIBUTOR	▪ Is the spray bar at the proper height? ▪ Are all nozzles are uniformly angled 15 to 30 degrees from the spray bar? ▪ Are all nozzles free of clogs? ▪ Is the spray pattern uniform and does it properly overlap (double or triple)? ▪ Is the application pressure correct? ▪ Is the distributor properly calibrated and correct size nozzle tips installed?
CHIP SPREADER	▪ Do the spreader gates function properly and are their settings correct? ▪ Is the scalping screen in good condition? ▪ Is the chip spreader's calibration uniform across the entire chipper head? ▪ Are the truck hook-up hitches in good condition?
ROLLERS	▪ What type of roller will be used on the project (pneumatic-tired roller recommended)? Do rollers meet weight requirements? ▪ Does the roller tire sizes, ratings, and pressures comply with the manufacturer's recommendations and specifications? ▪ Are the tire pressures the same on all tires? ▪ Do all tires have a smooth surface?
HAUL TRUCKS	▪ Is the truck box clean and free of debris and other materials? ▪ Is the truck hook-up hitch in working order? ▪ Is a truck box apron or extension required for loading the chip spreader?
WEATHER REQUIREMENTS	▪ Do the specifications describe a range of dates when chip sealing can be done? ▪ Air and surface temperatures have been checked at the coolest location on the project? ▪ Air and surface temperatures meet agency requirements? ▪ Are high winds expected? High winds can create problems with the emulsion application. ▪ Will the expected weather conditions delay the breaking of the emulsion? High temperatures, humidity, and wind will effect how long the emulsion takes to break. ▪ The application of emulsion should not begin if rain is likely within 24 hours.

EQUIPMENT INSPECTIONS	
DETERMINING APPLICATION RATES	▪ Agency guidelines and requirements have been followed? ▪ Has a chip seal design been done? ▪ Is the surface oxidized or porous? More oil is applied to dried-out and porous surfaces. ▪ Is the traffic volume on the road low? More oil is applied on roads with low traffic volumes. ▪ Is the surface smooth, non-porous, or bleeding? Less oil is applied to smooth, non-porous, and asphalt-rich surfaces. ▪ Is the traffic volume on the road high? Less oil is applied on roads with high traffic volumes. ▪ Is there a salt and pepper appearance after the chips have been applied?
BINDER CALIBRATION CONSIDERATIONS	
CHECKING APPLICATION RATES	**Binder – Method A (Recommended for Calibration)** ▪ The weight of a 0.84 m^2 ($1yd^2$) carpet, pan, or non-woven geotextile material is recorded. ▪ The carpet, pan, or non-woven geotextile material is placed on the road surface. ▪ The distributor applies oil over the carpet, pan, or geotextile material. ▪ The weight of the carpet and oil, pan and oil, or geotextile material and oil is recorded. ▪ The weight of the carpet, pan, or geotextile material without oil is subtracted from the weight of the carpet, pan, or geotextile material with emulsion. ▪ The weights applied to the area of carpet (i.e., kg/m^2 or lb/yd^2) must be converted to the units of the control mechanism, which is l/m^2 or gal/yd^2, through knowledge of the specific gravity of the emulsion. If the distributor is not spraying the binder at the correct application rate, adjustments must be made to the controls and the process described above repeated until the correct application rate is achieved. Although this is the responsibility of the contractor, the inspector should verify that the distributor is spraying the binder at the correct application rate.

BINDER CALIBRATION CONSIDERATIONS	
CHECKING APPLICATION RATES	**Binder – Method B (Recommended for Random Checks)** ▪ Park the distributor on level ground and measure the number of liters or gallons of emulsion. Mark the locations of the front and back tires. ▪ Measure off a known distance for a test section. ▪ Have the distributor apply emulsion to the test section. ▪ Return the distributor to the original level ground and re-measure the number of liters or gallons of emulsion. ▪ Subtract the number liters or gallons after application from the original number of liters or gallons to obtain the number of liters or gallons applied. ▪ Divide the number of liters or gallons applied by number of square meters or square yards covered by emulsion to give the application rate in l/m^2 or gal/yd^2. ▪ If the distributor is not spraying the binder at the correct application rate, adjustments must be made to the controls and the process described above repeated until the correct application rate is achieved. Although this is the responsibility of the contractor, the inspector should verify that the distributor is spraying the binder at the correct application rate.
CHIP CALIBRATION CONSIDERATIONS	
CHECKING APPLICATION RATES	**Chips – Method A (Recommended for Calibration)** ▪ Weigh a 0.84 m^2 (1 yd^2) tarp or geotextile material. ▪ Place the tarp or geotextile material on the roadway. ▪ Have the chip spreader apply the chips over the tarp or geotextile material. ▪ Weigh the tarp or the geotextile material with the chips. ▪ Subtract the original weight of the tarp or geotextile material from the weight of the tarp or geotextile with the chips. Divide the weight of the chips by the area of the tarp or geotextile to give the application rate in kg/m^2 or lb/yd^2.

CHIP CALIBRATION CONSIDERATIONS	
CHECKING APPLICATION RATES	**Chips – Method B (Recommended for Random Checks)** ▪ Weigh a haul truck empty. ▪ Load the haul truck with chips and reweigh the truck. ▪ Subtract the weight of the empty truck from that of the loaded truck to obtain the weight of the chips. ▪ Empty all the chips into the chip spreader. ▪ Have the chip spreader apply all of the chips from the weighed truck. ▪ Measure the length and width of the area over which the chips were spread. ▪ Divide the weight of the chips by the area over which they were spread to determine actual rate in kg/m^2 or lb/yd^2.
PROJECT INSPECTION RESPONSIBILITIES	
BINDER APPLICATION	▪ Is roofing felt or building paper used to start and stop binder application? ▪ Is the binder within the required application temperature range? ▪ Does the application look uniform? ▪ Are any nozzles plugged? ▪ Is there streaking in the applied binder? ▪ Are application rates randomly checked? ▪ Is the speed of the distributor adjusted to match the chip spreader to prevent stop-and-start operations? ▪ Is the distributor stopped if any problems are observed?
CHIP APPLICATION	▪ Are enough trucks on hand to maintain a steady supply of chips to the spreader? ▪ The application starts and stops with neat, straight edges? ▪ The binder application starts and stops on building paper or roofing felt? ▪ The chip spreader follows closely [30 m (33 yds) or less] behind the distributor when an emulsion is used? ▪ The chip spreader travels slowly enough to prevent chips from rolling when they hit the surface? ▪ Are the chips in a surface damp condition? ▪ No binder is on top of the chips? ▪ The application is stopped as soon as any problems are detected? ▪ Does the application appear uniform? ▪ Do the chips have a salt and pepper appearance? ▪ Check the percent chip embedment in the binder and adjust binder or chip application rate if required.

PROJECT INSPECTION RESPONSIBILITIES	
TRAFFIC CONTROL	▪ The signs and devices used match the traffic control plan? ▪ The work zone complies with Caltrans methods? ▪ Flaggers do not hold the traffic for extended periods of time? ▪ The pilot car leads traffic slowly — 40 kph (25 mph) or less—over fresh chip seals? ▪ Signs are removed when they no long apply? ▪ Any unsafe conditions are immediately reported to a supervisor?
ROLLING	▪ The rollers follow closely behind the chip spreader? ▪ The entire surface is rolled at least twice? ▪ Roller speeds kept at 5 mph (8-9 kph) maximum? ▪ The roller's first pass is on the meet line? ▪ Rollers do not drive on exposed emulsion? ▪ All stop, starts, and turns are made gradually?
TRUCK OPERATION	▪ Trucks travel slowly on the fresh seal? ▪ Stops and turns are made gradually? ▪ Truck operators avoid driving over exposed binder? ▪ Trucks stagger their wheel paths when backing into the chip spreader? This helps to eliminate chip roll over and aids in rolling.
LONGITUDINAL JOINTS	▪ The meet line is only as wide as the spray from the end nozzle—about 20 cm (8 in)? ▪ The distributor lines up so that the end nozzle sprays the meet line? ▪ The meet lines are not made in the wheel paths? ▪ The meet lines are made at the center of the road, center of a lane, or edge of a lane? ▪ The meet lines are not left uncovered overnight?
TRANSVERSE JOINTS	▪ All binder and chip applications begin and end on building paper or roofing felt? ▪ The building paper or roofing felt is disposed of properly?
BROOMING	▪ Brooming does not dislodge the aggregate? ▪ Brooming begins as soon as possible, but not until sufficient bond has formed between the chip and the binder? Check with the binder manufacturer for their recommendation or refer to agency requirements. ▪ Are misters on mobile pickup brooms operating?

PROJECT INSPECTION RESPONSIBILITIES	
OPENING THE CHIP SEAL TO TRAFFIC	▪ Traffic travels slowly–24 mph (40 kph) or less–over the fresh seal coat until the chip seal is broomed and opened for normal traffic? ▪ Reduced speed limit signs are used when pilot cars are not used? ▪ Are pavement markings placed before opening chip seal to normal traffic? ▪ Are all construction-related signs removed when opening chip seal to traffic and traffic control is removed?
CLEAN UP	▪ Is all loose aggregate from brooming removed from the roadway? ▪ Are binder spills cleaned up?

Disclaimer

This chapter is 1 of 8 included in the Caltrans Maintenance Technical Advisory Guide (TAG). The information presented in this chapter is for educational purposes only. It does not represent a policy or specification nor does it endorse any of the products and/or processes discussed.

CHAPTER 6 FOG SEALS

1.0 INTRODUCTION

Fog seals are a method of adding asphalt to an existing pavement surface to improve sealing or waterproofing, prevent further stone loss by holding aggregate in place, or simply improve the surface appearance. However, inappropriate use can result in slick pavements and tracking of excess material.

The Asphalt Emulsion Manufacturers Association (AEMA) defines a fog seal as “a light spray application of dilute asphalt emulsion used primarily to seal an existing asphalt surface to reduce raveling and enrich dry and weathered surfaces” (1). Others refer to fog seals as enrichment treatments since they add fresh asphalt to an aged surface and lengthen the pavement surface life (2). Fog seals are also useful in chip seal applications to hold chips in place in fresh seal coats. These are referred to as flush coats. This can help prevent vehicle damage arising from flying chips. The Asphalt Institute also adds that fog seals can seal small cracks (3).

1.1 FUNCTION OF A FOG SEAL

A fog seal is designed to coat, protect, and/or rejuvenate the existing asphalt binder. The addition of asphalt will also improve the waterproofing of the surface and reduce its aging susceptibility by lowering permeability to water and air. To achieve this, the fog seal material (emulsion) must fill the voids in the surface of the pavement. Therefore, during its application it must have sufficiently low viscosity so as to not break before it penetrates the surface voids of the pavement. This is accomplished by using a slow setting emulsion that is diluted with water. Emulsions that are not adequately diluted with water may not properly penetrate the surface voids resulting in excess asphalt on the surface of the pavement after the emulsion breaks, which can result in a slippery surface. Figure 1 conceptually shows a fog seal application.

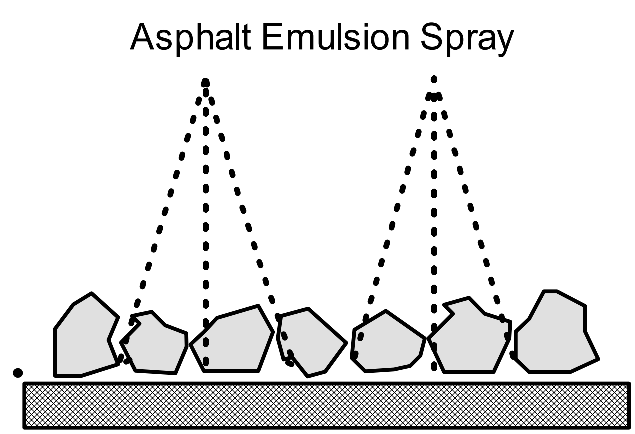

Figure 1: Schematic of Fog Seal Application (5)

During application, the emulsion wets the surface of the aggregate and the existing binder film. Cationic (positively charged) emulsions can displace water from the surface of an aggregate or aged asphalt film. The emulsion then breaks by loss of water and chemical action, forming a film of new binder on the aggregate and existing binder film. The rate at which the emulsion breaks is dependent on several factors with weather conditions (e.g., wind, rain, temperature, etc.) being dominant factors. For anionic (negatively charged) emulsions, there is no surface specific interaction with most aggregates. The emulsion breaks due to water loss by evaporation and absorption of water by the aggregates and surface voids of the pavement.

1.2 FUNCTION OF A REJUVENATING SEAL

Rejuvenating emulsions (e.g. Reclamite (oil emulsion), PASS (asphalt, oil and additives) and Topien C (asphalt, oil and additives)) have oils that soften the existing binder, thus reducing its viscosity. These also improve the flexibility of the binder, which reduces the likelihood of cohesive failure. This may be beneficial in situations where the surface has an open texture and the existing binder is brittle from age. As with conventional emulsions, if these types of emulsion do not penetrate the surface, they may create a slippery surface after they break.

2.0 FOG SEAL PROJECT SELECTION

Fog seals are used as a method of enrichment of a pavement surface and as a method of holding stone in place. Thus, they are suitable to treat raveled and aged pavements. There is, at the present time, no simple way of quantifying the degree of aging in a pavement other than by visual inspection. Different asphalts will age at different rates and the experience of individual districts is key to determination of treatment timing. Some modified asphalts such as asphalt rubber and polymer modified asphalts will age at a slower rate than conventional binders. Fog seals will not correct distresses such as cracking, base failures, excessive stone already lost, or any other severe pavement defects.

On the traveled way, fog seals should only be used where surface penetration of the emulsion can be expected; that is, aged and raveled hot mix surfaces, chip-sealed surfaces, and open graded asphalt surfaces. On shoulders, gores, or dikes, penetration is desirable, but it is not essential. Fog seals darken the pavement surface and create distinct demarcation in these regions.

In general, traffic level is not a determining factor except in job set up. For situations requiring that the sealed pavement be opened to traffic shortly after the application of the seal, a blotter coat of sand may be used to prevent pick-up.

2.1 OLD OR DAMAGED SURFACES

All asphalts harden as they age, primarily due to oxidation, volatile loss and other aging mechanisms (4). Hardening of an asphalt film takes place at different rates according to the access of air and temperature conditions in the pavement. Permeable pavements or pavements with high void contents can therefore age faster. Water ingress can also carry dissolved oxygen and trace elements that may promote aging. This means that pavements with open surfaces tend to age faster than those with closed surfaces. However, if modified binders are used (e.g., asphalt rubber, polymer modified asphalt), the thicker films created by the higher binder content reduce the rate of aging.

Aging results in a binder that is more brittle. These binders eventually experience cohesive binder failures under traffic loads and stone loss or raveling. In some cases, the asphalt produces oxidized compounds that are acidic and bond well to the aggregate; however, these compounds may also react with water causing adhesive failure or stripping.

Fog seal use on the traveled way should generally be limited to only those locations having an open surface texture. This includes chip seals, heavily aged dense graded and open graded. However, the seal may fill voids and reduce or eliminate the drainage function of Open-Graded Friction Coarse (OGFC). Figure 2 shows a typical fog seal application, while Figures 3 through 5 shows a range of suitable and unsuitable surfaces for fog seal project selection. The results of good fog seal applications are shown in Figures 6 and 7. It is important to always check the application rate and ensure that the emulsion has been diluted correctly.

Figure 2: Fog Seal Application

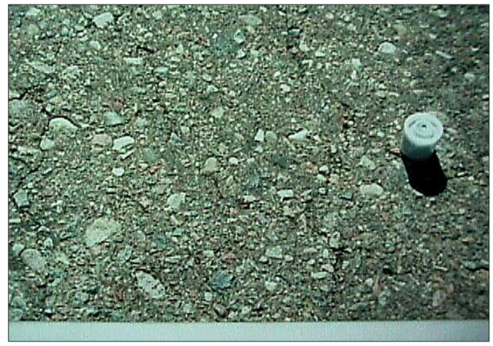

Figure 3: Suitable Surface, Heavily Aged Dense Graded HMA

Figure 4: Unsuitable Surface, Dense Graded HMA With Closed Surface

Figure 5: Suitable Surface, Open Graded HMA

Figure 6: Chip Seal Before and After Fog Seal

a) Before Treatment b) After Treatment

Figure 7: Suitable Surface, Open Texture Dense Graded HMA

Fog seals (with sand blotter coats) may be used as a pavement maintenance treatment on lower speed roads or low traffic volume roads and shoulders. This protects the hot mix asphalt or chip seal surface. In some instances (where traffic is straight), a fog seal with a blotter coat may also be acceptable. The sand will generally be removed by the traffic leaving a good surface texture.

2.2 NEW SURFACES

Flush coats (fog seals with light sanding) are used as a construction seal for new chip seals to lock the chips in place. This reduces vehicle/windshield damage due to flying chips when traffic is allowed on the new seal. These fog seals with sand blotter coats may also be used as a pavement maintenance treatment on lower speed roads or low traffic volume roads. This protects the hot mix asphalt or chip seal surface.

Fog seals are also suitable for sealing new shoulders, gores, or dikes. During construction on milled or ground HMA surfaces, fog seals may be used to keep dust down and prevent rock loss before the next surface is placed.

2.3 SURFACE PROTECTION

Fog seals may be used to protect a hot-mix asphalt (HMA) surface that is not aged significantly (i.e., within 1-2 years of placement after a major rehabilitation or maintenance treatment). This creates a layer of asphalt that seals surface voids and prevents air and water ingress. Do not seal any pavement less than one year old unless the pavement is showing severe raveling resulting from an oil shortage in the mix.

2.4 FOG SEAL PERFORMANCE – BENEFITS AND LIMITATIONS

Fog seals are an inexpensive way of arresting raveling and adding binder back into aged surfaces. They can also hold chips in place in fresh chip seals, (or older chip seals beginning to loose rock) reducing the potential for vehicle damage.

Fog seals are not useful as seal coats on tight surfaces without the addition of aggregates as they will reduce surface texture and may create a slippery surface. Fog seals should not be used on Rubberized Asphalt Concrete (RAC) or polymer modified mixes unless the pavements are over five years old as these binders age at a different rate.

The application of fog seals is also limited by weather. A cut off date in the fall (e.g. September 1st) will ensure that rain will not be a factor and that the emulsion will fully cure before freezing conditions are encountered. In addition, seal coats applied in the winter have less time to penetrate the pavement and are more prone to cause slick surface conditions.

3.0 FOG SEAL MATERIALS AND SPECIFICATIONS

3.1 WHAT MATERIALS ARE USED?

The materials used in fog seals are usually asphalt emulsion and water. In some cases, the emulsions are made with a range of additives for special purposes. For example, rejuvenation oils may be used to soften and revitalize the aged binder in the pavement. Rejuvenation treatments require special attention in design and application and are covered in SSP 37-600 and SSP 37-600_M.

The emulsion types recommended for fog seals may be cationic (i.e., a positive surface charge on the asphalt particles), or anionic (i.e., a negative surface charge on the asphalt particles). The primary types used are CSS-1h and SS-1h. In some circumstances, CQS-1h (and LMCQS-1h) will give a faster set. These are still nominally CSS type emulsions, but will not usually pass the cement-mixing test. Caltrans Standard Specifications (6) provides the required properties for the standard emulsions referred to above. The cement-mixing test (a part of AASHTO test method T59 as required in Caltrans specifications on emulsions) may be omitted as this relates to aggregate mixing stability and not fog sealing.

Note that asphalt emulsions of this type contain up to 43% water. However, any dilution referred to is *additional* water added to the emulsion. Residual asphalt is the binder left after *all* water (i.e., any added water and the original emulsion water) has evaporated.

Rejuvenating emulsions may take several forms and should only be used on pavement showing significant age related distress associated with stiffening of existing binder. They may be emulsions of rejuvenating oils and may include asphalt, polymer latex, and other additives. These are defined in manufacturer's literature and are covered by SSP 37-600 and SSP 37-600_M. The main rejuvenating emulsions that have been used in California are trade named "Reclaimite (oil emulsion), PASS (asphalt, oil and additives) and Topien C (asphalt, oil and additives)". For such products, the manufacturer should be consulted to ensure correct handling.

3.2 DESIGN CONSIDERATIONS

Fog seals are designed for application rate and sometimes dilution rate. This is also a part of the construction process as it is very surface dependent (see Section 4.4).

ESSENTIAL EMULSION TERMINOLOGY

- **Original emulsion** – An emulsion of paving asphalt and water that contains a small amount of emulsifying agent. Original slow-setting grade emulsions contain up to 43 percent water and original rapid setting grade emulsions contain up to 45 percent water.
- **Diluted emulsion** – An original emulsion that has been diluted by adding an amount of water equal to or more than the total volume of original emulsion.
- **Residual asphalt content** – The amount of paving asphalt remaining on the pavement surface after the emulsion has broken and cured (after all water has evaporated).

4.0 FOG SEAL CONSTRUCTION

4.1 SITE CONDITIONS

To be effective, fog seals need to break quickly (revert to solid asphalt) and cure completely (lose water to form a cohesive film). This should be at a rate that allows traffic to be accommodated without the binder being picked up by vehicle tires. To achieve this behavior, the film forming properties of the binder must be adequate (i.e., the binder must be able to coalesce into a continuous film prior to allowing traffic on the new seal). Asphalt films do not form well at low temperatures in the absence of low viscosity diluents. Thus, warm conditions with little to no chance of rain are necessary to ensure successful applications. Fog seals should not to be applied when the atmospheric temperature is below 10°C (50°F), and pavement temperature below 15°C (59°F).

If unexpected rain occurs, prior to the emulsion breaking, the emulsion may wash out of the pores of the pavement and break on the surface of the pavement creating a slippery surface.

4.2 SURFACE PREPARATION

Immediately before applying a fog seal, the pavement surface must be cleaned with a road sweeper, power broom, or flushed with a water pump-unit to remove dust, dirt, and debris. The pavement surface must be clean and dry before applying the fog seal. If flushing is required, it should be completed 24 hours prior to the application of the fog seal to allow for adequate drying.

4.3 MATERIALS PREPARATION

Asphalt emulsions (original emulsions) contain up to 43% water, but must be diluted further before use. This additional dilution reduces viscosity (see Figure 8) and allows the application of small amounts of residual binder to be adequately controlled. Generally, the supplier will dilute the original emulsion, in the field or at the plant. A dilution rate of 50% (1:1) (equal parts water to equal parts emulsion) is recommended. Dilution water must be potable and free from detectable solids or incompatible soluble salts (hard water).

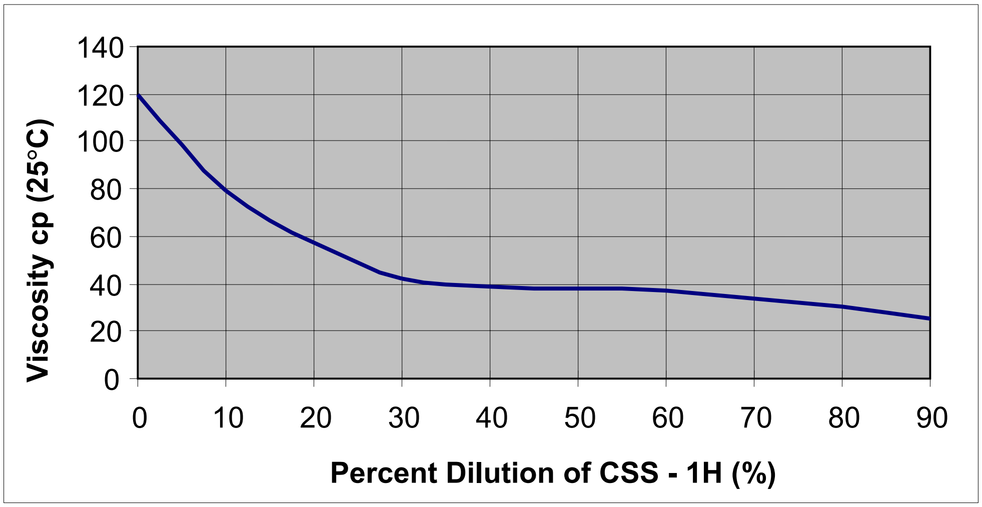

Figure 8: Viscosity Change with Dilution (5)

Water can be checked for compatibility with the emulsion by mixing a small amount of the emulsion in a can (approximately 1 liter). The materials are mixed for 2 to 3 minutes with a stirrer and the resulting mixture is poured through a pre-wetted 150 μm sieve. If more than 1% by weight of material is retained on the sieve, the water is not compatible and clogging in spray jets may result. This test is illustrated in Figure 9.

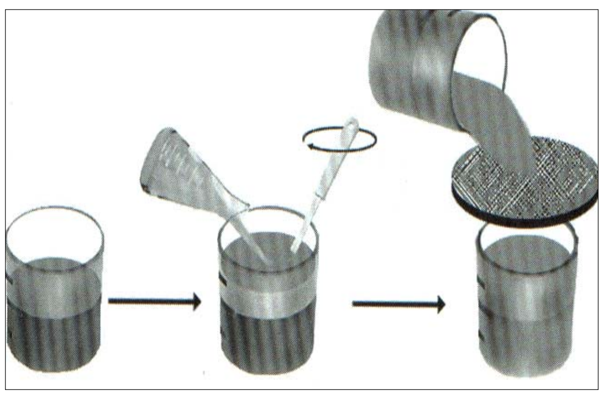

Figure 9: Simple Water Compatibility Test Method (3)

Incompatible water may be treated with 0.5 to 1.0% of a compatible emulsifier solution (the emulsion manufacturer can provide advice regarding compatible solutions). The emulsifier solution should be added to the water tanker and circulated for 10 to 15 minutes via pump before adding to the emulsion. If a water treatment is used, the compatibility test should be repeated using the treated water to ensure compatibility.

The emulsion should be diluted no more than 24 hours before its intended use (7). This is to avoid settlement of the diluted emulsion. Water is always added to the emulsion and not the other way around. The emulsion may be circulated using a centrifugal or other suitable pump to ensure uniformity (7).

4.4 Application Rates and Spraying

Properly calibrated distributor trucks shall be used to apply the emulsion (see Figure 2). Spray nozzles with 4 to 5 mm (1/8” to 3/16”) openings are recommended (7). The emulsion may be heated to 50°C (122 °F) maximum, although, generally the emulsion is sprayed at ambient temperature (7). The emulsion is sprayed at a rate that is dependant on the surface conditions (see Table 1). A test section representative of the entire surface should be chosen to approximate application rates (see Section 4.5). Typical application rates for diluted emulsion (1:1) range from 0.15 to 1.0 l/m^2 (0.03 to 0.22 gal/yd^2) depending on the surface conditions (5). A 1:1 diluted emulsion is an original emulsion that has been subsequently diluted with equal parts water.

Table 1: AEMA Recommendations for Application Rates (5)

% Original Emulsion	Dilution Rate	Tight Surface*		Open Surface**	
		(l/m^2)	(gal/yd^2)	(l/m^2)	(gal/yd^2)
50	1:1	0.15 - 0.5	0.03 – 0.11	0.4 - 1.0	0.09 – 0.22

* *A tight surface is of low absorbance and relatively smooth (7).*
** *An open surface is relatively porous and absorbent with open voids (7).*

Ideally, one-half of the application should be sprayed in each direction to prevent build up on one side of stones only (this is particularly important in the case of chip seals) and rough surfaces. Build up on one side can result in a slippery surface and inadequate binder to fully enrich the surface or hold the stone.

4.5 Estimating Application Rates

To estimate the application rate, the RE shall take a one-liter can of diluted emulsion (usually 1:1 dilution rate) and pour evenly over an area of 1 m^2. This represents a diluted application rate of 1 l/m^2. If the emulsion is not absorbed into the surface after 2-3 minutes, decrease the application rate of the emulsion and apply to a new 1 m^2 area and repeat until the approximate application rate is found. If, after the first test, the surface looks like it can absorb more emulsion, increase the application rate of the emulsion and spread it over a new 1 m^2 area. Repeat until the approximate application rate is found. This same procedure can be followed using gallons and square yards to determine application rate.

4.6 Traffic Control

Traffic control should be in place before work forces and equipment enters onto the roadway or into the work zone. Traffic control is required both for the safety of the traveling public and the personnel performing the work. Traffic control includes construction signs, construction cones and/or barricades, flag personnel, and pilot cars to direct traffic clear of the construction operation. For detailed traffic control requirements, refer to the Caltrans project specifications and the Caltrans Code of Safe Operating Practices.

Traffic control is also required to protect the integrity of the application. The curing time for the fog seal material will vary depending on the pavement surface conditions and the weather conditions at the time of application. Under ideal conditions, including increasing air and surface temperatures, it is suggested that traffic be kept off the fog seal material for at least two hours and acceptable skid test (CT 342) values are achieved.

4.7 Safety (Personal Protective Equipment–PPE)

All employees are advised to wear and use the safety gear required for a fog seal operation. This includes, but is not limited to, items such as hard hats, approved Caltrans shirts, safety vests, earplugs, gloves, and safety glasses (8, 9).

4.8 Quality Control

Quality control and workmanship are critical to the performance and life of a fog seal treatment. There must be a cooperative effort between the Caltrans representative and the contractor's representative to conduct inspections of all project equipment before and during the project. The primary pieces of equipment for a fog seal operation are the boot truck/equipment and distributor bar. It is critical that each is functioning as required by the project specifications. The spray bar must be set to the appropriate height (distance) from the pavement surface and the nozzles must be set at the proper angle to assure a uniform application of material (1). The material temperatures should also be measured for quality control purposes.

The emulsion must be certified to specification according to established sampling and testing procedures (6). Excess emulsion can create slick pavements.

It is recommended that project inspections be conducted so that any deficiencies in workmanship or materials are addressed and corrected. This process will also assist the department in identifying the performance of various fog seal materials; how they are performing on various surface conditions and how they are performing in various climatic zones.

4.9 Post Treatment

Sand blotters may be used, at approximately 1 kg/m^2, to allow early opening to traffic. Sweeping may be required. The Resident Engineer or district maintenance personnel should assess this after application and opening to traffic. Even with sand cover, traffic control may be required to keep speeds down.

Skid resistance (coefficient of friction) can be measured using CT 342. It is recommended that this be done after the application has cured to ensure the proper value is measured. The final surface shall yield a coefficient of friction not less than 0.30 as determine by CT 342. A treated pavement shall not be opened to traffic until an acceptable value is recorded. If a treated pavement does not produce an acceptable coefficient of friction, see Table 3 for corrective action. Permeability may be monitored by CT 341 to ensure that an effective seal has been achieved. This should be done at the discretion of the Resident Engineer.

5.0 TROUBLESHOOTING

This section provides information to assist field personnel in troubleshooting problems with fog seals, along with "dos and don'ts" that address common problems that may be encountered during the course of a project.

5.1 TROUBLESHOOTING GUIDE

The troubleshooting guide presented in Table 2 associates common problems to their potential causes. For example, a slick surface may be caused by wet pavement, a high application rate, or rain. Cold weather could also contribute to slick pavements as the emulsion break may be delayed. The emulsion will be tacky and pickup if the existing road surface is dry or dusty, or the wrong emulsion is used.

In addition to the troubleshooting guide, Table 3 lists some application problems and their recommended solutions.

TABLE 2: TROUBLE SHOOTING FOG SEAL PROBLEMS

CAUSE	PROBLEM						
	SLICK SURFACE	NOT BREAKING	WASHES OFF	TACKY PICKS UP	WILL NOT DILUTE	BREAKS TOO FAST	DILUTION WRONG
Road Wet	•	•	•				
Road Too Dry				•		•	
Road Dusty				•		•	
Hard Water					Anionic		
Alkaline Water					Cationic		
Acidic Water					Anionic		
Application Too High	•	•	•	•			•
Application Too Low						•	•
Wrong Emulsion		•	•	•	•	•	
Rain	•	•	•				
Cold Weather	•	•					
Hot Weather				•		•	

TABLE 3: APPLICATION PROBLEMS AND RELATED SOLUTIONS

PROBLEM	SOLUTION
Spattering of the Emulsion	▪ Reduce the rate of dilution. ▪ Ensure the spray bar height is set correctly. ▪ Ensure the spray pressure is not set too high.
Streaking of the Emulsion	▪ Ensure the emulsion is not too cold. ▪ Ensure the emulsion viscosity is not too high. ▪ Ensure the nozzles are at the same angle. ▪ Ensure the spray bar is not too high or too low. ▪ Ensure the spray bar pressure is not too high. ▪ Ensure all nozzles are not plugged.
Bleeding or Flushing of the Emulsion	▪ Ensure the emulsion application rate is not too high. ▪ Check application and dilution rate and recalibrate sprayer, if necessary.
Surface Coefficient of Friction is too Low per CT 342	▪ Apply coating of clean dry sand. ▪ Sweep sand with rotary broom to absorb excess binder. ▪ Perform CT 342. ▪ Repeat process until coefficient of friction is at least 0.30.

**Do not open treated surface until coefficient of friction is at least 0.30 as determined by CT 342.*

5.2 Dos and Don'ts

The following dos and don'ts list provides a quick reference to avoid making common mistakes with fog seals.

Do check water compatibility before dilution.
Do check dilution - has it been done, by whom, and when?
Do ensure that there is no contamination of the base emulsion by water, oils, or other liquids.
Do prevent contamination by other emulsions.
Do protect emulsions from freezing or localized boiling due to the application of direct heat.
Do heat emulsion gently and ensure heating coils are under the liquid level (max 50°C (122°F)).
Do load from the bottom of tankers or sprayers to avoid foaming.
Do check equipment and nozzles.
Do check application rates.
Do exercise proper traffic control.
Do ensure the know-how is available on the job.
Do add water to emulsion, not emulsion to water.
Don't store diluted emulsion longer than 24 hours.
Don't continuously stir or circulate emulsion.
Don't apply emulsion if air temperature is <10°C (50°F) and pavement temperature <15°C (59°F).
Don't apply emulsion if rain or cool temperatures are imminent.
Don't continue application if adequate breaking period is not available.
Don't open treated surface to traffic until coefficient of friction is at least 0.30 as determined by CT 342.

6.0 KEY REFERENCES

The Asphalt Institute, "A Basic Asphalt Emulsion Manual", Manual Series No. 19, Lexington, Kentucky, 1999.

Booth, EHS, Gaughan, R., Holleran, G., "Some Uses of Bitumen Emulsions in SA and NSW", Proceedings, Australian Road Research Board, pp. 387-401, March 1988.

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Hicks R.G., Holleran G., "Purpose and Use of Fog Seals and Rejuvenators", Sealer Binder Workshop, Foundation For Pavement Preservation, Federal Highway Administration, March 2002.

6. California Department of Transportation, "Standard Specifications", Sections 37 and 94, Sacramento, California, 1999.

7. Asphalt Emulsion Manufacturers Association, "Recommended Performance Guidelines", AEMA, Washington, D.C., 1990.

8. California Department of Transportation, "Caltrans Code of Safe Operating Practices", Chapter 12, Sacramento, California, 1999.

9. California Department of Transportation, "Caltrans Code of Safe Operating Practices", Appendix C, Sacramento, California, 1999.

10. California Department of Transportation, "Standard Specification", Section 40-1.01, Sacramento, California, 1999.

APPENDIX A

SUGGESTED FIELD CONSIDERATIONS FOR FOG SEALS

The following field considerations are a guide through the important aspects of performing a fog-sealing project. The various tables contain items that should be considered in order to promote a successful job outcome. Thorough answers to these questions should be determined, as required, before, during, and after application of fog seal. The appropriate staff to do this will vary by job type and size. Some topics may need attention from several staff members. The field personnel should be acquainted with its contents. The intent of the tables is not to form a report but to bring attention to important aspects and components of the project process. Some information is product specific and contained in the relevant standard specifications, standard special provisions, or special provisions.

PRELIMINARY RESPONSIBILITIES	
PROJECT REVIEW	▪ Is the project a good candidate for a fog seal? ▪ What is the existing surface type? ▪ Has an assessment been made of the surface absorption? ▪ How much stone has been lost? ▪ How much bleeding or flushing exists? ▪ Review project for bid/plan quantities. ▪ What is the relative cost?
DOCUMENT REVIEW	▪ Bid specifications. ▪ Special provisions. ▪ Emulsion Specifications. ▪ Traffic control plan (TCP). ▪ Material safety data sheets.
MATERIALS CHECKS	▪ Emulsion selection. Type and dilution rate. ▪ The emulsion is from an approved source (if required)? ▪ The emulsion has been sampled and submitted for testing (if required)? ▪ The water to be used is compatible with the emulsion? ▪ Is sand required? Is it within specification and dry? ▪ Is the emulsion temperature within application temperature specification?
PRE-SEAL INSPECTION RESPONSIBILITIES	
SURFACE PREPARATION	▪ Is the surface clean and dry? ▪ Have all pavement distresses been repaired? ▪ Has the existing surface been inspected for drainage problems?

EQUIPMENT INSPECTION RESPONSIBILITIES	
BROOM	▪ Are the bristles the proper length? ▪ Can the broom be adjusted vertically to avoid excess pressure on the surface?
SPRAY DISTRIBUTOR	▪ Is the spray bar at the proper height? ▪ Are all nozzles uniformly angled at 15 to 30 degrees from the spray bar axis? ▪ Are all nozzles free of clogs? ▪ Is the spray pattern uniform and does it properly overlap (double or triple)? ▪ Is the application pressure correct? ▪ Is the distributor properly calibrated? ▪ Is there a working and calibrated thermometer on site? ▪ Has water been added to emulsion in correct proportion and circulated? ▪ Is the application rate being monitored throughout the day/project?
SAND SPREADER	▪ Do the spreader gates function properly and are their settings correct? ▪ Is the sand spreader's calibration uniform across the entire head? ▪ Is the sand free flowing? ▪ Are the truck hook-up hitches in good condition?
TRUCKS	▪ Is the truck box clean and free of debris and other materials? ▪ Is the truck hook-up hitch in working order? ▪ Is a truck box apron or extension required for loading the sand spreader?
ALL EQUIPMENT	▪ Is all equipment free of leaks? ▪ Is all equipment calibrated and clean?

SITE CONSIDERATIONS	
TRAFFIC CONTROL	▪ Do the signs and devices used match the traffic control plan? ▪ Does the work zone comply with Caltrans traffic control policies as laid out in the Caltrans Safety Manual? ▪ Do flaggers not hold the traffic for extended periods of time? ▪ Does the pilot car lead traffic slowly — 40 kph (25 mph) or less—over fresh sand blotted fog seals? If not sanded, allow at least 2 hours before opening to traffic. ▪ Are unsafe conditions promptly reported to a supervisor (contractor or agency)? ▪ Are signs removed or covered when they no long apply?

<table>
<tr><th colspan="2">SITE CONSIDERATIONS</th></tr>
<tr><td>WEATHER REQUIREMENTS</td><td>

Are minimum surface and air temperatures adhered to?
Are air and surface temperatures checked at the coolest location on the project?
Do air and surface temperatures meet agency requirements?
Are high winds expected during application of the fog seal? High winds can create problems with the diluted emulsion application.
Will the expected weather conditions delay the breaking of the emulsion? High temperatures, humidity, and wind will effect how long the emulsion takes to break.
Is the application of the fog seal discontinued if rain is likely?
</td></tr>
<tr><th colspan="2">BINDER CONSIDERATIONS</th></tr>
<tr><td>BINDER APPLICATION</td><td>

Are the agency guidelines and requirements being followed?
Has a check been done on the absorption ability of surface?
Is the surface oxidized and porous? More oil can be applied to dried-out and porous surfaces.
Is the surface smooth, non-porous, or bleeding (asphalt rich)? Do not apply to smooth, non-porous, and asphalt-rich surfaces.
Is the traffic volume on the road high? Less oil must be applied on roads with high traffic volumes.
Does the emulsion soak into the surface? If not, application rate is too high.
Is the surface texture coarse? If so, spray should be applied in both directions to avoid build up on one side of stones.
Are manhole covers and drainage inlets covered to keep binder from entering water bodies?
</td></tr>
<tr><td>CHECKING APPLICATION RATES</td><td>
Binder - Method A (Recommended for Calibration)

The weight of a 0.84 m^2 ($1yd^2$) carpet, pan or, non-woven geotextile material is recorded and placed on the road surface.
The distributor applies emulsion over the carpet, pan, or geotextile material.
The weight of the carpet and emulsion, pan and emulsion, or geotextile material and emulsion is recorded.
The weight of the carpet, pan, or geotextile material without emulsion is subtracted from the weight of the carpet, pan, or geotextile material with emulsion.
The weights applied to the area of carpet (i.e., kg/m^2 or lb/yd^2) must be converted to the units of the control mechanism, which is l/m^2 or gal/yd^2, through knowledge of the specific gravity of the emulsion. If the distributor is not spraying the binder at the correct application rate, adjustments must be made to the controls and the process described above repeated until the correct application rate is achieved. Although this is the responsibility of the contractor, the inspector should verify that the distributor is spraying the binder at the correct application rate.
</td></tr>
</table>

BINDER CONSIDERATIONS

CHECKING APPLICATION RATES

Example – Checking Fog Seal Application Rate (Method A)

- Given:
  Applying a Fog Seal with a 1:1 diluted emulsion.
  Tight surface texture.
  Recommended application rate of 0.15 – 0.5 l/m^2 (0.03 – 0.11 gal/yd^2) (see Table 1).
  Specific gravity of Emulsion (G_E) = 1.010.
  Unit Weight of Water (γ_W) = 1 g/cm^3 or 1000 kg/ m^3 (62.4 lb/ft^3).
  Conversion Factor (C_{fl}) = 1000 l/m^3 (7.5 gal/ft^3).

Find the actual application rate ($W_{A'}$).

- Measure the weight of a 1 m^2 (1 yd^2) carpet (W_C).
  (W_C) = 1.8144 kg (4.0 lb)
- Measure the weight of 1 m^2 (1 yd^2) carpet and applied emulsion (W_{C+E}).
  (W_{C+E}) = 2.1944 kg (4.7 lb)
- Calculate the weight of emulsion covering the 1 m^2 (1 yd^2) carpet (W_E).
  (W_E) = (W_{C+E} - W_C)
  (W_E) = (2.1944 kg – 1.8144 kg) (4.7 lb - 4.0 lb)
  (W_E) = 0.38kg (0.7 lb)
- The application rate is the weight of emulsion applied per unit area (W_A).

$$(W_A) = \left(\frac{W_E}{1m^2}\right) \text{ or } \left(\frac{W_E}{1yd^2}\right)$$

$$(W_A) = \left(\frac{0.38kg}{1m^2}\right) \text{ or } \left(\frac{0.7lb}{1yd^2}\right)$$

$$(W_A) = 0.38\frac{kg}{m^2} \text{ or } 0.7\frac{lb}{yd^2}$$

Convert this application rate to gal/yd^2.

- Calculate the unit weight of the emulsion (γ_E) by multiplying the specific gravity of the emulsion (G_E) by the unit weight of water (γ_W).

$$(\gamma_E) = (G_E \times \gamma_E)$$

$$(\gamma_E) = \left(1.010 \times 1000\frac{kg}{m^3}\right) \text{ or } \left(1.010 \times 62.4\frac{lb}{ft^3}\right)$$

$$(\gamma_E) = 1010.0\frac{kg}{m^3} \text{ or } 63.024\frac{lb}{ft^3}$$

BINDER CONSIDERATIONS

CHECKING APPLICATION RATES

Example **– Checking Fog Seal Application Rate (Method A) (continued)**

- Convert the unit weight of the emulsion (γ_E) to kg/l (lb/gal) (γ_{Ekg}) by dividing (γ_E) by (C_{f1}).

$$(\gamma_{Ekg}) = \left(\frac{\gamma_E}{C_{f1}}\right)$$

$$(\gamma_{Ekg}) = \left(\frac{1010.0\frac{kg}{m^3}}{1000\frac{l}{m^3}}\right) \text{ or } \left(\frac{63.024\frac{lb}{ft^3}}{7.5\frac{gal}{ft^3}}\right)$$

$$(\gamma_{Ekg}) = 1.01\frac{kg}{l} \text{ or } 8.4\frac{lb}{gal}$$

- Convert (W_A) in kg/m^2 (lb/yd^2) to ($W_{A'}$) in l/ m^2(gal/yd^2) by dividing (W_A) by (γ_{Ekg}).

$$(W_{A'}) = \left(\frac{W_E}{\gamma_{Ekg}}\right)$$

$$(W_{A'}) = \left(\frac{0.38\frac{kg}{m^2}}{1.01\frac{kg}{l}}\right) \text{ or } \left(\frac{0.7\frac{lb}{yd^2}}{8.4\frac{lb}{gal}}\right)$$

$$(W_{A'}) = 0.3763\frac{l}{m^2} \text{ or } 0.08\frac{gal}{yd^2}$$

Check this value against the recommended application rates given in Table 1. For the given surface condition and dilution rate this application rate is acceptable.

BINDER CONSIDERATIONS	
CHECKING APPLICATION RATES	**Binder – Method B (Recommended for Random Checks)** ▪ Park the distributor on level ground and measure the number of liters or gallons of emulsion. ▪ Measure off a known distance for a test section. ▪ Have the distributor apply diluted emulsion to the test section. ▪ Park the distributor on level ground and re-measure the number of liters or gallons of emulsion. ▪ Make necessary adjustments to volume based on temperature corrections per Standard Specifications section 93-1.04. ▪ Subtract the number liters or gallons after application from the original number of liters or gallons to obtain the number of liters or gallons applied. ▪ Divide the number of liters or gallons applied by the number of square meters or square yards covered by emulsion to give the application rate in l/m^2 or gal/yd^2. ▪ If the distributor is not spraying the binder at the correct application rate, adjustments must be made to the controls and the process described above repeated until the correct application rate is achieved. Although this is the responsibility of the contractor, the inspector should verify that the distributor is spraying the binder at the correct application rate throughout the project.

PROJECT INSPECTION RESPONSIBILITIES	
BINDER APPLICATION	▪ Is building paper used to start and stop emulsion application for straight edges? ▪ Is the emulsion within the required application temperature range? ▪ Does the application look uniform? ▪ Are any nozzles plugged? ▪ Is there streaking on the applied emulsion? ▪ Are application rates randomly checked? ▪ Is the speed of the distributor adjusted to match that of the sand spreader (if used) and to avoid start-and-stop operations? ▪ Is the distributor stopped if any problems are observed?
TRUCK OPERATION	▪ Are the trucks staggered across the fresh fog seal coat to avoid driving over the same area? ▪ Do the trucks travel slowly on the fresh seal? ▪ Are stops and turns made gradually? ▪ Do truck operators avoid driving over exposed oil?

PROJECT INSPECTION RESPONSIBILITIES	
OPENING A FOG SEAL TO TRAFFIC	▪ Are results from CT 342 at least 0.30? ▪ Does traffic travel slowly — 40 kph (25 mph) or less—over the fresh seal until seal is broomed and opened to normal traffic? If not sanded, allow 2 hours before opening to traffic. ▪ Are reduced speed limit signs used when pilot cars are not used? ▪ Are pavement markings placed after brooming and before opening to normal traffic? ▪ Are all construction related signs removed when opening to normal traffic?
CLEAN-UP	▪ Is all loose (excess) sand from brooming operation removed from travel way? ▪ Are binder spills cleaned up?
REMOVAL OF EXCESS BINDER FROM SURFACE	
SAND APPLICATION	▪ Are enough aggregate trucks on hand to maintain a steady supply of sand to the spreader? ▪ Is clean dry sand being used? ▪ Does the sand application appear uniform? ▪ Is sand used only once?
BROOMING	▪ Does brooming begin as soon as possible after sand is applied? ▪ Is initial brooming done lightly with a rotary broom to distribute and set sand in surface? ▪ Is secondary brooming done to remove loose sand coated with excess binder? ▪ Is brooming process repeated until results from CT 342 at least 0.30?

CHAPTER 7 SLURRY SEALS

1.0 SLURRY SURFACING DESCRIPTION

This chapter provides an overview of the types of slurry seals presently used in California, including materials and specifications, mix design, project selection, details regarding construction, and a troubleshooting guide to assist the Engineer if problems arise during the placement of these mixtures. In addition, it contains an Appendix listing suggested field considerations when placing a slurry surfacing.

1.1 GENERAL DESCRIPTION

Slurry seals are a mixture of asphalt emulsion, graded aggregates, mineral filler, water and other additives. The mixture is made and placed on a continuous basis using a travel paver (Slurry Surfacing Machine). The travel paver meters the mix components in a predetermined order into a pug mill. The typical mixing order is aggregate followed by cement, water, the additive and the emulsion. Figure 1 illustrates the process of slurry surfacing.

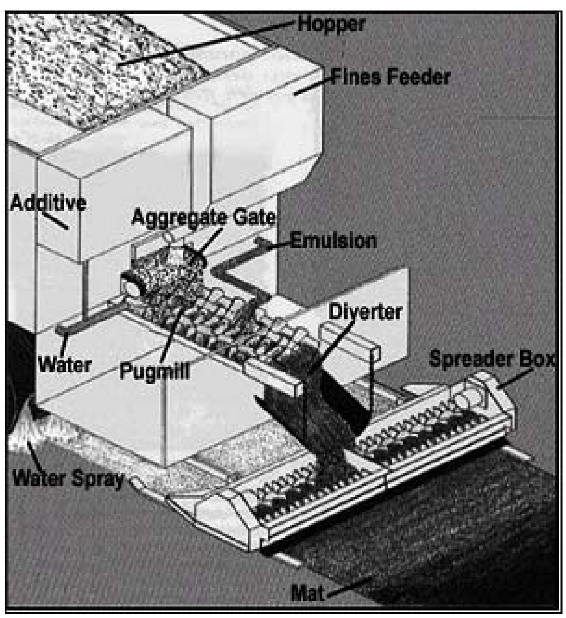


Figure 1: Schematic of a Slurry Surfacing Machine (1)

The resulting slurry material is a free flowing composite material that is spread via a spreader box over the existing road surface. The consistency of the slurry material allows it to spread over the pavement, wetting it, and forming an adhesive bond to the pavement.

The slurry mixture contains asphalt emulsion that breaks onto the pavement surface through heterogeneous or homogenous flocculation. The asphalt particles coalesce into films, creating a cohesive mixture. The mixture then cures, by loss of water, into a hardwearing, dense-graded asphalt/aggregate mixture that is bonded to the existing pavement.

A slurry surfacing does not add any structural capacity to an existing pavement; they are applied as a maintenance treatment to improve the functional characteristics of the pavement surface. The types of slurry surfacing and the pavement characteristics they improve are discussed next.

1.2 PURPOSE OF A SLURRY SEAL

A slurry seal is a thin surface treatment that is laid in a thickness equal to the largest stone in the grading of its component aggregate. It may include either a conventional or polymer modified emulsion, and the slurry seal may be slow or quick setting. The emulsion is usually cationic in nature, but may be anionic. Slow set systems break mostly by evaporation; quick set systems have emulsifiers that react physio-chemically with the aggregate surfaces. These quick set emulsions maintain a degree of chemical break. For both systems, breaking and curing times are dependant on the environmental conditions at the time of application; at high temperatures the emulsion in quick set systems breaks and cures very quickly such that the surface treatment can be opened to traffic within about one hour; slow set systems typically require several hours to break and cure. In cooler conditions, the times before opening to traffic are longer for both systems. For this reason, slurry seals should not be applied at night.

A slurry seal is used to:

- Seal sound, oxidized pavements.
- Restore surface texture by providing a skid-resistant wearing surface.
- Improve waterproofing characteristics.
- Correct raveling.
- Provide a new surface where weight restrictions preclude the use of heavier overlays (e.g., bridge decks).
- Provide a new surface where height restrictions are a problem (e.g., overcrossings)

A slurry seal should not be used to:

- Correct surface profile.
- Fill potholes.
- Alleviate cracking (with or without polymer modification).

2.0 MATERIALS AND SPECIFICATIONS

The main materials used in slurry surfacing are:

- Asphalt Emulsion
- Water
- Aggregate
- Cement
- Additives

2.1 ASPHALT EMULSION

Asphalt emulsions are defined in Chapter 1 of this advisory guide as dispersions of asphalt in water stabilized by a chemical system. In the case of slurry surfacing, the emulsion may be cationic or anionic; however, cationic emulsions are the most common. Caltrans Standard Specifications Section 94 (2) provides specifications for the main emulsion types. Emulsions used in slurry seals are either slow setting (SS) or quick setting (QS). Common slow and quick setting emulsions include:

- CSS-1h
- CQS-1h
- QS-1h
- SS-1h

These emulsions are specially formulated for compatibility with the aggregate and to meet the appropriate mix design parameters. These emulsions are defined in Chapter 1 of this guide, Section 94 of the Standard Specifications (2), and in Reference 3 identified at the end of this chapter.

Emulsion specifications are based on standard emulsion characteristics, such as stability, binder content, and viscosity. In some quick set slurry systems polymer is added to the emulsion. The polymer enhances stone retention, especially in the early life of the treatment. The added polymer also reduces thermal susceptibility. Polymers also improve softening point and flexibility, which enhance the treatment’s crack resistance.

Emulsions are usually modified with latex, which is an emulsion of rubber particles. The latex does not mix with the asphalt; rather, the latex and the asphalt particles intermingle to form a sort of 3-D structure, as illustrated in Figure 2. The latex used is either neoprene or styrene butadiene styrene (SBR) for slurry seal. When modified with latex, slurry seal emulsions are referred to PMCQS-1h or, more commonly, LMCQS-1h (1).

Latex may separate from the emulsion due to the differences in density. If separation occurs, the latex must be remixed into the emulsion by circulation in the tanker before the modified emulsion is transferred to the slurry machine for application (3).

Basic emulsion requirements are shown in Table 1. Key requirements include the binder content and residual properties. The viscosity is of importance as is the storage stability to ensure that the emulsion can be used effectively in the field.

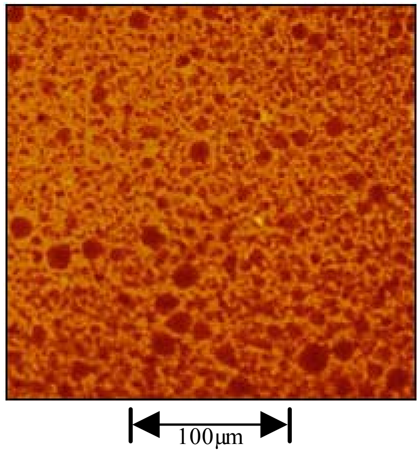


Figure 2: Micrograph of a Latex/Asphalt Cured Film (3)

Table 1: Typical Emulsion Properties for Polymer Modified Slurry Quick Set (3)

TEST	TYPICAL SPECIFICATION	METHOD
Residue	62% min	AASHTO T 59
Sieve Content	0.3% max	AASHTO T 59
Viscosity @ 25°C, SSF	15-90	AASHTO T 59
Stability (1 day)	1% max	ASTM D244
Storage Stability (5 days)	5% max	ASTM D244
Residue pen @ 25°C	40-90	ASTM D244
R&B SP, °C	57 min	AASHTO T 53
Torsional Recovery	18% min (LMCQS-1h)	CT 331
Polymer Content	2.5% min (LMCQS-1h)	CT 401

2.2 AGGREGATES

2.2.1 Aggregate Characteristics

The aggregate's key physical characteristics for suitable incorporation into a slurry surfacing mix are defined by:

- **Geology:** This determines the aggregate's compatibility with the emulsion along with its adhesive and cohesive properties.
- **Shape:** The aggregates must have fractured faces in order to form the required interlocking matrix (1). Rounded aggregates result in poor mix strength.
- **Texture:** Rough surfaces form bonds more easily with emulsions.
- **Age and Reactivity:** Freshly crushed aggregates have a higher surface charge than aged (weathered) aggregates. Surface charge plays a primary role in reaction rates.
- **Cleanliness:** Deleterious materials such as clay, dust, or silt can cause poor cohesion and adversely affect reaction rates.
- **Soundness and Abrasion Resistance:** These features play a particularly important role in areas that experience freeze-thaw cycles or are very wet.

Caltrans specifies three aggregate grading sizes for slurry seals: Types I, II and III (2). The gradation for each type is listed in Table 2.

Table 2: Caltrans Slurry Surfacing Aggregate Gradings (2)

SIEVE SIZE	PERCENTAGE PASSING		
	TYPE I	TYPE II	TYPE III
9.5mm	-	100	100
4.75 mm	100	94-100	70-90
2.36mm	90-100	65-90	45-70
1.18mm	60-90	40-70	28-50
600-µm	40-65	25-50	19-34
75-µm	10-20	5-15	5-15

The primary difference among these gradations is the aggregate top size. This indicates the amount of residual asphalt required by the mixture and the purpose to which the slurry is most suited. The Type I slurries are the finest and are used for lightly trafficked roads or parking lots. Type II slurries are coarser and are suggested for raveling and oxidation on roadways with moderate to heavy traffic volumes. Type III slurries have the coarsest grading and are appropriate for filling minor surface irregularities, correcting raveling and oxidation, and restoring surface friction. Type III slurries are typically used on arterial streets and highways.

The role of fines (i.e., aggregate particles 75 ?m and finer) in a slurry surfacing mix is to form a mortar with the residual asphalt to cement the larger stones in place. The fines content is essential for creating a cohesive hardwearing mix. Generally, the fines content should be at the mid-point of the grading envelope. The general aggregate quality requirements are listed in Table 3.

Table 3: General Aggregate Properties (2) and Aggregate Requirements (4)

Test	Slurry Seal Type			Test # and Purpose
	I	II	III	
Sand Equivalent (min)	45	55	60	CT 217 Clay Content
Durability Index (min)	55	55	55	CT 229 Resistance to wet/dry exposure

2.3 Cement and Additives

In most slurry surfacing, cement is used as a mixing aid allowing the mixing time to be extended and creating a creamy consistency that is easy to spread. Additionally, hydroxyl ions counteract the emulsifier ions, resulting in a mix that breaks faster with a shorter curing time. Cement is also a fine material and, as such, absorbs water from the emulsion, causing it to break faster after placement. Fine materials, as previously discussed, also promote cohesion of the mixture by forming a mortar with the residual asphalt.

Additives other than cement vary and are features of particular systems. They act as retardants to the reaction with emulsions, either as a prophylactic, slowing the emulsifier's access to the aggregate surface, or by preferentially reacting with the emulsifier in the system. Additives include emulsifier solutions, aluminum sulfate, aluminum chloride, and borax. Generally, increasing the concentration of an additive slows the breaking and curing times. This is useful when temperatures increase during the day.

3.0 MIX DESIGN

The performance of a slurry surfacing depends on the quality of the materials and how they interact during cure and after cure. The mix design procedure looks at the various phases of this process, which include:

- **Mixing:** Will the components mix together and form true, free flowing slurry?
- **Breaking and Curing:** Will the emulsion break in a controlled way on the aggregate, coat the aggregate, and form good films on the aggregate? Will the emulsion build up cohesion to a level that will resist abrasion due to traffic?
- **Performance:** Will the slurry surfacing resist traffic-induced stresses?

The steps in slurry design include:

- Prescreening of Materials
- Job Mix Design
- Final Testing

At each stage, mixing, breaking, curing, and performance issues are addressed.

3.1 PRESCREENING

Prescreening involves testing the physical properties of the raw materials. The emulsion type is selected based on job requirements and is checked against the requirements laid out in the specifications (Table 1). The aggregate is checked against specifications (Tables 2 and 3) and a simple mixing test is performed to assess compatibility with the emulsion. When both of these steps are satisfied, the job mix formula can be developed. During the overall process the materials may be changed at any time until satisfactory results are obtained.

3.2 JOB MIX DESIGN

3.2.1 Mixing Proportions

The ISSA test method (detailed in Technical Bulletin 102) determines the approximate proportions of the slurry mix components (5). In this test, a matrix of mix recipes are made up and the manual mixing time is recorded for each mixture. A minimum time is required to ensure that the mixture will be able to mix without breaking in the slurry machine.. At this stage, phenomena such as foaming and coating are visually assessed. Also at this stage, the water content and additive content can be determined to produce a quality mixture. Figure 3 illustrates a good slurry mixture consistency.

Figure 3: Good Mixture Consistency

The mixing time must be at least 180 seconds for a slurry seal at 25°C (77°F). The process may be repeated at elevated or reduced temperatures to simulate expected field conditions at the time of application. The best mix is chosen, based on good coating of mixing times in excess of the minimum required through the entire range of expected application temperatures.

3.2.2 Cohesion Build-up

Once the emulsion content is determined, three mixes are then made, one at the selected emulsion percentage from above, one at -2% of the selected emulsion content and one at +2% of the selected emulsion content. This allows a bracketing of the desired mix proportions. The ISSA test method detailed in TB 139 (5) is used to determine the cohesion build-up in a slurry mixture. This test may be performed at the expected field temperatures to provide the most accurate estimate of the treatment's characteristics. Table 4 lists mix requirements for slurry surfacing.

3.2.3 Abrasion Resistance (Wet Track Abrasion Test – WTAT)

Mixes are made at three emulsion contents, optimum, optimum +2%, and -2% of optimum. These mixes are then cured in circular molds for 16 hours at 60°C (140°F). The samples are then soaked for either 1 hour or 6 days, depending on the abrasion test (TB 100) (5) and the material. Slurry design requires a 1-hour soaking. After soaking, a standard rubber hose is orbitally ground over the surface of the sample (while still submerged) for a set period of time. The wear loss is then calculated. The test equipment is shown in Figure 4, while the abrasion resistance requirements are listed in Table 4.

The results of the abrasion test are plotted along with the specification requirements. This allows selection of the minimum binder content of the mixture.

Table 4: Typical Mix Requirements (7)

PROPERTY	TEST	SLURRY SEAL REQUIREMENTS
Wear Loss (Wet Track Test)	TB 100 (1 hr soak) (6 day soak)	800 g/m^2 max N/A
Traffic Time (Wet Cohesion Test)	TB 139 30 minutes 60 minutes	N/A 0.2 kg-m min
Adhesion (Wet Strip) Integrity SB	TB 114 TB 144	>90% N/A
Excess Binder	TB 109	
Deformation	TB 147	
Slurry Seal Consistency, mm	TB 106	30 max (slow set only)
Compatibility	T115	Pass

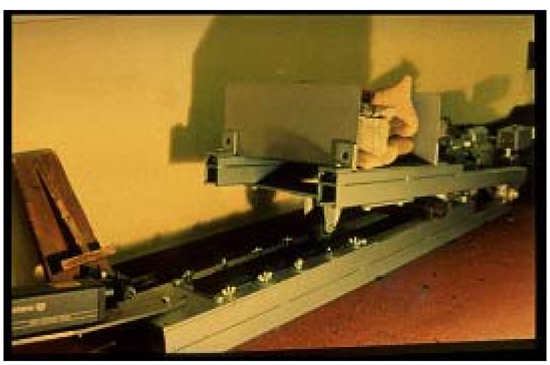
a) Mixer Equipped with sample Mold and Rubber Hose Attachment

b) Orbital Grinding of Sample Using Rubber Hose Attachment

Figure 4: Wet Track Abrasion Test Apparatus and Test in Progress

3.2.4 Upper Binder Limit

The upper binder limit is determined through the use of a deformation measurement. The Loaded Wheel Tester (LWT), the ISSA test procedure detailed in TB 147 (5), is used for the deformation measurement. In this test, a loaded wheel is placed on a cured strip of the mixture and the surface is tested. Once the surface has been tested, hot sand is poured onto the surface and the sample is then retested. When the second round of testing is complete, the amount of sand retained on the sample is measured. This provides a measure of the free asphalt on the surface of the sample. Figure 5 illustrates the test apparatus along with a series of tested samples.



a) Testing Apparatus

b) Tested Samples Showing Retained Sand

Figure 5: Loaded Wheel Test and Excess Asphalt Test Apparatus and Test Samples

3.2.5 Optimum Binder

The optimum percentage emulsion or binder content is found by plotting the results obtained from the Wet Track Test (TB 100) and the Excess Binder Test (TB 109) (5). Figure 6 illustrates a typical plot of test results. The optimum binder content is close to the intersection of the two plotted lines, but the testing does not account for all the factors influencing the mix. For example, the optimum binder content at the intersection of the plotted results is adjusted for the expected traffic conditions. A rule of thumb is to select the highest binder content that passes both tests for low traffic conditions and the lowest binder content for heavy traffic conditions. Note that this requires an experienced designer to select the optimum and this must be based on field knowledge and experience. This is a weakness in the current design process.

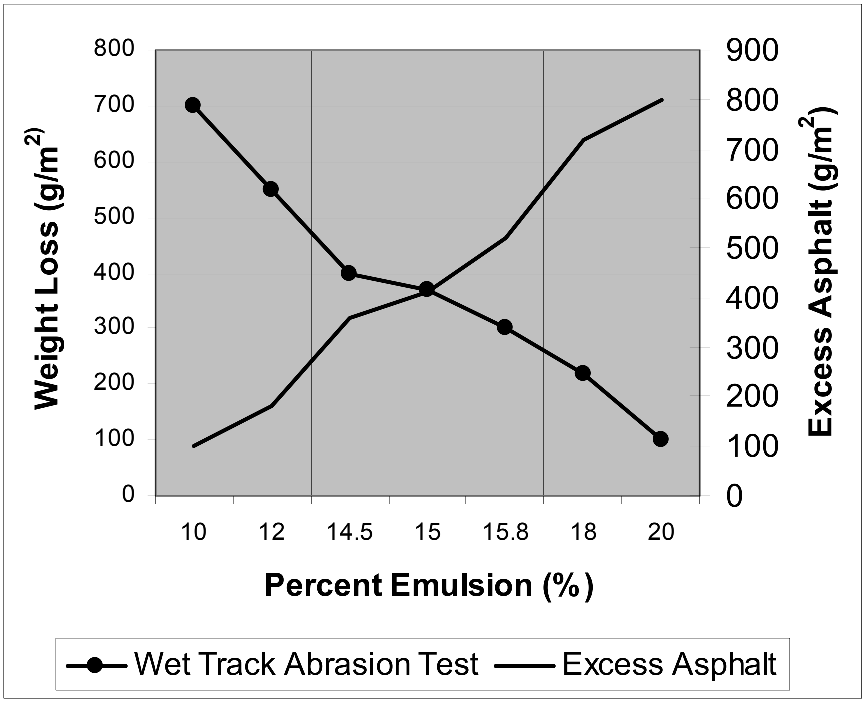


Figure 6: Determining Optimum Binder Content

3.3 FINAL TESTING

Once the job mix components have been selected, the mix is tested to determine its properties and ensure compliance with the specifications listed in Table 4. If the mix conforms to the specifications, the emulsion content and aggregate grading is reported as the job mix formula.

Field adjustments may be made to the job mix formula to accommodate climatic variables during application. As a result of the mix design process, adjustments are limited to the amount of additives (cement and retardant) and water content required to ensure a good homogeneous mix at the time of application.

4.0 PROJECT SELECTION

4.1 DISTRESS AND APPLICATION CONSIDERATIONS

Slurry surfacing may be used for a range of applications, but job selection is critical and often pretreatments such as pothole patching, crack sealing, and dig outs are required. Table 5 lists general job selection criteria for slurry surfacing treatments and typical application rates.

Table 5: Job Selection Criteria

APPLICATIONS	AGGREGATE TYPE		
	I	II	III
Void Filling	S	S	
Wearing Course (AADT)			
<100	S	S	
100-1000		S	S
1000-20,000			S
Minor Shape Correction (10-20mm)			S
Application Rates (kg/m2)	3.5-5.5	6-11	12-18
Key: (S = Slurry Seal)			

The main use of slurry surfacing materials is for pavement preservation as a part of a program of periodic surfacing before distresses appear. The main criteria for project selection are:

- Sound and well drained bases, surfaces, and shoulders.
- Free of distresses, including potholes and cracking.

Distress modes that can be addressed using slurry surfacing include:

- **Raveling:** Loose surfaces or surfaces losing aggregate may be resurfaced using slurry seals.
- **Oxidized pavement with hairline cracks:** These surfaces may be resurfaced using slurry seals.
- **Rutted pavements:** Deformation resulting from consolidation of the surfacing only. Rutting due to base failure of significant plastic deformation of the HMA cannot be treated except as a temporary measure.

Distress modes that cannot be addressed using slurry surfacing include:

- **Cracking** (including reflection cracking)
- **Base Failures** of any kind
- **HMA Layers** that exhibit plastic shear deformation

Slurry surfacing will not alleviate the cause of these distresses. As a result, the distresses will continue to form despite the application of a slurry surfacing.

4.2 LIFE EXPECTANCY OF SLURRY SURFACINGS

Slurry seals have been estimated to last around 5 to 7 years (6). Much longer service lives (up to 15 years) have been observed when the seals are placed as true preventive maintenance treatments on suitable roads (6). Traffic is not a limiting factor.

The main failure mechanism is wear. Over time, the surface oxidizes abrades under traffic. Premature treatment failure occurs from placement on highly deflecting surfaces, cracked surfaces, pavements with base failures, and on dirty or poorly prepared surfaces (resulting in delamination).

5.0 CONSTRUCTION PROCESS

The main components of the construction process include:

- Safety and Traffic Control,
- Equipment Requirements,
- Stockpile/Project Staging Area Requirements,
- Surface Preparation,
- Application Conditions,
- Types of Applications,
- Quality Issues,
- Post Construction Conditions, and
- Post-Treatments.

Appendix A, "Suggested Field Considerations", at the end of this chapter, provides a series of tables to guide project personnel through the important aspects of applying a slurry surfacing.

5.1 SAFETY AND TRAFFIC CONTROL

Traffic control is required both for the safety of the traveling public and the employees performing the work. Traffic control should be in place before work forces and equipment enter onto the roadway or into the work zone. Traffic control includes construction signs, construction cones and/or barricades, flag personnel, and pilot cars to direct traffic clear of the maintenance operation. For detailed Traffic Control requirements, please refer to the Caltrans project specifications and the Caltrans Code of Safe Operating Practice (7).

Traffic control is required to ensure that the slurry surfacing has had adequate time to cure prior to reopening to traffic. The curing time for the slurry surfacing material will vary depending on the pavement surface conditions and the weather conditions at the time of application. Additional traffic control considerations are listed in the Field Considerations section (Appendix A) of this chapter.

5.2 EQUIPMENT REQUIREMENTS

Equipment requirements for slurry machines are covered in Caltrans Standard Specifications Section 39 (2). Calibration requirements are discussed in California test method CT109. Modern equipment, as shown in Figure 7, can be used to place slurry seal.

A slurry seal spreader box is a drag box, as shown in Figure 8. The drag box is pulled behind the paver by means of chains. This box may or may not have augers; for quick set systems augers should be used. The slurry seal should be easy to work and spread, and not cause any hang-up in the box.

The design mix is proportioned by weight while the slurry surfacing machines deliver materials by volume. Due to this different nature of the measurements, it is essential that calibration be done with the actual job materials. No machine should be allowed to work on a Caltrans job without a proper calibration.

Figure 7: Slurry Surfacing Machine (8)

Figure 8: Slurry Seal Box with Augers (8)

5.3 STOCKPILE/PROJECT STAGING AREA REQUIREMENTS

The stockpile and project staging area must meet some basic requirements. These requirements include:

- A clean, well-drained pad for aggregate piles.
- A front-end loader for loading machines or Flow Boy-type vehicles in continuous operation.
- A salt-free water supply.
- An emulsion tanker.
- An additive tanker.

The stockpile and staging area should be as close as possible to the job site. Figure 9 illustrates a typical stockpile and staging area.

Figure 9: A Typical Stockpile and Project Staging Area

Operations should be scheduled to run as smoothly as possible and provide good traffic flow through the work zone. Aggregates that are below optimum moisture content should be remixed using the front-end loader to avoid segregation. In some cases aggregates that are separating in the stockpile or during loading may need to be sprayed with water to avoid fines loss.

5.4 SURFACE PREPARATION

The main objective of surface preparation is to provide a clean and sound surface on which the slurry surfacing is applied. The first step of surface preparation is to restore the pavement's structural integrity and functional performance characteristics through crack sealing and patching (see Chapters 3 and 4 of this guide for more information on these procedures).

Immediately before the slurry surfacing is applied, the road must be swept clean of all debris including clay and hard-to-remove materials (such as organic matter) are present, high power pressure washing may be required. If left on the road, these types of contaminants will cause delamination of the treatment in these areas. Thermoplastic road markings must also be removed prior to placing a slurry surface, or at least abraded to produce a rough surface. Paint markings require no pretreatment. Rubber on the roadway should be removed prior to applying a slurry surface.

Utility inlets should be covered with heavy paper or roofing felt adhered to the surface of the inlet. The paper is removed once the slurry surfacing has sufficiently cured. In addition to covering the inlets, all starts, stops, and handwork on turnouts should be done on roofing felt to ensure sharp, uniform joints and edges. Figure 10 illustrates the various surface preparation steps along with illustrations of delamination resulting from poor surface preparation.

5.5 APPLICATION CONDITIONS

The application conditions required are addressed in detail in the Caltrans Standard Specifications Section 39 (2). The basic requirement for success is that the emulsion must be able to break and form continuous films, as it is the only way a slurry mixture can become cohesive. As a result, humidity, wind conditions, and temperature (both surface and air) are important and need to be considered. Modifications to additives should be made according to the changing environment during application. In any case, application of a slurry seal is generally not suitable for night work. This is due to the lower evaporation rate at night, which results in longer breaking and curing times.

For a conventional slurry seal project, air temperature should be a minimum of 10°C (50°F) and rising. Humidity should be 60% or less and a slight breeze is advantageous. Work should not be started if rain is imminent. Slurry seals will typically resist rain induced damage after as little as one hour but typically require at least three hours to cure to a fully waterproof state. Additionally, breaking time for a slurry is effected by temperature. Work should not be started if freezing temperatures are anticipated within 24 hours of construction. Figure 11 shows the effect of temperature on the breaking rate of emulsion.

5.6 QUALITY ISSUES

Quality control is critical during the constriction process to achieve a uniform surface finish. The main areas of concern are discussed below.

5.6.1 Longitudinal Joints

Longitudinal joints may be overlapped or butt jointed. They should be straight or curve with the traffic lane. Overlaps should not be in the wheel paths and should not exceed 75 mm (3 in) in width. Figure 12 illustrates high quality and poor quality longitudinal joints.

a) Sweeping

b) Dirty surfaces Result in Poor Adhesion (Delamination)

c) Cover Utilities with Kraft Paper

d) Slurry Covers Inlet and Paper Cover

e) Peel Off Paper Covering Once Treatment has Cured

f) Starting Transverse Joints on Roofing Felt Produces Clean Joints

Figure 10: Surface Preparation Methods

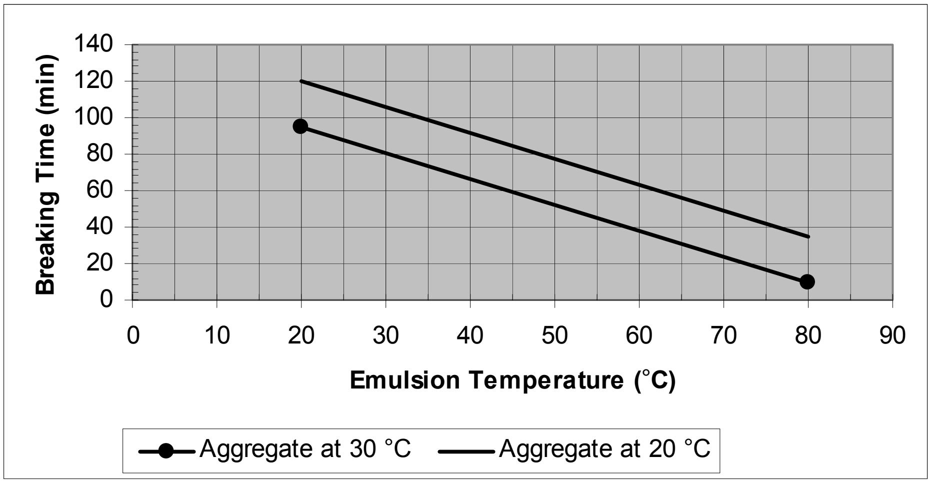


Figure 11: Effect of Temperature on Break Rate

a) High Quality Longitudinal Joint

b) Poor Quality Longitudinal Joints

Figure 12: Longitudinal Joints

5.6.2 Transverse Joints

Transverse joints are inevitable when working with batch systems; every time a truck is emptied a transverse joint is required. Transitions at these joints must be smooth to avoid creating a bump in the surface. The joints must be butted to avoid these bumps and handwork should be kept to a minimum. The main difficulty in obtaining a smooth joint occurs as the slurry machine starts up at the joint. Some contractors tend to over wet (add too much water) to the mix at start-ups. This leads to poor texture and scarring at the joints. Starting transverse joints on roofing felt can eliminate these problems. Figure 13 illustrates high quality and low quality transverse joints.

a) High Quality Transverse Joint **b) Low Quality Transverse Joint**

Figure 13: Transverse Joints

5.6.3 Edges and Shoulders

Slurry sealed edges and shoulders can be rough and look poor. The edge of the spreader box should be outside the line of the pavement and edge boxes should be used when shoulders are covered. Figure 14 illustrates high quality and poor quality edge and handwork.

a) High Quality Edges and Shoulder **b) Poor Quality Edges and Shoulder**

Figure 14: Edges and Shoulders

5.6.4 Uneven Mixes and Segregation

Poorly designed slurry mixtures or mixtures with low cement content or too high a water content may separate once mixing in the box has ceased. This leads to a black and flush looking surface with poor texture. Separated mixes may lead to a "false slurry" where the emulsion breaks onto the fine material. In such instances delamination may occur, resulting in premature failure. These types of mixes can be recognized as non-uniform mixes that appear to be setting very slowly. Figure 15 illustrates segregation and delamination resulting from a false slurry.

a) Segregation

b) Delamination from a False Slurry

Figure 15: Poor Mixes

5.6.5 Smoothness Problems

Slurry mixtures follow the existing road surface profile and thus do not have the ability to significantly change the pavement's smoothness. However, when using stiffer mixes the spreader box may, if incorrectly set up, chatter or bump as the material is spread and produce a washboard effect. The chattering may be addressed by making the mixture slower to set, adjusting the rubbers on the box, or adding weight to the back of the spreader box. Figure 16 illustrates the washboard effect.

Figure 16: Wash Boarding Effect

5.6.6 Damage Caused by Premature Reopening to Traffic

The slurry seal must build sufficient cohesion to resist abrasion due to traffic. Early stone shedding is normal, but should not exceed 3%. If a mixture is reopened to traffic too early it will ravel off quickly, particularly in high stress areas. It is important that the mixture has formed adequate cohesion before it is opened. Choosing the right time to reopen a surface to traffic is based largely on experience. However, a general rule of thumb for a slurry seal is that it can be opened when it has turned black. Figure 17 illustrates raveling caused by premature opening to traffic.

Figure 17: Traffic Damage Caused by Early Trafficking

5.7 POST CONSTRUCTION CONDITIONS

Emulsion systems do not lose all water in the first hours after placement; the total water loss process can take up to several weeks. During this period the surface will be water resistant; however, if the water freezes, it can cause rupture of the binder film and subsequent raveling. For this reason, projects should not be started without a 2-week window when freezing weather will not occur.

Asphalt emulsion based systems cannot re-emulsify; however, if not fully cured, these systems can be tender enough to re-disperse under the effects of traffic loading and excessive water, especially ponding water. In this process, broken aggregates or asphalt particles that have not fully coalesced into films are dispersed in water, which disintegrates the emulsion. Thus, while light rain 3 hours after placing a slurry seal is acceptable, heavy rain coupled with heavy traffic will likely lead to surface damage, especially in high shear (e.g., turning movement) areas. Figure 18 illustrates damage caused by heavy rain in a high shear location.

Figure 18: Damage Due to Post Application Heavy Rain with Shear

5.8 POST TREATMENTS

5.8.1 Rolling

Slurry seals will lose stone until the surface voids have been closed off, but it is acceptable for approximately 3% of surface stone to be lost. To limit the amount of loss, rolling with pneumatic rollers may be incorporated. For rut filling applications, rolling is almost always recommended. The roller should be light (6-7 tonnes maximum) and non-ballasted. One to two passes at a slow speed are recommended. This allows the water to be pressed to the surface, promoting evaporation and curing. Larger stones will be punched into the surface, reducing early raveling. Figure 19 illustrates a typical roller operation.

Figure 19: Rolling a Slurry Surfacing

5.8.2 Sweeping

On heavily trafficked roads or where opening has lead to excessive stone loss, sweeping is essential. A suction broom is the best type of sweeper to use. Sweeping should be done just prior to opening to traffic and at periods determined by the level of stone loss. Figure 20 illustrates a suction broom.

5.8.3 Sanding

Sanding may be used to reduce the times that cross streets or intersections are closed. Sanding is the application of a fine layer of dry, washed sand that is broadcast over the slurry surface. Sanding may also be used on wet spots. Sanding should not be done until the slurry can withstand walking traffic. Figure 21 illustrates the use of sanding at a cross street.

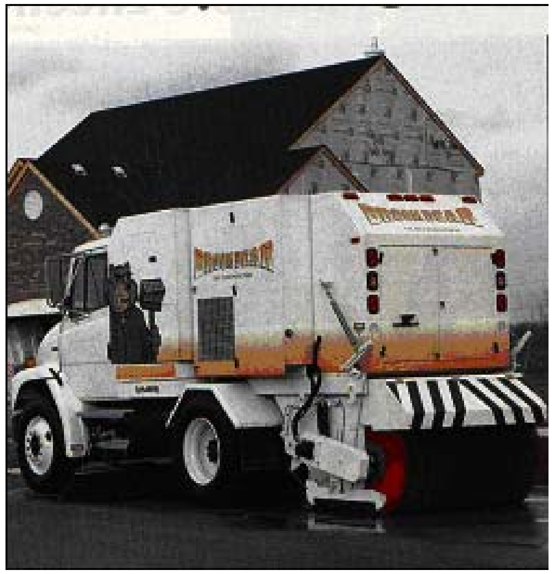


Figure 20: Sweeping with a Suction Broom

Figure 21: Sanding at a Cross Street

6.0 TROUBLESHOOTING

This section provides information to assist the maintenance personnel in troubleshooting problems with slurry seals along with "dos and don'ts" that address common problems that may be encountered during the course of a project. The troubleshooting guide presented in Table 6 associates common problems to their potential causes. For example, an unstable emulsion, too little water in the mix, incompatibility between the emulsion and the aggregate, and so on, may cause a slurry surface to delaminate.

Table 6: Trouble Shooting Slurry Seal Job Problems

CAUSE	PROBLEM									
	BROWN	WHITISH	WON'T SET	POOR COATING	DELAYED OPENING TO TRAFFIC	BREAKS IN BOX	RAVELS	FLUSHES	DELAMINATION	SEGREGATION
EMULSION										
Emulsion Unstable				•		•			•	
Emulsion too Stable	•		•		•		•			
Emulsion too hot						•				
Too Little Emulsion	•			•			•			
Too Much Emulsion								•		
MIX										
Too many fines				•		•	•			
Too much cement		•				•				
Too little cement			•		•		•			•
Too little additive				•		•	•			
Too much additive		•	•		•		•			
Too much water	•		•		•		•	•		•
Too little water		•		•		•	•		•	
Aggregate/emulsion not compatible			•	•	•		•		•	•
CONDITIONS										
Too hot	•			•		•	•	•		
Too cold			•		•		•		•	
Rain	•		•	•	•		•	•	•	
High humidity		•	•							
SURFACE										
Fatty			•					•		

In addition to the troubleshooting guide, Table 7 lists some commonly encountered problems and their recommended solutions.

Table 7: Common Problems and Related Solutions

PROBLEM	SOLUTION
UNEVEN SURFACE – WASH BOARDING	• Ensure the spreader box is correctly set up. • Ensure the viscosity of the mix is not too high. • Make adjustments so that the mix does not break too fast. • Wait until the ambient temperature is lower. • Use water sprays on the front of the spreader.
POOR JOINTS	• Reduce the amount of water at start up. • Use water spray if runners of spreader box are running on fresh material.
EXCESSIVE RAVEL	• Add cement and reduce additive so that the mix breaks and cures faster. • Check aggregate to ensure the clay fines are not too high. • Control traffic longer and at low speeds. • Wait until fully cured before allowing traffic. • Wait until mix is properly set before brooming or opening to traffic.

7.0 REFERENCES

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APPENDIX A

SUGGESTED FIELD CONSIDERATIONS FOR SLURRY SURFACING PROJECTS

The following tables are guides to the important aspects of performing a slurry surfacing project. The tables list items that should be considered in order to promote a successful job outcome. As thoroughly as possible the answers to these questions should be determined, as required, before, during, and after construction. The appropriate staff to do this will vary by job type and size. Some topics may need attention from several staff members. The field supervisor should be acquainted with its contents.

The intention of the table is not to form a report but to bring attention to important aspects and components of the slurry surfacing project process. Some information is product specific and contained in the relevant standard specifications, special standard provisions, or special provisions.

PRELIMINARY RESPONSIBILITIES	
PROJECT REVIEW	• Is the project a good candidate for slurry surfacing? • What is the depth and extent of any rutting? • How much and what type of cracking exists? • Is crack sealing needed? • How much bleeding or flushing exists? • Is the pavement raveling? • What is the traffic level? • Is the base sound and well drained? • Review project for bid/plan quantities.
DOCUMENT REVIEW	• Bid specifications. • Mix design information. • Special provisions. • Construction manual. • Traffic control plan (TCP).
MATERIALS CHECKS	• Has a full mix design and compatibility test has been completed? • Is the binder from an approved source (if required)? • Has the binder been sampled and submitted for testing? • Does the aggregate meet all specifications? • Is the aggregate clean and free of deleterious materials? • Is the aggregate dry? • Is the emulsion temperature within application temperature specifications?

PRE-SEAL INSPECTION RESPONSIBILITIES	
SURFACE PREPARATION	• Is the surface clean and dry? • Have all pavement distresses been repaired? • Has the existing surface been inspected for drainage problems?
EQUIPMENT INSPECTION CONSIDERATIONS	
BROOM	• Are the bristles the proper length? • Can the broom be adjusted vertically to avoid excess pressure?
SLURRY SEAL EQUIPMENT	• Has each machine been calibrated with the project's aggregate and emulsion? • Who carried out calibration and what documentation has been provided? • Is the machine fully functional? • Has the machine been calibrated for this project's aggregate and certified. Is the spreader rubber clean and not worn? • Is the texture rubber clean and set at the right angle? • Are all paddles in the pug mill intact? • Is the spreader box clean?
ROLLERS (IF USED)	• Do the roller tire pressures comply with the manufacturer's specification? • What type roller will be used on the project (pneumatic-tired roller recommended)? • Do the roller tire size, rating, and pressures comply with manufacturer's recommendations? • Is the pressure in all tires the same? • Do all tires have a smooth surface?
STOCKPILE	• Is the stockpile site well drained and clean? • Does the Contractor have all of the equipment required at the stockpile site (loaders, tankers, and so on)?

EQUIPMENT INSPECTION CONSIDERATIONS	
EQUIPMENT FOR CONTINUOUS RUN OPERATIONS	• Is all equipment free of leaks? • Are Flow boys or other nurse units clean and functional? • Are there enough units to allow continuous running with minimal stops for cleaning box rubbers?
SITE CONSIDERATIONS	
WEATHER REQUIREMENTS	• Have air and surface temperatures been checked at the coolest location on the project? • Do air and surface temperatures meet agency requirements? • Are adverse weather conditions expected? High temperatures, humidity, and wind will affect how long the emulsion takes to break. • The application of the slurry surfacing does not begin if rain is likely? • Are freezing temperatures expected within 24 hours of the completion of any application runs?
TRAFFIC CONTROL	• Do the signs and devices used match the traffic control plan? • Does the work zone comply with Caltrans requirements? • Flaggers do not hold the traffic for extended periods of time? • Unsafe conditions, if any, are reported to a supervisor (contractor or agency)? • The pilot car leads traffic slowly, 40 kph (24 mph) or less? • Signs are removed or covered when they no longer apply?
APPLICATION CONSIDERATIONS	
DETERMINING APPLICATION RATES	• Have agency guidelines and requirements been followed? • Have rut filling and leveling course application rates been calculated or estimated separately? • Has a full mix design been done? • Is more material applied to dried-out and porous surfaces? • Is more material applied on roads with low traffic volumes? • Is less material applied to smooth, non-porous, and asphalt-rich surfaces? • Has moisture content been adjusted in the application rate?

PROJECT INSPECTION RESPONSIBILITIES	
SLURRY SURFACING APPLICATION	• Has a test strip been done and is it satisfactory? • Have field tests been carried out and are the results within specification? • Are enough trucks on hand to keep a steady supply of material for the slurry machine? • Does the application start and stop with neat, straight edges? Will an edge box be used? • Does the application start and stop on building paper or roofing felt? • Are drag marks present due to oversize aggregate or dirty rubbers? • Are rubbers cleaned regularly and at the end of each day? • Does the machine take a straight, even line with minimal numbers of passes to cover the pavement? • Is the mix even and consistent? • Are fines migrating to the surface? • Is the application stopped as soon as any problems are detected? • Does the application appear uniform? • Does the surface have an even and uniform texture? • Is the application rate checked based on amounts of aggregate and emulsion used? • What is the time between spreading, foot traffic, and opening to vehicular traffic?
ROLLING	• Does rolling wait until the mat is stable? Roller is 5-6 tonnes (7) maximum. • Is the entire surface rolled only once? • Do the rollers travel slowly, 8-9 kph (5 mph) maximum?
TRUCK OPERATION	• Are trucks staggered across the fresh seal coat to avoid driving over the same area? • Do trucks travel slowly on the fresh seal? • Are stops and turns made gradually? • Do truck operators avoid driving over the new slurry? • Do truck operators stagger their wheel paths when backing into the paving unit?
LONGITUDINAL JOINTS	• Is the meet line overlapped a maximum of 75 mm (3 in)? • Do the spreader box runners avoid running on fresh mat? • Are the meet lines made at the center of the road, center of a lane, or edge of a lane not in the wheel paths?

PROJECT INSPECTION RESPONSIBILITIES	
TRANSVERSE JOINTS	• Do all applications begin and end on building paper or roofing felt? • Mixture is not too wet at start up? • Is the building paper or roofing felt disposed of properly?
BROOMING	• Does brooming begin after the slurry surfacing can carry traffic? • Does brooming dislodge the slurry surfacing? • Is the surface raveling? Follow-up brooming should be done if raveling is high or if traffic is high.
OPENING THE SLURRY SURFACING TO TRAFFIC	• Does the traffic travel slowly — 40 kph (24 mph) or less—over the fresh slurry surfacing? • Are reduced speed limit signs used when pilot cars are not used? • After brooming, have pavement markings been placed before opening to traffic? • Have all construction-related signs been removed when opening to normal traffic?
CLEAN UP	• Have all loose aggregate from brooming been removed from traveled way prior to opening to traffic? • Have all binder spills been cleaned up?

Disclaimer

This chapter is 1 of 8 included in the Caltrans Maintenance Technical Advisory Guide (TAG). The information presented in this chapter is for educational purposes only. It does not represent a policy or specification nor does it endorse any of the products and/or processes discussed.

CHAPTER 8 THIN MAINTENANCE OVERLAYS

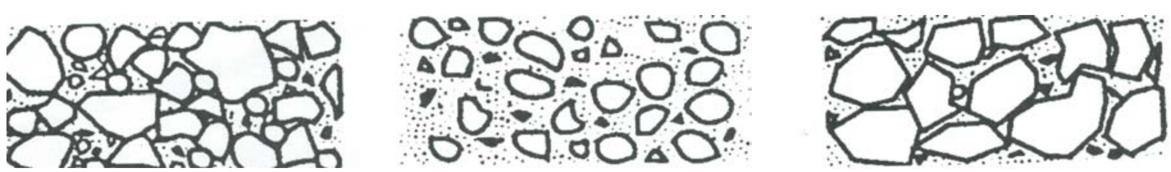
1.0 INTRODUCTION

For the purposes of this advisory, maintenance overlays are defined as thin treatments using a hot mix system as defined in the Standard Specifications or Standard Special Provisions of the California Department of Transportation (1-10). A thin treatment for the purposes of this chapter is a non-structural layer and is applied as a maintenance treatment, either corrective or preventive. Nationally, thin treatments are less than 37.5 mm (1.5 inches) in thickness. In Caltrans, thin blankets are 30 mm (1.2 inch) thick.

Historically, three maintenance overlay types have been used extensively by Caltrans, either alone or in combination with other treatments such as Stress Absorbing Membrane Inter-layer (SAMI). They include:

- Dense Graded Thin Blankets (Type A and B)
- Open Graded (Conventional Type O and Type O-High Binder)
- Gap Graded Mixes (Type G)

The different mixes are defined based on their aggregate grading, binder content, and voids content. Figure 1 illustrates, in general, the differences in aggregate structure for these mix types.



a) Dense Graded b) Gap Graded c) Open Graded

Figure 1: Stone Matrices Created by Different Gradings (12)

This chapter describes each of these mix types in further detail and provides an overview of the design and construction of these mixtures.

2.0 DENSE GRADED THIN OVERLAYS

2.1 WHAT IS A DENSE GRADED OVERLAY?

Dense graded mixtures have an aggregate structure that is continuously graded (sized) from the largest to the smallest aggregate in the system. They are mixed in a continuous drum type hot mix plant or a batch plant. Normally AR-4000 or 8000 asphalts are used in these mixes; however the asphalts may be modified to adjust properties for different climatic and anticipated distress conditions. For example, performance based asphalts (PBA-6) may be used if it is anticipated that thermal cracking may occur due to a single severe temperature drop (13) and/or during cooler (night) paving conditions. Asphalt rubber (wet process) is not usually used in dense graded mixtures due to the more difficult compaction characteristics associated with thin layers and less resistance to reflective cracking.

The aggregate gradations for dense graded mixes are provided in the Standard Specifications (1).
It should be noted that for thin overlays of 25 to 37 mm (1 to $1^1/_2$ in) the stone size is limited to a maximum of one-half the thickness of the layer. Hence, 19 mm (0.75 in) is not usually used and 12.5 mm (0.5 in) medium mixes are usually the upper limit. Table 1 shows the required aggregate physical requirements as specified in the Standard Specifications (1).

Table 1: Aggregate Requirements for Asphalt Concrete Mixes (1)

Tests	California Test	Asphalt Concrete Type	
		A	B
Percentage of Crushed Particles:	**205**		
Coarse Aggregate (Min.)		**90%**	**25%**
Fine Aggregate (Passing 4.75-mm, Retained on 2.36-mm) (Min.)		**70%**	**20%**
Los Angeles Rattler:	**211**		
Loss at 100 Rev. (Max.)		**10%**	**—**
Loss at 500 Rev. (Max.)		**45%**	**50%**
Sand Equivalent:	**217**		
Contract Compliance (Min.)		**47**	**42**
Operating Range (Min.)		**50**	**45**
Film Stripping (Max.)[a]	**302**	**—**	**—**
K_c Factor (Max.)	**303**	**1.7**	**1.7**
K_f Factor (Max.)	**303**	**1.7**	**1.7**

[a] After mixing with asphalt binder.

2.2 PERFORMANCE

Dense graded mixtures have relatively low air void contents and are designed as an abrasion resistant and functionally impermeable wearing course. Historically, dense graded mixtures have been the most commonly used mix type for overlaying asphalt or portland cement concrete pavements. The following paragraphs provide a brief overview of the distresses that occur in dense graded thin overlays as well as the factors influencing job selection, service lives, and costs.

2.2.1 Distresses Addressed

Conventional dense graded thin overlays should only be placed on structurally sound pavements. That is because they offer little structural improvement, but they can renew the surface in terms of functional performance (i.e., ride quality). They can be used to mitigate the following distresses present in an existing pavement:

- Raveling
- Oxidation
- Minor cracking
- Minor surface irregularities
- Skid problems
- Pavement water proofing (requires correct tack coating practices)

When used in association with a SAMI, or fabric interlayer, they may also address reflective cracking. In addition, modified systems such as PBA 6a and PBA 6b can be used to address low temperature cracking and reflective cracking.

2.2.2 Primary Distress Modes

Dense graded thin overlays exhibit the following distress modes:

- Permanent deformation due to heavy traffic and high temperatures.
- Fatigue cracking due to repeated traffic loading.
- Reflection cracking due to cracks in the existing pavement reflecting up through the overlay.
- Raveling due to a number of factors including oxidation and hardening of the binder, water damage, low binder content, and low compaction.
- Stripping (water damage) caused by binder-aggregate incompatibility.
- Delamination due to poor compaction and/or tack coat practices.

Often, these can be addressed by selection of the correct binder and proper mix design. The principal failure modes of dense graded thin overlays are delamination, raveling and cracking due to poor compaction. Thin layers cool faster than thick layers reducing the time available for proper compaction. Thus, if a thin overlay is not compacted to the target air voids, it will tend to be less cohesive and ravel or delaminate.

2.2.3 Job Selection

Thin blanket overlays should only be used on sound pavements where minor defects may be present and all construction requirements can be met, especially compaction. Variables that affect job selection include:

- **Traffic Loading:** In low volume roads, variations in traffic need to be taken into account. Selection should be based on the worst-case scenario. For high volume roads, the principal failure modes are fatigue cracking and permanent deformation. To resist fatigue cracking a thin blanket can be used to extend the pavement life for 1-3 years depending on the mix type.

- **Existing Pavement Condition:** Dense graded thin overlays should only be used on pavements that do not possess a significant amount of distress. For example, existing pavements with significant quantities of medium to high severity fatigue cracking are poor candidates for a thin overlay. Conversely, pavements that possess distresses that affect the functional performance of the existing pavement (e.g., rideability, poor skid resistance, oxidation, etc.) are generally good candidates for thin overlays provided that a structural enhancement of the existing pavement is not required. Sometimes a thin overlay (with a SAMI) is placed over poor roads to prolong the period until rehabilitation.

- **Environment:** With proper mix design (i.e., appropriate binder type and content for a given aggregate type and gradation) these mixes have been successfully used in a range of climates. In all climates fatigue cracking can be the principle mode of failure. In hot climates permanent deformation (rutting) can be the principle mode of failure whereas in climates where large temperature swings occur thermal cracking can be the principal mode of failure. Use of a dense graded thin overlay must take into account the climate in which it is placed in order to avoid distresses that commonly occur in a particular climate.

- However, in practice, Caltrans maintenance typically overlays medium to high fatigue cracked pavements to slow deterioration and prevent pot holes from occurring. The thin overlay is often a stop gap treatment until the proper corrective action can be taken.

2.2.4 Service Life and Costs

Dense graded thin overlays have been shown to last 2 to 10 years, but more commonly last between 4 and 6 years (11). The life of the overlay is directly affected by the condition of the existing pavement that received the overlay, the climate (environmental conditions) in which the overlay was placed, and the traffic loading experienced by the overlay. For example, a thin overlay placed on a pavement in poor condition would not be expected to last as long as one placed on a pavement in good condition. Similarly, a thin overlay placed on a pavement in good condition but with heavy traffic would not be expected to last as long as one placed on the same pavement, but with much lighter traffic.

Numerous factors influence the cost of dense graded thin overlays. Several of the principle factors contributing to the cost of placing a dense graded thin overlay include:

- Materials (binder and aggregate with or without modifiers).
- Location of the project (e.g., urban versus rural area, proximity to hot mix plant, etc.).
- Thickness of the overlay.
- Special construction requirements (e.g., stricter control of compaction relative to conventional overlays or night work).

Chapter 2 provides a simplified method of selecting cost effective treatments.

2.3 DESIGN AND SPECIFICATIONS

The Hveem method, developed by Caltrans Translab in the 1940s, is presently used for dense graded hot mix design. The Hveem method is covered extensively through various references (1, 13, 14, 16) and the test methods may be found on http://www.dot.ca.gov/hq/esc/ctms/indexhtml.

The Hveem method uses a series of test methods to determine optimum binder content. These test procedures include use of a centrifuge to measure surface porosity and particle roughness (CT303). CT206 and 208 are used to measure the specific gravity of the fine and coarse aggregate respectively. Knowing the specific gravity of the fine and coarse aggregate and conducting CT 303 leads to the approximate bitumen ratio). A series of test specimens is prepared at a range of asphalt contents above and below the approximate bitumen ratio (i.e., approximate binder content). This preparation method uses a kneading compaction device. A stability test to evaluate the resistance to deformation (CT366) is performed, as well as a swell test to determine the effect of water on volume change and permeability of the specimen (CT305). Finally the specimens are tested for moisture vapor susceptibility (CT307) to determine the extent to which the stability values are affected by moisture vapor. Table 2 shows the required properties of the mixture as specified in the Standard Specifications (1).

Table 2: Mix Properties (1)

TESTS	CALIFORNIA TEST	ASPHALT CONCRETE TYPE	
		A	B
Swell (Max.) (Millimeters)	**305**	**0.76**	**0.76**
Moisture Vapor Susceptibility (Min.)	**307**	**30**	**25**
Stabilometer Value (Min.):			
(9.5-mm & 4.75-mm Max. AC)	**366**	**30**	**30**
All Others	**366**	**37**	**35**

2.4 MATERIAL REQUIREMENTS

Dense grade asphalt concrete (DGAC) must be comprised of materials capable of resisting degradation during construction as well as providing good long-term durability. Thus, the aggregates must be sufficiently hard to resist breakage during compaction and be sufficiently compatible with the binder so as to resist de-bonding of the binder in the presence of water (i.e., resist stripping). Other characteristics, such as particle shape, are also important. Similarly, the binder must be of sufficient quality to resist the effects of aging (i.e., oxidation and associated hardening). In this sense, it is desirable to have a relatively soft binder or to have a mixture with a relatively thick binder film. However, the binder must also be hard (stiff enough) and the mixtures not have too thick a binder film so as to resist permanent deformation. Thus, the binder grade (e.g., AR 4000, AR 8000, etc.) are often selected to resist these conflicting requirements. Modified binders can be incorporated into the mixture to assist in optimizing resistance to a particular distress mode.

Chapter 1 has more information on materials requirements. Additional information on the use of performance-based asphalts (PBAs) can be found in Caltrans Standard Special Provision S8-M20 (10). Information on the use of rubber-modified mixtures can be found in the Caltrans Asphalt Rubber Usage Guide (17).

2.5 CONSTRUCTION

2.5.1 Manufacture

Aggregates and binder are mixed using either a batch plant or drum mixing plant (1). References 13 and 14 have extensive sections on plant types and correct operation. Important factors prior to mixing are appropriate storage of binder and aggregates and adequate drying of aggregates. Correct proportioning of aggregates and binder is important as is correct mixing temperatures (see Chapter 1) to allow full coating of the aggregates during the actual mixing process.

2.5.2 Storage

DGAC may be stored in silos for no more than 18 hours. Material with hardened lumps cannot be used. The Standard Specifications (1) details storage silo requirements as does References 13 and 14.

2.5.3 Hauling

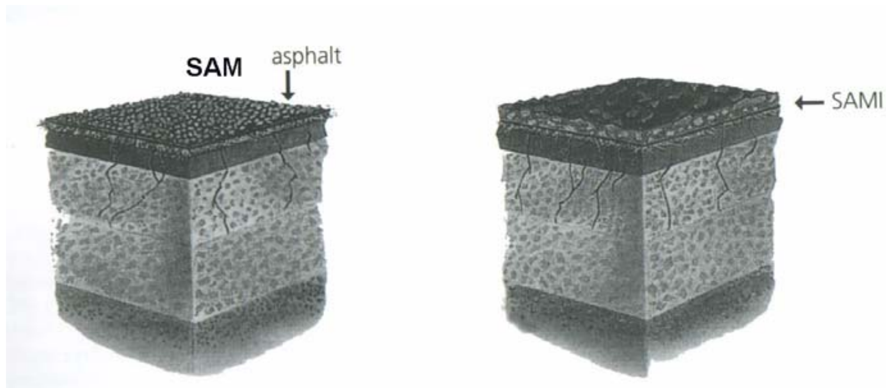
Standard hauling equipment (i.e., end dump vehicles, bottom dump vehicles, or live bottom dump vehicles) may be used for the construction of dense graded thin overlays. Reference 14 contains further information regarding these types of vehicles. Tarping is advised to prevent any crusting of the mixture (i.e., hardening of the first few centimeters of the mixture exposed to ambient temperatures), especially in night and cool weather work with modified mixes, or when long haul distances are required. Release agent should be used on the truck tray. On no account should diesel or other petroleum materials be used as release agents as these will soften the mixture.

Care must be taken in handling the mixture to ensure segregation does not occur. This may happen if the mix is not correctly loaded at the plant, is poorly designed, or not handled correctly. For larger jobs, a re-mixer “shuttle buggy” might be considered.

2.5.4 Surface Preparation

Surface preparation is critical for good performance of any overlay. Thin maintenance overlays should only be placed on sound pavements. This means that pavement failures must be repaired first. Cracks should be sealed and any pot holes patched. Crack sealing and patching practices were covered in Chapters 3 and 4, respectively.

In some cases a SAM or SAMI (Figure 2) may be used over pavements with low severity fatigue cracking in small quantities (e.g., isolated areas). The overlay may be applied a year or more after a SAM seal or immediately following application of a SAMI. Surfaces should be thoroughly swept before application of the overlay to remove debris that could prevent a good bond between the existing pavement and the overlay. Flushing with water may be needed where the pavement is exposed to agriculture product drippings.



a) Stress Absorbing Membrane Seal **b) Stress Absorbing Membrane Interlayer**

Figure 2: SAM Seal and SAMI (12)

2.5.5 Tack Coat (Paint Binder)

Tack coats are applications of asphalt sprayed onto an existing pavement prior to an overlay being applied. The tack coat promotes adhesion between old and new pavement layers (15).

Good tack coat practice must be followed. The Standard Specifications Section 39-4.02 (1) specifies how to apply tack coats in a manner satisfactory to Caltrans. Surfaces must be clean before the tack coat is applied. If a good bond is not formed between the thin overlay and the existing pavement, it can de-bond resulting in a slippage failure or delamination. If too much tack coat is applied, it may bleed up through the layer, especially under heavy traffic.

Tack coat should be applied via a calibrated distributor with nozzles set at an angle of about 30 degrees to the spray bar. The height should allow a triple overlap (see Chapter 4). The tack coat must be applied in one application at a rate from 0.10 to 0.45 l/m^2 (0.02 to 0.10 gal/yd^2), with the exact rate determined by the Engineer (1).

2.6 LAYDOWN

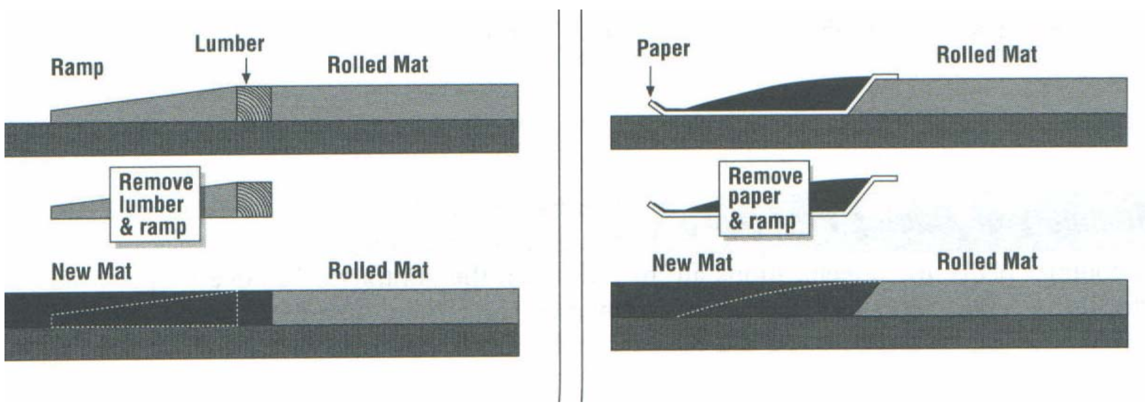
Dense graded mixes may be windrowed ahead of the paver and picked up with a pick up device (loader) and deposited in the paver hopper. The length of the windrow must be as short as possible to ensure excessive cooling does not occur. If conditions are good (i.e., little or no wind and higher temperatures), this is usually about 50 meters (160 ft) maximum (11). If conditions are poorer than this, the length of the windrow should be kept less than 50 meters (160ft). Table 3 summarizes minimum application temperatures for the various stages of the construction process. Every effort should be made to avoid segregation of the mixture during the paving operation. In addition, mix that is left in the paver hopper too long and, thus, allowed to cool below the minimum laydown temperature should not be combined with fresh mix.

Table 3: Recommended Application Temperatures (1-10)

MATERIAL	MINIMUM AIR TEMPERATURE, (ºC)	MINIMUM MIX LAYDOWN TEMPERATURE, (ºC)	MINIMUM BREAKDOWN ROLLING TEMPERATURE, (ºC)	MINIMUM FINISHING TEMPERATURE, (ºC)
CONVENTIONAL (AR 4000)	10	125	120	95
PBA	10	125	125	95

**These are minimum temperatures. It is recommended that spreading and compacting be performed at temperatures above these minimums, but not to exceed 163°C (325°F).*

When paving operations are to be discontinued for an extended period (e.g., end of day), it is necessary to construct a transverse joint across the pavement being placed. This can be accomplished in a number of ways and the type of joint constructed depends primarily on whether or not traffic will be allowed to travel over the joint between the time the joint is constructed and paving operations resume. If traffic won't be allowed to travel over the joint, it is recommended that a butt joint be constructed as illustrated in Figure 3a. Conversely, if traffic is allowed to travel over the joint, it will be necessary to construct a tapered joint as illustrated in Figure 3b. References 13 and 14 provide detailed guidance for constructing transverse joints.



a) Butt Joint **b) Tapered Joint**

Figure 3: Transverse Joint Formation (13)

Longitudinal joints occur between adjacent travel lanes or between travel lanes and a paved shoulder. During the paving operation of a lane of pavement, the material along the edge of the pavement (i.e., where the longitudinal joint will exist) normally has about a 60-degree incline relative to the surface of the existing pavement. Prior to placement of the adjacent lane of pavement (or shoulder), this material can be either cut back (using a saw or cutting wheel attached to a grader or front-end loader) by about 50 mm (2 in) to create a vertical face, or an overlapping joint can be constructed.

Whenever a joint is created by "cutting back the joint," tack coat should be applied to the newly exposed face of the longitudinal joint. Cutting back the joint helps to ensure that adequate density of the mixture exists at the longitudinal joint.

Properly overlapping, raking, and compacting the longitudinal joint can typically also result in adequate joint density. Figure 4 illustrates compaction of an overlapped joint. If the mix along the joint is clean, a tack coat is not normally needed prior to placement of the adjacent lane of pavement.

Reference 13 provides detailed guidance for constructing longitudinal joints.

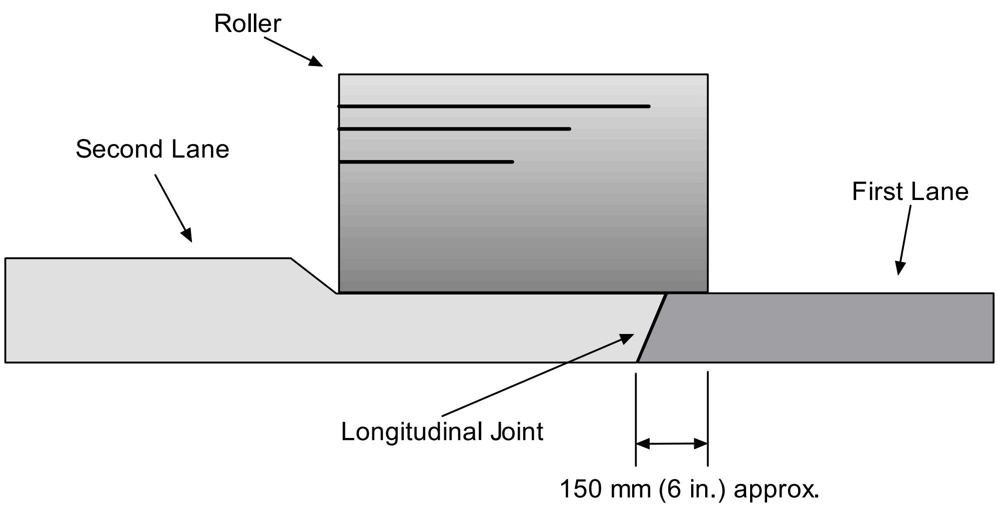


Figure 4: Formation of Longitudinal Joints (13)

2.6.1 Rolling

There are several stages of rolling used for dense graded mixtures. Because thin layers lose temperature rapidly, the rolling temperatures must be strictly monitored. The stages for compaction include initial breakdown using a vibratory roller, kneading compaction using a pneumatic roller, and finishing using a static roller as illustrated in Figure 5 (21). The actual temperatures would vary some based on binder type.

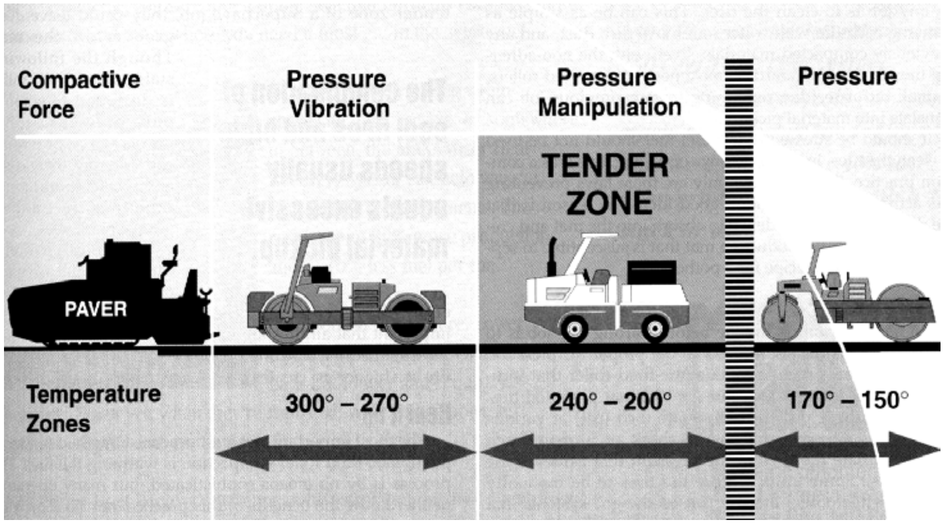


Figure 5: Rolling Regimes (21)

2.6.2 Acceptance

Dense graded asphalt pavements are usually accepted based on aggregate grading, binder content, and relative compaction of the in-place mixture. Aggregate grading must conform to the standard specification. The binder content must conform to that determined by the Engineer as detailed in Section 39 of the Standard Specifications (1). The relative compaction may be measured in the field using a nuclear density gauge as detailed in CT 375 and shall not be less than 96.0 percent (2). However, if it less than 96.0 percent and greater than or equal to 93.0 percent, the contractor may request that the mixture remain in place and accept a penalty (i.e., reduced compensation) for the work if agreed upon by the Engineer. Mixtures placed with a relative compaction of less than 93.0 percent must be removed and replaced at the contractor's expense.

2.7 POST TREATMENTS

Dense graded materials usually require no post-laydown treatments.

3.0 OPEN GRADED MIXES

3.1 WHAT IS AN OPEN GRADED AC OVERLAY?

Open Graded Asphalt Concrete (OGAC), also referred to as Open Graded Friction Course (OGFC), is a surface course with an aggregate gradation that provides an open void structure as compared with conventional dense graded asphalt concrete (11, 20). Air void content typically ranges between 15 to 25% in OGAC mixtures (11, 22, 23) resulting in a highly permeable mixture relative to DGAC (which normally is relatively impermeable). The porous nature of OGAC mixtures allows surface water to quickly drain away from the surface by allowing the water to flow through the mixture. The principal benefit derived from OGAC mixtures is a significant reduction in splash and spray relative to DGAC mixtures and PCC pavements. Other benefits include a reduction in tire noise and an increase in the frictional characteristics relative to DGAC mixtures. The use of modifiers such as asphalt rubber and PBA 6a and PBA 6b may be used to address different environmental and climatic conditions, and allow for thicker films to improve durability.

The aggregate gradations for open graded mixes are given in the Standard Specifications (1). Table 4 shows the required characteristics of such aggregates as specified in the Standard Specifications (1). The mixture requirements are based on a drain down test and are discussed in Section 3.4.

Table 4: Aggregate Properties Required (1)

CALIFORNIA TEST METHOD	OPEN GRADED ASPHALT CONCRETE
CT 205 Percentage of Crushed Particles:	
Coarse Aggregate (Min.)	**90%**
Fine Aggregate *(Passing 4.75-mm, Retained on 2.36-mm) (Min.)*	**90%**
CT 211 Los Angeles Rattler:	
Loss at 100 Rev. (Max.)	**10%**
Loss at 500 Rev. (Max.)	**40%**
CT 302 Film Stripping (Max.)	**25%**

3.2 PERFORMANCE

OGAC is designed as an abrasion resistant wearing course that can quickly drain water from the road surface. The following paragraphs provide a brief overview of the distresses that occur in open graded thin overlays as well as the factors influencing job selection, service lives, and costs.

3.2.1 Distresses/Conditions Addressed

Conventional open graded thin overlays should only be placed on structurally sound pavements because they offer no structural improvement, but they can renew the surface in terms of functional performance (i.e., ride quality). They can be used to mitigate the following distresses present in an existing pavement (22, 23):

- Skid problems/ Hydroplaning
- Splash and spray
- Noise problems
- Raveling
- Oxidation
- Minor surface irregularities (ride quality)
- Surface reflection problems
- Bleeding surfaces

When used in association with a SAMI, OGAC mixes may also enhance resistance to reflective cracking. In addition, modified systems such as asphalt rubber, PBA 6a, and PBA 6b can be used to address low temperature cracking and reflective cracking. Also, because durability is a function of film thickness (24), the use of modifiers (e.g. asphalt rubber) that increase in-service viscosity allow thicker films resulting in higher resistance to oxidation and raveling (22, 23). The void structure also allows absorption of free surface asphalt to mitigate bleeding pavements.

3.2.2 Principal Distress Modes

OGAC overlays exhibit the following distress modes (11, 12, 22):

- Permanent deformation due to heavy traffic and high temperatures.
- Shear failures in high stress areas.
- Fatigue cracking due to repeated traffic loading.
- Reflection cracking due to cracks in the existing pavement reflecting up through the overlay.
- Raveling due to a number of factors including oxidation and hardening of the binder, water damage, low binder content, and low compaction.
- Stripping caused by binder-aggregate incompatibility.
- Delamination due to poor compaction and/or tack coat practices.
- Clogging of air voids causing loss of permeability.
- Rich and dry spots due to drain down of binder during transport and application.
- Isolated areas of softened binder due to fuel/oil spills.

Often, these can be addressed by selection of the correct binder and proper mix design and job selection. Open graded thin overlays are not suitable for every job. The performance of OGAC thin overlays is based on maintaining the void structure.

3.3 JOB SELECTION

3.3.1 Where Should OGAC be Used?

- In California, OGAC is generally used in new construction, major rehabilitation projects, and also in maintenance overlays. OGAC is used as a wearing course (i.e., surface treatment over dense graded asphalt concrete pavements and occasionally on portland cement concrete (PCC) pavements). OGAC is generally used on the traveled way and extending 0.3m (1 ft) on the shoulder (20). In maintenance applications, the distress mode of the existing pavement must be determined and addressed.
- Conventional open graded overlays should be placed on sound pavements. Type O and type O-HB can be used to slow reflection cracking.

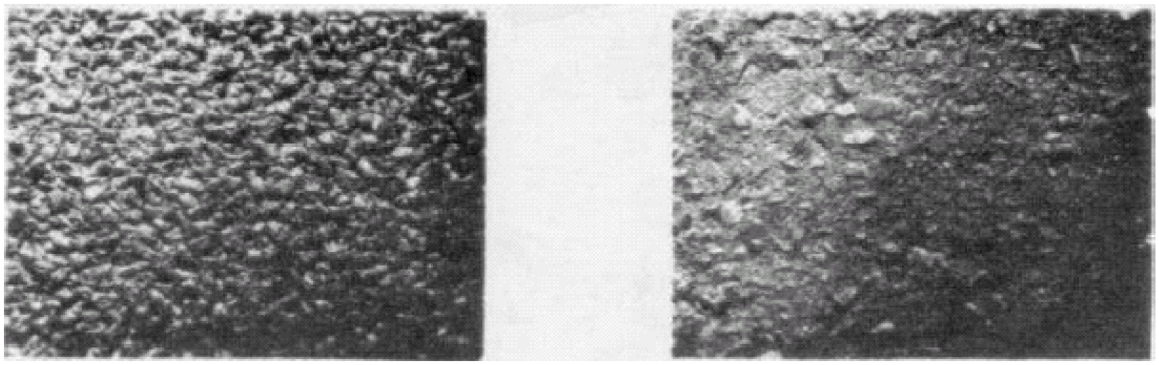
Reflective Cracking may be better addressed by utilizing Rubberized OGAC with an increased high binder content (RAC-O (HB)).

3.3.2 When Should OGAC be Used?

OGAC is a desirable application for the surface layer of AC pavements where its benefits are important. This is especially the case whenever the traffic count is high and the rainfall is moderate or high. Specifically, OGAC should be used when the following are issues:

- **Wet Weather Accidents:** Consider the use of OGAC when the Traffic Accident Surveillance and Analysis System (TASAS) Report reveals a high frequency of wet weather accidents or when the Traffic Safety Report recommends the use of OGAC to minimize wet weather accident occurrences.

- **Skid Resistance:** When frictional properties of the pavement surface are suspect, a skid test should be conducted to determine the existing coefficient of friction of the pavement surface (CT 342). Figure 6 shows typical surface textures of OGAC compared with DGAC.



Typical Open Graded **Typical Dense Graded**

Figure 6: Typical Texture (25)

- **Wet-night Visibility:** Another consideration for the use of OGAC is when the TASAS Report reveals a high percentile confidence level for wet weather and nighttime accident occurrences. OGAC may also be considered for placement to reduce splash and spray due to rain and increase the visibility of pavement delineation. It can be placed on both asphalt and portland cement concrete pavements.

- **Cross Slope:** When the cross slope is less than 2% and there are two or more lanes in one direction, OGAC may be especially helpful to assist in the draining of water from the pavement surface.

- **Noise:** OGAC has been reported to reduce road noise (22, 23, 26, 27, 28). Caltrans continues to research traffic noise on various roadway surfaces. Caltrans has reported in a study on I-80 that traffic noise levels have decreased and continue to be lower than baseline conditions 35-months after the application of OGAC (26). The life expectancy of the noise benefit will vary with the mix and binder type.

- **Structural Adequacy:** Most districts do not consider OGAC to be a structural layer, rather it is considered a sacrificial layer only.

- **Oxidation Reduction:** OGAC has been successfully used as a protection layer to prevent asphalt aging in the main structural layers.

- **Mitigation against Flushing and Bleeding:** OGAC when applied to a pavement provides void structure to accommodate any potential flushing or bleeding in the underlying pavement.

- **Mitigation of Cracking:** Type O-HB can be used to mitigate cracking.

3.3.3 Where and When Should OGAC Not be Used?

OGAC should not be used on:

- **Unstable Pavements:** OGAC should not be used on any pavement that exhibits substantial cracking, rutting, bleeding, or depressions. The extent of pavement distress precluding the use of OGAC has not been quantified at this time by Caltrans.

- **Snow or Icy Areas:** In snow areas, where tire chains, studded tires, or snowplows will detrimentally affect the aggregate and binder, the result may lead to stripping of the aggregate and contribute to raveling and pavement deterioration.

- **Areas with Severe Turning Movements:** High shear areas are not recommended for placement of OGAC due to potential for scuffing. These areas may include parking areas, intersections, ramp terminals, or curbed sections.

- **Curb and Gutter/Dense Graded:** Open Graded AC should not be placed adjacent to curb and gutter or Dense Graded AC where water may be held back and stored, thus, creating a ‘bath’ that may cause striping or saturation of the structural section.

- **Muddy Areas:** Areas where mud may be tracked onto the pavement from un-surfaced side roads will fill the voids and reduce the surface water drainage characteristics of the OGAC.

- **Fuel or Oil Spill Areas:** OGAC should not be placed in areas where dripping of oil or fuel from slow or stopped vehicles is prevalent.

- **Mill and Fill Areas:** Mill and fill areas should not generally be candidates for OGAC as a bathtub effect may be created. If OGAC were to be used as the final course, a leveling course would be required first.

3.3.4 Special Maintenance Requirements of OGAC

At this time only removal and replacement is allowed for repairing a failed or aged OGAC. However, New Mexico DOT has successfully placed thin bonded wearing courses over open graded mixes as an alternative to milling them out.

Permeability must be maintained to ensure water flow is unimpeded**.** Maintenance on roadways surfaced with OGAC should avoid any activities that may obstruct the lateral flow of water through the OGAC. These activities may include crack sealing or patching a small failed area with Dense Graded Asphalt Concrete (DGAC) thus creating a ‘dam’ where water may be retained or stored and contribute to further failure of the OGAC surfacing. When large areas of patching are involved, OGAC should be replaced with OGAC. Traffic striping may also inhibit lateral water flow if the striping materials are applied at a heavy rate or excessive amount of reflective beads are used.

Winter maintenance is not as great an issue as once thought. OGAC has different thermal and icing properties compared with DGAC. Thermal conductivity is up to 70% less according to National Asphalt Pavement Association (32). It will thus act as an insulating layer and accumulate ice and frost faster than DGAC.

General maintenance of OGAC to prevent clogging is important in some areas. Water hose, high-pressure cleaners, and specialized cleaning vehicles have been used successfully.

3.3.5 Service Life and Costs

OGAC overlays have been shown to last 2 to 10 years, but more commonly 4 to 6 years (11). The life of the overlay is directly affected by the condition of the existing pavement that received the overlay, the climate (environmental conditions) in which the overlay was placed, and the traffic loading experienced by the overlay. For example, a thin overlay placed on a pavement in poor condition would not be expected to last as long as one placed on a pavement in good condition. Similarly, a thin overlay placed on a pavement in good condition but with heavy traffic would not be expected to last as long as one placed on the same pavement but with much lighter traffic.

Numerous factors influence the cost of open graded thin overlays. Several of the factors contributing to the cost of placing these overlays include:

- Materials (binder and aggregate with or without modifiers).
- Location of the project (e.g., urban versus rural area, proximity to hot mix plant, etc.).
- Thickness of the overlay.
- Special construction requirements.

Chapter 2 (Framework for Treatment Selection) provides a simplified method of comparing cost effectiveness of different treatments.

3.4 DESIGN AND SPECIFICATION OF OGAC

Caltrans uses CT 368 to design OGAC mixes. The California method was revised in 2002 and is based on an aggregate grading designed to give a minimum of 18% voids using CT 367, and a drain down test (CT 368). This test determines the optimum level of conventional binder that may be used without excessive drain down in transportation or during placement of the mixture. For modified systems, the drain down is only established for AR 4000 and this value is used in the design requirements. In high binder open graded mixes only asphalt rubber binders are used and the binder content is adjusted upwards by 1 to 2% based on the field experience with these mixtures. At the time of this writing, the Department has decided that moisture susceptibility testing is not required for OGAC.

3.4.1 Materials Requirements

Further information on the materials requirements for binders and aggregates are covered in Chapter 1 and Reference 25. The special requirements of OGAC mixtures are related to its specific properties. The void structure must remain intact to ensure that it remains permeable. As air can penetrate easily and promote aging the void structure itself will promote accelerated aging compared with dense graded materials. For this reason, the binders used in OGAC mixtures must be more resistant to the effects of aging than those used for DGAC mixtures. Modified binders and asphalt rubber provide improved resistance to aging.

The texture of the mixture at the surface affects skid resistance. To achieve this, the aggregate should be hard and abrasion resistant and the mixture must be resistant to permanent deformation so that the open void structure remains intact. The requirements for aggregates were shown in Table 6 and the gradings were shown in Table 5. It has been found that coarser gradings give a more open void structure (11, 23). These tend to give good stone on stone contact and deformation resistance and the voids are less susceptible to becoming clogged.

Binders for OGAC include AR 4000, AR 8000, some PBA grades or Asphalt Rubber (see SSPs in References 1-10). Modified systems such as asphalt rubber can be used to address low temperature cracking, reflective cracking and night paving. PBA 6a and PBA 6b may be used to address low temperature cracking and to overcome problems of lower temperature paving conditions (e.g., night paving). The void structure allows absorption of free surface asphalt to overcome bleeding pavements. As durability is a function of film thickness (24), the use of modifiers that increase in-service viscosity will allow thicker films and higher resistance to oxidation and raveling (21). All modifiers appear to improve the abrasion resistance of the mixes (23).

It has been found in various studies that modified binders give superior service lives as they prevent binder drain down in application and in service (29, 30, 31). This is due to the elastomeric nature of the binders that resists flow at even high production and service temperatures. They also improve rutting resistance and are less thermally susceptible.

3.4.2 Mix Requirements

Table 5 shows materials typically used.

Table 5: Binder Selection (1-10)

BINDER TYPE	APPLICATION
AR-4000	Considered conventional strategy over existing pavement.
AR-8000	May be considered in areas with high temperatures. (i.e. desert areas)
PBA-6	May be placed when ambient temperature is 10°C or higher. (i.e. cool weather, night work) *Refer to SSP #39-010_A09-07-01*
Asphalt Rubber	Used over cracked pavements, areas of high thermal cracking (especially high binder versions), and night work.

3.5 MANUFACTURE AND CONSTRUCTION

Manufacturing and construction methods are similar to those for dense graded materials. The methods must address the following important issues (11).

3.5.1 Manufacture

No specific modifications are required to plants. Binder tanks should have agitation, especially if asphalt rubber binders are used and all limitations must be observed for storage time and temperatures (1-10). Binder proportioning requires a mass flow meter to ensure accuracy.

Appropriate temperatures must be carefully controlled during the mixing process. Temperatures that are too high will promote drain down and 'fat' spots or 'dry' spots in the final surfacing. Temperatures that are too low may result in inadequate coating of the aggregate.

3.5.2 Storage

In general, open graded mixes should not be stored for more than two hours. This is due to the potential for binder drain-down.

3.5.3 Transport

Standard transport equipment may be used. Tarping may help prevent loss of heat and crusting of the mixture; especially during night and cool weather work using modified mixes. This is critical for haul times longer than 30 minutes in the daytime and for night work. Release agents may be used on the truck bed. Diesel or other petroleum materials should never be used as release agents since these will soften the mixture. Hauling distance should be as short as possible. Currently no maximum distance has been specified. It should be such that the application temperatures in Table 3 are met.

3.5.4 Laydown

The following are issues associated with laydown.

Safety. Standard Caltrans safety and traffic control procedures must be followed. These procedures are detailed in Reference 17. Traffic is not allowed on OGAC until final rolling has been completed.

Surface Preparation: This is the same as for dense graded thin overlays.

- Thermoplastic markings should be removed according to Caltrans guidelines.
- All crack and joint sealing should be performed prior to placing the OGAC. Allow for adequate cure time for crack and joint sealants. Hot applied sealants require three to four months while cold applied products require one year.
- Overlay of an existing OGAC surface will require removal of the existing OGAC prior to placing new OGAC. This will prevent water entrapment and poor bonding. This should be considered at the planning stage since this item of work may be a substantial cost to the project. Conformance to current standards and policy for removal and disposal of pavement grindings should be adhered to.

Tack Coating: Good tack coat practice must be followed correctly. (See Caltrans Paint (Tack) Coat Guidelines and Reference 1). This requires a heavier tack coat than DGAC as the tack coat assists in waterproofing the underlying pavement. If the surface is milled, a heavier than conventional coat will be required to ensure the more absorbent surface is waterproofed.

Paving Guidelines: The rules shown in Table 6 apply to laydown of the OGAC mix.

Table 6: Laydown Rules*

ANTICIPATED AMBIENT TEMPERATURE	RULES
>20°C	OGAC may be placed using windrow and pick up machines. The length of the windrow should be usually limited to 50 m. There should be little or no wind
13°C - 20°C	OGAC should be placed by end-dumping into the paving machine, not by windrowing. Keep rollers within 15 m of paving machine. Tarp trucks for hauls >30 minutes. Mix in hopper to be 90-120°C.
10°C – 13°C	In addition to above rules, PBA-6 (polymer modified) asphalt binder should be used. Asphalt rubber binders may also be used. Maximum mixing temperature can be raised to 163°C. Mix temperature in hopper to be 135°C.
<10°C	OGAC should not be placed.

**Ensure all Standard Specifications and SSPs (1-10) are followed.*

Wind is an important factor. Cold wind may reduce the surface temperature quickly making compaction difficult. On very cool and windy days placement may need to be suspended.

Transverse joints are more difficult to make in open graded mixtures due to these mixtures being more difficult to work by hand as compared with dense graded mixtures. Handwork should be minimized. For this reason, transverse butt joints should be constructed or joints should be avoided by continuous paving. Longitudinal joints are made in a similar manner to those for dense graded mixtures.

Rolling: The rollers used for open graded mixtures are solely steel wheeled operated in static mode (pneumatic rubber tired rollers are not used because they will close up the voids in the surface by kneading action and the mix may stick to the tires). The ballasted weight should be no more than 8 to 10 tons. Two passes of the roller are usual. Rolling temperatures are shown in Table 7. Rollers should NOT roll unsupported edges, as this will tend to collapse the void structure creating a flattened and sealed edge (13).

Table 7: Application Temperatures (1-10)

MATERIAL	MINIMUM AIR TEMPERATURE, (°C)	MIX LAYDOWN TEMPERATURE, (°C)	MINIMUM BREAKDOWN ROLLING TEMPERATURE, (°C)	MINIMUM FINISHING TEMPERATURE, (°C)
Conventional (AR4000)	20	95-120*	ASAP (90)	80
PBA	10	163	135	121
Asphalt Rubber	13-18	143-163	127	95
	≥18	138-163	121	95

These are minimum temperatures. It is recommended that spreading and compacting be performed at temperatures above these minimums, but not to exceed 163°C (325°F).
** Laydown temperature not to exceed 120°C to avoid effects of drain down.*

3.6 POST TREATMENT

If traffic can be kept off the mix, no treatment is required. However, in most cases, sanding is carried out on rubberized mixes to prevent initial traffic pick up. Clean sand is spread using a sand spreader at about 0.5 to 1 kg/m^2 (1 to 2 lbs/yd^2) after rolling is complete (5,8,9).

3.7 SAMPLING AND ACCEPTANCE

This should be carried out according to Caltrans CT 125. OGAC is usually accepted based on aggregate grading; mix binder content, and visual inspection.

4.0 GAP GRADED MIXTURES

Gap graded mixtures currently placed in California are, in general, solely Rubberized Asphalt Concrete (RAC) Type G which uses asphalt rubber binders (8). However, MB type G mixtures have been used in pilot projects. This section covers only asphalt rubber modified mixes.

4.1 WHAT IS A GAP GRADED MIXTURE?

A gap graded mixture consists of an aggregate grading that has a missing fraction. The Type G gradings are shown in Table 8.

Table 8: Type G Graded Aggregates (8)

19 mm Maximum, Coarse

Sieve Sizes	Percentage Passing		
	Proposed Gradation Limits	Operating Range	Contract Compliance
25mm	—	100	100
19 mm	—	95-100	90-100
12.5 mm	83-87	X±5	X±7
9.5 mm	65-70	X±5	X±7
4.75 mm	33-37	X±5	X±7
2.36 mm	18-22	X±4	X±5
600 µm	8-12	X±4	X±5
75 µm	—	2-7	0-8

12.5 mm Maximum, Medium

Sieve Sizes	Percentage Passing		
	Proposed Gradation Limits	Operating Range	Contract Compliance
25 mm	—	—	—
19 mm	—	100	100
12.5 mm	—	90-100	90-100
9.5 mm	83-87	X±5	X±7
4.75 mm	33-37	X±5	X±7
2.36 mm	18-22	X±4	X±5
600 µm	8-12	X±4	X±5
75 µm	—	2-7	0-8

In California, the gap (missing fraction) is used to accommodate the asphalt rubber binder. This is intended to allow for stone on stone contact for deformation resistance and the extra binder has been found to aid in fatigue and reflection cracking resistance. The CRM increases the viscosity of the binder allowing high binder contents without bleeding. The increase in voids allows the mix to accommodate the larger particulate rubber present in asphalt rubber binders (11). The binder content may be 7 to 9% by weight with asphalt rubber binders.

The purpose of gap grading is to provide improved stone-to-stone contact by reducing the fine aggregate content so as to provide a strong aggregate skeleton that creates space for more engineered binder than a dense graded mix can hold. Gap grading is also a good way to increase the VMA of a mixture.

Stone matrix asphalt (SMA), also a gap graded mixture, uses fibers to prevent drain-off. The modifier used in these mixtures makes the binder thick enough to stay in the matrix so that binder content may be higher than that for a dense graded mix. Voids characteristics of gap graded mixtures should be similar to those of DGAC, although VMA can be somewhat higher.

4.2 PERFORMANCE

4.2.1 Distresses/Conditions Addressed

Gap graded thin overlays should only be placed on structurally sound pavements because they offer no structural improvement, but they can renew the surface in terms of functional performance (e.g., ride quality). They can be used to mitigate the following distresses present in an existing pavement:

- Raveling,
- Oxidation,
- Reflection cracking,
- Minor surface irregularities, and
- Flushing Surfaces
- Skid Problems

Although not as free draining as open graded mixes, some improvement is noted in skid related problems (i.e., hydroplaning and spray and splash) and noise reduction.

4.2.2 Principle Distress Modes

Type G thin overlays can exhibit the following distress modes:

- Permanent deformation due to heavy traffic and high temperatures.
- Shear failures in high stress areas.
- Fatigue cracking due to repeated traffic loading.
- Reflection cracking due to cracks in the existing pavement reflecting up through the overlay.
- Raveling due to a number of factors including oxidation and hardening of the binder, water damage, low binder content, and low compaction.
- Stripping caused by binder to aggregate incompatibility.
- Delamination, due to poor compaction and/or tack coat practice.

Often, these can be addressed by proper mix design and job selection. In California, asphalt rubber binders are used in these mixes.

4.3 JOB SELECTION

4.3.1 Where Should Gap Graded Asphalt Concrete be Used?

Type G mixes are used as a surface treatment over dense graded asphalt concrete pavements and occasionally on portland cement concrete pavements. It should be placed over structurally sound pavements and may be used in new construction and rehabilitation projects. These mixes are generally used on the traveled way and should be placed across the entire roadbed, from outside edge of shoulder to outside edge of shoulder to provide uniform frictional properties and proper drainage. Properly designed and constructed type G mixtures have low permeability and have good durability characteristics (due to high binder content).

4.3.2 Where Should Gap Graded Asphalt Concrete Not be Used?

Type G mixes should not be used on unsound pavement exhibiting substantial cracking, rutting, bleeding, or depressions. The extent of pavement distress precluding the use of these mixes has not been quantified at this time. Type G should not be considered for use on bridge decks as a surface course unless approved by Headquarters Structures Department.

4.3.3 Service Life and Costs

Costs of Type G mixes are similar to OGAC. Caltrans has not performed any LCCA on these mixes.

4.4 DESIGN AND SPECIFICATION

The design of Type G mixtures is similar to that for dense graded mixtures as indicated in SSP 39-400_M (8) except that CT 367 is modified in the following ways:

- The aggregates must have a grading and quality resulting in a mixture containing 7 to 9% asphalt rubber binder by weight of dry aggregate.
- The air void content used to select the optimum binder content varies according to traffic index (level) and climatic region as detailed in SSP 39-400_M (8).
- Laboratory mixing is done from 149 to 163ºC (300 to 325°F) and compaction from 143 to 149ºC (289 to 300°F)
- A minimum stabilometer value of 23 (CT304 and 366) is required.
- A minimum VMA of 18% is required as determined by the test described in Asphalt Institute Mix Design Methods for Asphalt Concrete (MS-2) (16).

Asphalt rubber materials requirements are provided in Chapter 1. The aggregate for Type G rubberized asphalt concrete shall conform to the grading contained in SSP 39-400_M (8) and shall meet the quality provisions specified for Type A asphalt concrete in Section 39-2.02, "Aggregate," of the Standard Specifications (1).

4.5 CONSTRUCTION

Construction methods for Type G mixtures are similar to those for dense graded materials as detailed in Section 2.5. The following are important issues (11).

4.5.1 Manufacture

No specific modifications to plants are required. Binder tanks require agitation, especially if asphalt rubber binders are used and all limitations must be observed on storage time and temperatures (Chapter 1 and Reference 8).

Mixing temperatures must be in the correct range to allow full coating of the aggregates. Temperatures that are too low do not allow adequate coating of the aggregates whereas temperatures that are too high can result in smoke or excess fumes.

4.5.2 Storage

In general, Type G mixes should not be stored for more than two hours due to stability limitations in the asphalt rubber binder.

4.5.3 Hauling

Standard hauling equipment (i.e., end dump vehicles) may be used for the construction of Type G overlays. Reference 17 contains further information regarding on these types of vehicles. Tarping may help to prevent temperature loss and crusting of the mixture (i.e., hardening of the first few centimeters of the mixture exposed to ambient temperatures); especially in night and cool weather work with modified mixes. Release agent may be used on the truck bed. On no account should diesel or other petroleum materials be used as release agents as these will soften the mixture.

4.5.4 Safety

Standard Caltrans safety and traffic control procedures must be followed. These procedures are detailed in Reference 17. Traffic is not allowed on Type G mixes until final rolling has been completed and sand applied. Sand is recommended to prevent pick-up of the mix.

4.5.5 Surface Preparation

This is the same as for dense graded thin overlays. Where agriculture product drippings are an issue, flushing is an option. It needs to be completed 24 hours in advance of the overlay to allow drying time. When cracks are being treated, especially fatigue cracks, a membrane or SAMI may be used as a surface preparation. Membranes may also be used to waterproof the underlying layer.

4.5.6 Tack Coat

Good tack coat practice must be followed. The Standard Specifications (1) specifies how to apply tack coats in a manner satisfactory to Caltrans. Surfaces must be clean before the tack coat is applied. If a good bond is not formed between the thin overlay and the existing pavement, it can de-bond resulting in a slippage failure or delamination. If too much tack coat is applied, it may bleed up through the layer, especially under heavy traffic.

4.5.7 Laydown

Type G mixes may be windrowed ahead of the paver and picked up with a pick up device (loader) and deposited in the paver hopper. The length of the windrow must be as short as possible to ensure excessive cooling does not occur. If conditions are good (i.e., little or no wind and higher temperatures), this is usually about 50 meters (160 ft) maximum (11). If conditions are poorer then this, the length of the windrow should be kept shorter than 50 meters (160 ft). Table 9 summarizes minimum application temperatures for the various stages of the construction process. Every effort should be made to avoid segregation of the mixture during the paving operation. In addition, mix that is left in the paver hopper too long and, thus, allowed to cool below the minimum laydown temperature should not be combined with fresh mix.

Table 9: Recommended Application Temperatures (8)

MATERIAL	MINIMUM AIR TEMPERATURE, °C	MIX LAYDOWN TEMPERATURE, °C	MINIMUM BREAKDOWN ROLLING TEMPERATURE, °C	MINIMUM FINISHING TEMPERATURE, °C
Asphalt Rubber	13 to 18	143	127	95
	≥18	138	121	95

These are minimum temperatures. It is recommended that spreading and compacting be performed at temperatures above these minimums, but not to exceed 163°C (325°F).

Transverse joints are more difficult to construct in Type G mixtures due to the lower workability by hand of such mixes as compared dense graded mixtures. Handwork should be avoided if possible, however, if required handwork should be done as soon as possible. For this reason transverse joints should be constructed as a butt joint or avoided by continuous paving. Longitudinal joints are made in a similar manner to dense graded mixtures (Section 2.5.4).

4.5.8 Rolling

Static steel wheeled rollers should be used on Type G mixtures. Pneumatic rubber tired rollers are not allowed as the mix will stick to the tires. The ballasted weight should be no more then 7,000 to 8,000 kg (8 to 9 tons). Rolling temperatures are shown in Table 9.

Type G mixes often require more compactive effort than dense graded mixes, and vibratory compaction is generally required for breakdown rolling. The breakdown roller should follow as closely behind the paver as practicable. If the mix is tender, then the roller should lay back only the minimum time necessary for rolling. Breakdown rolling should achieve 90 to 95% of the required compaction. This will ensure that adequate compaction is achieved with the subsequent intermediate roller passes. Finish rolling is mostly for cosmetics. If density has not already been achieved at this stage, additional compaction will likely not increase density due to low mix temperature.

4.5.9 Acceptance

Type G mixes are usually accepted based on grading, binder content, and visual inspection.

4.6 POST-LAYDOWN TREATMENTS

If traffic can be kept off the mix, no treatment is required. Otherwise sand conforming to the Standard Specifications Section 90-3.03 (1) is applied after final rolling at 0.5 to 1 kg/m^2 (1 to 2 lb/yd^2) to avoid pick up by early traffic. Sweeping may be required after initial trafficking to remove the sand. This is generally done the next day.

5.0 TROUBLESHOOTING

This section provides information to assist maintenance personnel with troubleshooting problems associated with placing any of the thin HMA overlays. Table 12 presents a troubleshooting guide that associates common problems to their potential causes, whereas Table 13 lists some commonly encountered problems and their recommended solutions.

Table 12: Troubleshooting Guide (13)

Cause	Problem																
	Wavy Surface - Short Waves/ Ripples	Wavy Surface - Long Waves	Tearing of Mat - Full Width	Tearing of Mat - Center Streak	Tearing of Mat - Outside Streaks	Mat Texture - Nonuniform	Screed Marks	Screed Not Responding To Correction	Auger Shadows	Poor Precompaction	Poor Longitudinal Joint	Poor Transverse Joint	Transverse Cracking (Checking)	Mat Shoving Under Roller	Bleeding or Fat Spots in Mat	Roller Marks	Poor Mix Compaction
Fluctuating Head of Material	✔	✔				✔					✔						
Feeder Screws Overloaded	✔	✔				✔			✔								
Finisher Speed Too Fast	✔				✔												
Too Much Lead Crown in Screed					✔												
Too Little Lead Crown in Screed				✔													
Overcorrecting Thickness Control Screws	✔										✔						
Excessive Play in Screed Mechanical Connection	✔	✔					✔	✔				✔					
Screed Riding on Lift Cylinders	✔	✔				✔		✔		✔	✔	✔					
Screed Plates Worn Out or Warped			✔	✔	✔	✔											
Screed Plates Not Tight	✔					✔		✔				✔					
Cold Screed			✔	✔	✔	✔											
Moldboard on Strikeoff Too Low					✔												
Running Hopper Empty Between Loads		✔				✔											
Feeder Gates Set Incorrectly		✔		✔	✔												
Kicker Screws Worn Out or Mounted Incorrectly				✔													

Table 12: Troubleshooting Guide (Continued) (13)

Cause	Problem																
	Wavy Surface - Short Waves/Ripples	Wavy Surface - Long Waves	Tearing of Mat - Full Width	Tearing of Mat - Center Streak	Tearing of Mat - Outside Streaks	Mat Texture - Nonuniform	Screed Marks	Screed Not Responding To Correction	Auger Shadows	Poor Precompaction	Poor Longitudinal Joint	Poor Transverse Joint	Transverse Cracking (Checking)	Mat Shoving Under Roller	Bleeding or Fat Spots in Mat	Roller Marks	Poor Mix Compaction
Incorrect Nulling of Screed												✔					
Screed Starting Blocks Too Short												✔					
Screed Extensions Installed Incorrectly					✔	✔											
Vibrators Running Too Slow						✔				✔							
Grade Control Mounted Incorrectly	✔	✔						✔			✔						
Grade Control Hunting (Sensitivity Too High)	✔										✔						
Grade Control Wand Bouncing on Reference	✔										✔						
Grade Reference Inadequate	✔	✔															
Sitting Long Period Between Loads		✔				✔											
Improper Joint Overlap											✔						
Improper Mat Thickness for Max. Agg. Size			X			X		X		X							
Trucks Bumping Finisher		X					X										
Truck Holding Brakes		X					X										
Improper Base Preparation	X	X				X				X			X	X		X	X
Improper Rolling Operation	X										X	X	X	X		X	X
Reversing or Turning Too Fast of Rollers		X												X		X	X
Parking Roller on Hot Mat		X														X	X
Improper Mix Design (Agg)	X		X			X			X				X	X	X		X
Improper Mix Design (Asphalt)	X		X			X			X				X	X	X		X
Mix Segregation	X	X	X			X			X								
Moisture in Mix			X										X	X	X		X
Variation of Mix Temperature	X	X	X			X		X					X	X	X	X	X
Cold Mix Temperature			X	X	X	X		X		X	X	X					X

1.Find problem above
2. checks indicate causes related to paver
X's indicate other problems to be investigated.

Note: Many times a problem can be caused by more than one item, therefore, it is important that each cause listed is eliminated to assure solving the problem.

Table 13: Common Problems and Related Solutions

PROBLEM	CAUSES AND SOLUTIONS
Surface Waves	**CAUSES** • A fluctuating head of material in front of the paver screed causing it to rise and fall usually causes surface waves. • Worn or badly set screeds can cause surface waves. • A mix that is too stiff or that has cooled too much before compaction will cause surface waves. • Long waves can be caused by adjusting the screed too often and not allowing an adjustment to fully take effect before changing it again. • Dump trucks bumping the paver when delivering a load of mix can cause long waves. **SOLUTIONS** • The solution for avoiding surface waves is to control the material amount, temperature, and screed correctly. • Pave continuously with a pick up machine where possible.
Wash Boarding	**CAUSES** • Wash boarding is caused by improper use of vibratory rollers, either in amplitude setting or in speed of roller. **SOLUTIONS** • Use higher roller amplitudes for thicker layers and lower amplitudes for thinner layers. • Slow down the roller.
Tearing	**CAUSES** • Poor paver operation, or the mix being too cold and/or too stiff causes tear marks. **SOLUTIONS** • Tear marks can be avoided by adjusting the degree of crown and ensuring the mix temperature is correct.

Table 13: Common Problems and Related Solutions

PROBLEM	CAUSES AND SOLUTIONS
Non Uniform Texture-Segregation	**CAUSES** • The mixture separating in the hopper or in transportation causes segregation. • Poor paver set up. • Low mix temperature or poor grading or mix design. • Prone to occur in thin overlays. • Weak base layer. **SOLUTIONS** • Ensure thickness is at least twice that of largest stone size, mix design is correct, and the paver is properly set up. • Ensure mix temperature is correct.
Screed Marks	**CAUSES** • Transverse screed marks occur when the paver stops and starts and longitudinal screed marks occur when extensions are used on the screed. • Poor paver set up or worn or dirty screeds. • Low mix temperature or poor grading or mix design. **SOLUTIONS** • Set paver and screed correctly. Use windrowing to ensure paver does not stop. • Ensure the mix is in specification.
Surface Shadows	**CAUSES** • Caused by overloading augers in the paver. • May be caused by low mix temperature or poor grading or mix design. **SOLUTIONS** • Adjust the distance between the screed and the tractor of the paver. • Ensure that the level of mix is near the center of the auger shaft. The augers should NOT be totally covered with mix.

Table 13: Common Problems and Related Solutions

PROBLEM	CAUSES AND SOLUTIONS
Roller Checking and Roller Marks	**CAUSES** • Deflection under the roller (i.e., mix too hot) or mix design is poor. • Too much asphalt in the mix, too much middle size sand in the gradation (1.18-600μm sieve). **SOLUTIONS** • Wait until the mix cools further or adjust the mix design.
Bleeding and Fat Spots	**CAUSES** • High mix temperature or poor grading or mix design. • Too much asphalt in the mix or amount of fines too low in the grading. • Mix design not taking the correct traffic level into account. • Moisture in the mix or on the pavement. • Extremely high applications of tack coat. • Existing bleeding surface. **SOLUTIONS** • Solve by ensuring aggregates are dry during the mixing process, that pavement is not bleeding, that pavement is dry, and that mix is correctly designed for traffic and aggregate.
Shoving	**CAUSES** • Caused by excess asphalt in the mix. • Improper roller operation such as sudden reversal. • Rolling before the mat is stable enough. • Roller going too fast. **SOLUTIONS** • Ensure mix is at correct temperature. • Ensure roller is not going too fast. • Check and correct mix design if necessary. • Consider use of modified binders.

Table13: Common Problems and Related Solutions

PROBLEM	CAUSES AND SOLUTIONS
Delamination	**CAUSES** • Insufficient tack coat. • Mix is too cold during compaction. • Existing surface being too cold for paving. • Dirty surface on which an overlay is being placed. **SOLUTIONS** • Ensure paving temperatures are correct. • Ensure the surface is substantially free of debris.
Poor Joints	**CAUSES** • Paver operating at different elevations when paving adjacent lanes. • Poor joint practice, especially in compaction of thin layers. **SOLUTIONS** • Make sure joints are correctly formed and compacted at the correct temperature.
Raveling	**CAUSES** • Insufficient asphalt in the mix. • Poor compaction. **SOLUTIONS** • Ensure mix design conforms to the specification. • Ensure compaction is carried out at correct temperatures.

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APPENDIX A

SUGGESTED FIELD CONSIDERATIONS FOR MAINTENANCE OVERLAYS

The following field considerations are a guide for the important aspects of performing a maintenance overlay project. The various tables list items that should be considered in order to promote a successful job outcome. As thoroughly as possible, the answers to these questions should be determined before, during, and after application. The staff to do this work will vary by job type and size. Some topics may need attention from several staff members. The field maintenance personnel should be acquainted with its contents. The intention of the tables is not to form a report, but to bring attention to important aspects and components of the project process. Some information is product specific and contained in the relevant standard specifications, special standard provisions, or special provisions.

PRELIMINARY RESPONSIBILITIES	
PROJECT REVIEW	■ Is the project a good candidate for a thin overlay? ■ How much rutting is present, depth and extent? ■ Other profile problems observed? ■ How severe and what type of cracking exists? ■ Is crack sealing needed? ■ Is the pavement surface waterproof? ■ How much bleeding or flushing exists? ■ Is pavement raveling or oxidized? ■ What is the traffic level? ■ Is the base sound and well drained? ■ Is a drainage layer required? ■ Is pavement strengthening required? Use a structural overlay if it is. ■ Review project for bid/plan quantities.
DOCUMENT REVIEW	■ Application specifications and special provisions. ■ Mix design information. ■ Traffic control plan (TCP).
MATERIALS CHECKS	■ A full mix design has been done for the mixture? ■ The mix is produced by an approved source? ■ Has the tack coat emulsion been sampled and submitted for testing? ■ Aggregates meet all specifications and are not from a source known to have stripping problems? If so, what anti stripping treatment is to be used? ■ Aggregate is clean and free of deleterious materials and correct grading? ■ Is the tack coat emulsion properly prepared (diluted) before use? ■ Is the mix checked at the plant for temperature compliance and have samples been taken?

INSPECTION RESPONSIBILITIES	
SURFACE PREPARATION	■ Is the surface clean and dry? Has it been swept? ■ Have any areas with oily residue been scrubbed from the pavement? ■ Have all pavement distresses been repaired? ■ Has the existing surface been inspected for drainage problems? ■ Have all utilities been raised or masked?
EQUIPMENT INSPECTION CONSIDERATIONS	
BROOM	■ The bristles are the proper length? ■ The broom can be adjusted vertically to avoid excess pressure?
TACK COATER	■ Is the machine fully functional? ■ Has the machine been calibrated to accurately spray the correct level of tack coat? ■ Are all spray tips clean and not blocked? ■ Are nozzles angled correctly (approximately 30°)? ■ Is the spray bar at the correct height? Is there a double or triple overlap of spray fan?
PAVING MACHINE	■ Is the machine fully functional? ■ Is the paver clean and are the wings operating correctly? ■ Are flow gates clear, set at the right height, and functioning properly? ■ Are the conveyors functioning? ■ Are the augers clean and functioning? ■ Is the flow system (manual or automatic) operational? ■ Are material levels in the paver auger chamber set correctly? ■ Do the screed heaters work? ■ Is the screed clean and properly set? Is the angle of attack correct? ■ Is the automatic leveling system working and correctly set? ■ Is the paver speed correct for correct thickness and angle of attack? ■ Are the screed strike offs clean and providing a uniform mat? ■ In continuous jobs, is the pick up machine working correctly? ■ Is a materials transfer device being used? Is it working correctly? ■ Are the mixing and heating facilities fully operational?

EQUIPMENT INSPECTION CONSIDERATIONS	
ROLLERS	■ What types of rollers will be used on the project for break down and finish rolling? ■ Tandem or vibratory rollers - are they fully functional? CT 109? ■ Pneumatic roller - is it fully functional and do roller tire pressures comply with the manufacturer's specification? ■ Do the roller tire size, rating, and pressures comply with manufacturer's recommendations? ■ Ensure the tire pressure is the same on all tires. ■ All tires should have a smooth surface.
DUMP TRUCKS	■ What types of dump trucks are being used? ■ Are bottom dump trucks providing a clean and well-shaped windrow? ■ Do rear dump trucks have correct hitch for the paver?
WEATHER REQUIREMENTS	■ Have air and surface temperatures been checked at the coolest location on the project? ■ Do air and surface temperatures meet specification requirements?
DETERMINING APPLICATION RATES	■ Have Agency guidelines and requirements been followed? ■ Is rut filling or a leveling course required? If so, have material quantities been calculated or estimated to properly reprofile roadway? ■ Has a full mix design been done? ■ Are tack coat application rates correct for the pavement surface? More emulsion may be required on roads with porous surfaces and less for those with flushed surfaces.
CALIBRATION OF EQUIPMENT	■ Are machines calibrated? ■ Who carried out the calibration and what documentation has been provided?

EQUIPMENT INSPECTION CONSIDERATIONS	
TRAFFIC CONTROL	■ The signs and devices used match the traffic control plan. ■ Flaggers do not hold the traffic for extended periods of time. ■ Unsafe conditions, if any, are reported to the RE. ■ The pilot car leads traffic slowly–24 mph (40 kph) or less–over fresh overlays. ■ Signs are removed or covered when they no long apply.
PROJECT INSPECTION RESPONSIBILTIES	
TACK COAT APPLICATION	■ What is the emulsion temperature? ■ Wind, humidity, and temperature can affect set time and affect distribution. ■ Has tack coater application spray bar been checked for height, blocked nozzles? ■ Has application rate been checked? ■ Has the emulsion been diluted correctly? ■ Is the grade and ambient temperature satisfactory? ■ Is the application even and covering the entire pavement? ■ Is the emulsion allowed to turn black before paving? ■ Is the application in accordance with Caltrans guidelines? ■ Do the paver wheels pick up the tack coat during paving?
LAYDOWN OF DENSE GRADED MIX	■ Has a test strip been successfully laid and compacted? ■ Is the ambient and grade temperature correct? ■ Is the mix temperature correct? ■ Is the paver going at a uniform speed? ■ If continuous application is used with windrowing? Is the mixture the correct temperature? ■ If back dump trucks are used, are changeovers smooth causing no bumping of the paver? ■ Are the hopper, augers, and screed operating correctly? ■ Is the screed set at the correct height? ■ Is the mat being tamped uniformly and is the mat a uniform thickness? ■ Are height adjustments minimal? ■ Are height adjustments allowed sufficient times to be effective? ■ Is the mat uniform looking? ■ Are edge lines and joint overlaps neat and straight? ■ Is the job stopped if problems persist?

PROJECT INSPECTION RESPONSIBILTIES	
LAYDOWN OF RAC TYPE G MIX	■ Has a test strip been successfully laid and compacted? ■ Is the ambient and grade temperature correct? ■ Is there evidence of significant drain down of the mix? ■ Is the mix temperature correct? ■ Is the paver going at a uniform speed? ■ Are the paver wings kept open to avoid segregated mix being laid? ■ If back dump trucks are used, are changeovers smooth causing no bumping of the paver? ■ Are the hopper, augers, and screed operating correctly? ■ Is the screed set at the correct height? ■ Is the mat being tamped uniformly and is the mat a uniform thickness? ■ Are height adjustments minimal? ■ Are height adjustments allowed sufficient times to be effective? ■ Is the mat uniform looking? ■ Are edge lines and joint overlaps neat and straight? ■ Is the job stopped if problems persist? ■ Does the material have a dull or shiny look?
LAYDOWN OF OPEN GRADED MIX	■ Has a test strip been successfully laid and compacted? ■ Is the ambient and grade temperature correct? ■ Is the mix temperature correct? ■ Is there evidence of drain down? ■ Is the paver going at a uniform speed? ■ If continuous application is used with windrowing, is the mixture the correct temperature? ■ If back dump trucks are used, are changeovers smooth causing no bumping of the paver? ■ Are the hopper, augers, and screed operating correctly? ■ Is the screed set at the correct height? ■ Is the mat being tamped uniformly and is the mat a uniform thickness? ■ Are height adjustments minimal? ■ Is adjustments allowed time to be effective? ■ Is the mat uniform looking? ■ Are edge lines and joint overlaps neat and straight? ■ Is the job stopped if problems persist?

PROJECT INSPECTION RESPONSIBILTIES	
ROLLING DENSE GRADED MIX	■ Has a roller pattern been established? ■ Have the number of passes required for breakdown rolling been established? ■ Is the surface temperature of the mat correct at beginning of rolling? ■ Is the roller being operated at the correct speed? Does the mat check under the roller? ■ Ensure that no aggregate is crushed under breakdown rolling. ■ Is water being used to cool the mat? ■ Is finish rolling required? ■ How many passes? ■ Is the mat uniform looking? ■ Does mat meet density requirements? ■ Are edge lines and joint overlaps neat and straight? ■ Is the job stopped if problems persist?
ROLLING RAC TYPE G MIX	■ Has a roller pattern been established? ■ Have the number of passes required for breakdown rolling been established? ■ Is the surface temperature of the mat correct at beginning of rolling? ■ Is the roller being operated at the correct speed? ■ Does the mat check under the roller? If so, wait a little longer for cooling. ■ Is water being used to cool the mat? ■ How many passes? ■ Is the mat uniform looking? ■ Has density been met? ■ Does the mix pick up? ■ Are edge lines and joint overlaps neat and straight? ■ Is the job stopped if problems persist?

PROJECT INSPECTION RESPONSIBILTIES	
ROLLING OPEN GRADED MIX	■ Has a roller pattern been established? ■ Have the number of passes required for breakdown rolling been established? ■ Is the surface temperature of the mat correct at beginning of rolling? ■ Is the roller being operated at the correct speed? ■ Does the mat check under the roller? If so, wait a little longer for cooling. ■ Is the mat uniform looking? ■ Has density been met? ■ Does the mix pick up? ■ Are edge lines and joint overlaps neat and straight? ■ Is the job stopped if problems persist?
TRUCK OPERATION	■ Trucks are staggered across the fresh tack coat to avoid driving over the same area. ■ Trucks travel slowly on the fresh mix. ■ Stops and turns are made gradually. ■ Truck operators avoid driving over mat. ■ Trucks should stagger their wheel paths when backing over a previous pass.
LONGITUDINAL JOINTS	■ Is echelon paving used? ■ Are joints overlapped or cut back? ■ Has a notch device been used? ■ Is compaction at joints satisfactory? ■ If left open to traffic, are edges of runs feathered to prevent fall off of traffic? ■ Are joints flat and smooth? ■ How far does the end gate of the paver overlap the previous lane? ■ Minimal raking of the longitudinal joint should be done. ■ Compaction should be from the hot side of the joint. ■ Are the joints straight and compact? ■ Ensure no gaps!

PROJECT INSPECTION RESPONSIBILTIES	
TRANSVERSE JOINTS	■ Transverse joints should be minimal and are used at the end of paving or when problems occur in laying. ■ Butt joints require a vertical face to be constructed by hand. Is this done? ■ Is it done quickly to avoid mix cooling? ■ Compaction is done upstream of the joint, are runoff boards provided for the roller? ■ Tapered joints are used if traffic is to be carried over a transverse joint. ■ Is the mat uniform up to the joint? ■ Is treated paper or sand used on the edge for a temporary joint to form a ramp? ■ Is a ramp constructed just with mix? ■ When paving is recommenced, is the ramp or taper removed cleanly? ■ Is raking used excessively to form the joint? ■ Is the joint compacted transversely? ■ If there are restrictions, is the joint compacted longitudinally? ■ Is the joint tight and well compacted and close to being indiscernible?
BROOMING (IF REQUIRED)	■ Brooming begins after the mixture is available for traffic. ■ Follow-up brooming should be done if raveling is high or if traffic is high.
OPENING THE MIX TO TRAFFIC	■ The traffic travels slowly–40 kph (24 mph) or less–over the fresh mat. ■ Remove all construction related signs when opening to normal traffic.
CLEAN UP	■ All loose aggregate should be removed from travel way. ■ Remove spills from all areas including curbs, sidewalks, and radius applications.

APPENDIX A

GLOSSARY OF TERMS

GLOSSARY OF TERMS

AADT – Average annual daily traffic.

Adhesion – Adhesion is the interaction between two substrates such as the bond between a sealant material and the crack or joint sidewall or the bond between asphalt cement and aggregate. This may be physical, chemical or physiochemical in nature.

Agency Costs – *See Annual Costs*

Aggregate Interlock – The projection of aggregate particles or portions of aggregate particles from one side of a joint or crack in concrete into recesses in the other side of the joint or crack so as to affect load transfer in compression and shear and maintain mutual alignment. Aggregate interlock is the steric interaction of aggregates by which the fractured faces mesh and prevent both aggregates from moving. It is created by the aggregates moving on one or more axes until this interaction occurs.

Alligator Cracking – A series of interconnecting cracks in an asphalt pavement surface forming a pattern that resembles an alligator's hide or chicken wire. In its early stages, alligator cracking may be characterized by a single longitudinal crack in the wheel path (Alligator A Cracking). The cracks indicate fatigue failure of the surface layer generally caused by repeated traffic loadings. Hence, the term fatigue cracking is also used.

Analysis Period – The period of time used in making economic comparisons between treatment alternatives. The analysis period should not be confused with the pavement's design life (performance period).

Annual Costs – Any costs associated with the annual maintenance and repair of a pavement facility.

Application Temperature – The manufacturer's recommended temperature for use of the product. For hot-applied sealants, the application temperature is any temperature between the minimum application temperature and safe heating temperature. This also covers the application of binders (particularly emulsions) in chip seal operations, and is addressed in Caltrans Standard Specifications, sections 37 and 94.

Asphalt Cement – Fluxed or unfluxed asphalt specially prepared as to quality and consistency for direct use in the manufacture of asphalt pavements.

Asphalt Concrete – See hot mix asphalt concrete.

Asphalt Tack Coat (or paint binder) – A light application of asphalt, usually asphalt emulsion. It is used to ensure a bond between two bituminous pavement layers, or a bituminous layer placed over an existing portland cement concrete layer.

Asset Management – A systematic process of maintaining, upgrading, and operating physical assets cost-effectively. It combines engineering principles with sound business practices and economic theory, and it provides tools to facilitate a more organized, logical approach to decision-making. Thus, asset management provides a framework for handling both short and long-range planning.

Backer Material – A compressible material that is placed in joints or cracks before applying sealant to prevent bonding of the sealant on the bottom of the joint, to control sealant depth, and to prevent sagging of the sealant.

Bituminous Pavement – A pavement comprising an upper layer or layers of aggregate mixed with a bituminous binder such as asphalt cement, modified asphalt emulsion, or asphalt rubber. Surface treatments such as chip seals, slurry seals, sand seals, and cape seals are also considered bituminous pavement.

Bleeding – Movement of binder through the bituminous pavement to create a layer of binder on the surface. The bleeding creates a shiny black surface that may be tacky to the touch, especially at high temperatures. Bleeding is often found in the wheel paths on curves and in climbing lanes.

Block Cracking – A rectangular pattern of cracking in asphalt pavements that is often caused by hardening due to aging coupled with shrinkage due to thermal contraction of the asphalt mixture. Block cracking typically occurs at a uniformly spaced interval in pavements with low traffic volumes.

Blow-up – Buckling and shattering of PCC pavement resulting from thermal expansion and the resultant compressive forces exceeding the strength of the material. It generally occurs at transverse joints or cracks.

Bond Breaker – Any material used to prevent bonding of adjacent pavement layers. A thin bituminous layer is often used as a bond breaker between a concrete pavement and an unbonded concrete overlay.

Bonded Concrete Overlay – Increase in the pavement structure of a concrete pavement by the addition of a concrete overlay in direct contact with and adhering to the existing concrete surface. May be used to correct either functional or structural deficiencies.

Break – The process by which the globules of asphalt in an asphalt emulsion flocculate and coalesce to become separated from the water. The color of the emulsion will change from brown to black during the breaking process.

California Profilograph – A rolling straight edge used for evaluating pavement profile (smoothness) consisting of a 7.5m (25-ft) frame with a wheel located at the center of the frame that senses and records bumps and dips on graph paper or by a computer.

Cape Seal – A surface treatment where a slurry surfacing is placed over a chip seal. These may be placed on newly constructed surfaces. Cape seals are used to provide a dense, waterproof surface with improved skid resistance and ride quality. Use of polymer or asphalt rubber modified chip seals in cape seals may alleviate reflective cracking.

Carbide Milling – Surface removal with a milling machine equipped with carbide tipped milling teeth. The hardened carbide tips are resistant to ear and efficiently grind and pulverize concrete and asphalt surfaces.

Chemically Curing Sealant – A material that reaches its final properties through the reaction of the component materials when mixed.

Chip Seal – A surface treatment in which the pavement is sprayed with asphalt (generally emulsified) and then immediately covered with aggregate and rolled. Chip seals are used primarily to seal the surface of a pavement with non load-associated cracks and to improve surface friction, although they also are commonly used as a wearing course on low volume roads. Use of special binders such as asphalt rubber or polymer modified binders can make an effective crack alleviation treatment and allow significantly deflecting pavements to flex without premature cracking.

Cohesion – The internal bond within a joint sealant material. Cohesion loss is seen as a noticeable tear along the surface and through the depth of the sealant. Cohesion is the internal strength of any material. It may be physical or chemical in nature or both. This includes binders and mixes!

Cold Applied Sealant – A crack-sealing compound that is generally applied at ambient temperatures reaching final properties through a curing process.

Cold In-Place Recycling (CIR) – A process in which a portion of an existing bituminous pavement is pulverized or milled, and then the reclaimed material is mixed with rejuvenation oils or emulsions, emulsion or other new binder and, when needed, virgin aggregates (to ensure correct grading). The binder used most often is emulsified asphalt with or without a softening agent. The resultant blend is placed as a base for a subsequent overlay or surface treatment. The reclaimed material can also be mixed with rejuvenation agents without the addition of new binder.

Cold Milling – A process of removing pavement material from the surface of the pavement either to prepare the surface to receive overlays (by removing rutting, and surface irregularities) or to restore pavement cross slopes and profile. Also used to remove oxidized asphalt concrete (Also, *see carbide milling*).

Compressible Insert – Material used to separate freshly placed concrete (such as from a partial-depth or full-depth repair) from existing hardened concrete. This usually consists of a 12-mm (0.5 in) thick Styrofoam or compressed fiber material that is impregnated with asphalt.

Concrete – *See Portland Cement Concrete*

Construction Joint – A joint constructed in a transverse direction in PCC pavements to control cracking of the slab as it cures. Highway construction joints are created by sawing the concrete.

Continuously Reinforced Concrete Pavement (CRCP) – PCC pavement constructed with sufficient longitudinal steel reinforcement to control transverse crack spacings and openings in lieu of transverse contraction joints for accommodating concrete volume changes and load transfer.

Contract Maintenance – The range of contracting methods and vehicles used by public transportation agencies to accomplish maintenance programs or supplement activities that may be performed in-house. Contracts may be activity based where the agency provides specifications and compensation is either on a lump sum or unit price basis; or performance based, long-term total asset management contracting which requires the contractor to provide turnkey maintenance to an established level of service. Contract maintenance (in other areas) means contracts let to carry out routine and major maintenance on a defined set of roadways under a quality plan.

Corner Break – A portion of a concrete slab separated by a crack that intersects the adjacent transverse or longitudinal joints at about a 45° angle with the direction of traffic. The length of the sides is usually from 0.3 meters (1 ft) to one-half of the slab width on each side of the crack.

Corrective Maintenance – Maintenance performed once a distress becomes severe enough to cause pavement disintegration, excessive deformation or cracking. It is applied to the pavement (e.g., pothole filling, or spall repair) to repair the specific distress type.

Concrete Pavement Restoration (CPR) – A series of repair techniques used to preserve or improve the structural capacity or functional characteristics of a PCC pavement. CPR techniques each have a unique purpose to repair or replace a particular distress (kind of deterioration) found in PCC pavement and to manage the rate of deterioration. CPR techniques include:

- Full-depth repair
- Partial-depth repair
- Diamond grinding
- Joint and crack resealing
- Slab stabilization
- Dowel Bar Retrofit
- Cross-stitching cracks or longitudinal joints
- Retrofitting concrete shoulders
- Retrofitting edge drains

Crack – Fissure or discontinuity of the pavement surface not necessarily extending through the entire thickness of the pavement. Cracks generally develop after initial construction of the pavement and may be caused by thermal effects, excess loadings or deflections or repetitive loading at sub-fracture stresses.

Crack Filling – The placement of materials into non-working cracks to substantially reduce the intrusion of incompressibles and infiltration of water, while also reinforcing the adjacent pavement. Crack filling should be distinguished from crack sealing (*see below*).

Crack Sealing – A maintenance procedure that involves placement of specialized materials into working cracks to prevent infiltration of water into the underlying pavement layers (*See Working Crack*). Crack sealing is the introduction of materials that adhere to the crack walls, are flexible and elastomeric in nature. This allows significant strain to be absorbed by the material without fracture. Much of this strain will be recoverable. Thus the crack may open and close with thermal stresses or traffic loading and remain sealed.

Cross Stitching – A repair method that involves the drilling of holes diagonally across a crack in PCC pavement into which steel reinforcement bars are inserted and epoxied in place. The holes are alternated from side to side of the crack on a pre-determined spacing. This technique is generally used for longitudinal cracks that are still in no worse than fair condition. Cross-stitching increases slab integrity by adding steel reinforcement to hold the crack together.

Cure – A period of time following placement and finishing of a material such as concrete during which desirable engineering properties (such as strength) develop. Improved properties may be achieved by controlling temperature or humidity during curing. Also, it relates to emulsions as this is the phase during which water is lost and continuous films of asphalt cement are formed.

Curing – The maintenance of a satisfactory moisture content and temperature in concrete during its early stages so that desired properties may develop. *See above.*

Curing Blanket – A built-up covering of burlap sacks, matting, straw, waterproof paper, or other suitable material placed over freshly finished concrete.

Curing Compound – A liquid that can be applied as a coating to the surface of newly placed concrete to retard the loss of water, or in the case of pigmented compounds, also to reflect heat so as to provide an opportunity for the concrete to develop its properties in a favorable temperature and moisture environment. *See Curing*.

Dense-Graded Asphalt Pavement – An overlay or surface course consisting of a mixture of asphalt binder and a well-graded (also called dense-graded) aggregate. A well-graded aggregate is uniformly distributed throughout a full range of sieve sizes (S*ee Hot Mix Asphalt*).

Depression – Localized pavement surface areas at a lower elevation than the adjacent paved areas.

Design Life – The expected life of a pavement from its opening to traffic until structural rehabilitation is needed. The typical reporting of pavement life does not include the life of the pavement with the application of preventive maintenance. Design life (in mechanistic terms) is the number of ESAL's (i.e., repetitive loadings) the pavement can absorb before stiffness is reduced to 50% of the design or initial stiffness.

Diamond Grinding – A process that uses a series of diamond-tipped saw blades mounted on a shaft or arbor to shave the upper surface of a pavement to remove bumps, restore pavement rideability, and improve surface friction (*See also CPR*).

Discount Rate – The rate of interest reflecting the investor's time value of money. The discount rate is used to convert benefits and costs occurring at different times to a baseline date. Discount rates can incorporate an inflation rate depending on whether real discount rates or nominal discount rates are used. The discount rate is often approximated as the difference between the interest rate and the inflation rate.

Dowel – Most commonly a plain round steel bar (usually coated, such as with paint or epoxy), which extends into two adjoining slabs of a PCC pavement at a transverse joint placed parallel to the centerline so as to transfer shear loads.

Dowel Bar Retrofit – A rehabilitation technique that is used to increase the load transfer capability of existing jointed PCC pavements by placement of dowel bars across joints and/or cracks that exhibit poor load transfer (*See also CPR*).

Emulsified Asphalt – A dispersion of asphalt binder, water, and emulsifying agent. Spherical globules of asphalt 0.5-10 microns in diameter are dispersed in water by using an emulsifying agent. These asphalt globules are either anionic (negatively charged) or cationic (positively charged).

Equivalent Uniform Annual Cost (EUAC) – The net present value of all discounted cost and benefits of an alternative as if they were to occur uniformly throughout the analysis period. Net Present Value (NPV) is the discounted monetary value of expected benefits (i.e., benefits minus costs).

Fatigue Cracking – *See Alligator Cracking*.

Faulting – Differential vertical displacement of a slab or other member adjacent to a joint or crack. Faulting commonly occurs at transverse joints of PCC pavements that do not have adequate load transfer.

Fiber Modified Sealant – Generally a hot-applied sealant that is composed of unmodified or modified asphalt cement and heat resistant polymeric fibers. It is commonly used to seal cracks in asphalt concrete pavements.

Flush Coat – An application of a fog seal and sand cover to the surface of a newly placed chip seal.

Fog Seal – A light application of slow setting asphalt emulsion diluted with water and applied to the surface of a bituminous pavement. Fog seals are used to rejuvenate aged asphalt surfaces as well as to seal small cracks and surface voids. Fog seals may also be used to improve chip retention in newly applied chip seals or retard raveling in poorly compacted hot mix. Fog seals may be followed by a sand coat to allow opening to traffic without pick up of the binder on vehicle wheels.

Free Edge – An unrestrained pavement boundary.

Fuel Resistant Sealant – A joint or crack sealant compound that is resistant to and maintains serviceability after being exposed to fuel or other petroleum products.

Full-Depth Patching – Removal and replacement of a segment of pavement to the level of the subgrade to restore areas of deterioration in either flexible or rigid pavements.

Functional Performance – A pavement's ability to provide a safe, smooth riding surface. These attributes are typically measured in terms of ride quality *(see International Roughness Index)* or skid resistance (*see International Friction Index*).

Grinding Head – A shaft containing numerous diamond blades or carbide teeth on diamond grinding or cold milling equipment.

Grooving – The process used to cut slots into a pavement surface (usually, PCC pavements) to provide channels for water to escape beneath tires, improving wet pavement skid resistance and reducing the potential for hydroplaning.

Heater Scarification – Application of heat to a pavement surface to facilitate scarifying of the pavement surface. Heater scarification is the initial phase of a hot in-place recycling (HIR) process in which the surface of the old pavement is heated and mechanically raked before removal and recycling.

Hot Air Lance – A device that uses heated compressed air to clean, dry, and warm cracks in asphalt pavements prior to sealing.

Hot Applied Sealant – A crack or joint sealing compound that is applied in a molten state and cures primarily by cooling to ambient temperature.

Hot In-Place Recycling (HIR) – A process which involves softening of the existing asphalt surface with heat, mechanically removing the surface material, mixing the material with a recycling or rejuvenating agent, adding virgin asphalt and aggregate to the material (if required), and then returning the material to the pavement.

Hot Mix Asphalt Concrete (HMAC or HMA) – A controlled mixture of asphalt binder and well-graded, high quality aggregate compacted into a uniform layer of predetermined density. HMAC pavements may also contain additives such as anti-stripping agents and polymers.

Hydroplaning – Loss of contact between vehicle tires and the roadway surface that occurs when vehicles travel at high speeds on pavement surfaces with standing water.

Initial Costs – All costs associated with the initial design and construction of a facility, placement of a treatment, or any other activity with a cost component.

International Friction Index (IFI) – A measure of pavement macrotexture and wet pavement friction at 60 miles per hour as determined using measured friction at some test speed and macrotexture determined using ASTM E-965 or ASTM E-1845.

International Roughness Index (IRI) – A measure of a pavement's longitudinal surface profile as measured in the wheel path by a vehicle traveling at typical operating speeds. It is calculated as the ratio of the accumulated suspension motion to the distance traveled obtained from a mathematical model of a standard quarter car traversing a measured profile at a speed of 80 km/h (50 mph). The IRI is expressed in units of meters per kilometer or inches per mile and is an indication of pavement roughness.

Joint – A pavement discontinuity made necessary by design or by interruption of a paving operation.

Joint Depth – The measurement of a saw cut from the top of the pavement surface to the bottom of the cut.

Joint Deterioration – *See Spalling*.

Joint Filler – Compressible material used to fill a joint to prevent the infiltration of water or debris.

Joint Sealant – Compressible material used to minimize water and solid debris infiltration into the sealant reservoir and joint.

Joint Seal Deterioration - Break down of a joint or crack sealant, such as by adhesion or cohesion loss, which contributes to the failure of the sealant system. Joint seal deterioration permits incompressible materials or water to infiltrate into the pavement system.

Joint Shape Factor – Ratio of the vertical to horizontal dimension of the joint reservoir. The shape factor is dependent upon the type of sealant specified.

Jointed Plain Concrete Pavement (JPCP) – PCC pavement constructed with regularly spaced transverse joints to control all natural cracks expected in the concrete. Dowel bars may be used to enhance load transfer at transverse contraction joints (depending upon the expected traffic); however, there is no mid-slab temperature reinforcement.

Jointed Reinforced Concrete Pavement (JRCP) – Portland cement concrete pavement containing regularly spaced transverse joints and embedded steel mesh reinforcement (sometimes called distributed steel) to control expected cracks. Steel mesh is discontinued at transverse joint locations. Dowel bars are normally used to enhance load transfer at transverse joints. The transverse joint spacing of JRCP is typically longer than the joint spacing of JPCP.

Lane-to-Shoulder Drop off – Difference in elevation between the travel way and the shoulder surface.

Life Cycle Costing – An economic assessment of an item, system, or facility and competing design alternatives considering all significant costs of ownership over the economic life, expressed in terms of equivalent dollars. A method of determination of the cost of the pavement to the road owner over its design life.

Life Extension – The extension of the performance period of the pavement through the application of pavement treatments.

Liquid Asphalt (cutback) – Asphalt cement liquefied by blending with petroleum solvents.

Load-Transfer Assembly – Most commonly, the basket or carriage designed to support or link dowel bars in the desired alignment during jointed PCC pavement construction.

Load Transfer Efficiency – A measure of the ability of a joint or crack to transfer a portion of a load applied on one side of a joint or crack to the other side of the joint or crack.

Longitudinal Crack – A crack or discontinuity in a pavement that runs generally parallel to the pavement centerline. Longitudinal cracks may occur as a result of poorly constructed paving lane joints, thermal shrinkage, inadequate support, and reflection from underlying layers, or as a precursor to fatigue cracking. Longitudinal cracking that occurs in the wheel path is generally indicative of fatigue cracking.

Longitudinal Joint – A constructed joint in a pavement layer that is oriented parallel to the pavement centerline.

Low Modulus Sealant – A joint or crack sealing material, which exhibits elastomeric properties at low temperatures.

Map Cracking – A series of interconnected hairline cracks in PCC pavements that extend only into the upper surface of the concrete. These cracks are typically associated with alkali-silica reactivity (ASR).

Maximum Heating Temperature – The maximum temperature, as recommended by the manufacturer, to which a binder can be heated while conforming to all specification requirements and providing appropriate application characteristics.

Melter – A piece of equipment designed specifically to heat hot applied joint or crack sealant accurately and controllably to a temperature where it will flow.

Melter Applicator – A piece of equipment designed specifically to melt, heat accurately and controllably, and apply hot-applied sealants to pavement cracks or joints.

Microsurfacing – A mixture of polymer modified asphalt emulsion, mineral aggregate, mineral filler, water, and other additives, properly proportioned, mixed, and spread on a paved surface. Microsurfacing differs from slurry seal in that it is usually applied at more than a single stone thickness. Also, it has special emulsifiers for more rapid setting and, higher stiffness; it may be used for rut filling in stable pavements.

Mineral Filler – Mineral product with at least 70% passing the 0.075 mm (No. 200 sieve). Commonly used mineral fillers include, limestone dust, hydrated lime, portland cement, and fly ash.

Minimum Application Temperature – The minimum temperature, as recommended by the manufacturer, to which binder must be heated while conforming to all specification requirements and providing appropriate application characteristics.

Modified Asphalt Chip Seal – A variation on conventional chip seals in which the asphalt binder is modified with a polymeric material derived from a blend of ground tire rubber and natural rubber or latex rubber, or synthetic polymer modifiers to enhance the elastomeric, cohesive and/or adhesive characteristics of the binder.

Net Present Value – The value of future expenditures or costs discounted to today's dollars using an appropriate discount rate.

Open-Graded Friction Course (OGFC) – A thin HMA surface course consisting of a mix of an asphalt binder and open-graded aggregate. An OGFC helps to eliminate standing water on a pavement surface thereby reducing tire spray and hydroplaning potential.

Overbanding – Overfilling of a joint or crack reservoir so that a thin layer of crack or joint sealant is spread onto the pavement surface center over the joint or crack.

Partial-Depth Patching – Repairs of localized areas of surface deterioration of PCC pavements, usually for compression spalling problems, severe scaling, or other surface problems that are within the upper one-third of the slab depth.

Patch – Placement of a repair material to replace a localized defect in the pavement surface.

Pavement Distress – External (visible) indications of pavement defects or deterioration.

Pavement Preservation – The sum of all activities undertaken to provide, maintain and extend the life of roadways. This includes corrective, routine and preventive maintenance to keep the roadway in a safe and usable condition and delay the need for rehabilitation.

Pavement Preventive Maintenance – Planned strategy of cost-effective treatments to an existing roadway system and its appurtenances to preserve and extend the life of the system, retard deterioration, and maintain or improve the functional condition of the system without increasing the structural capacity.

Pavement Reconstruction – Replacement of an existing pavement structure by the placement of the equivalent of a new pavement structure. Reconstruction usually involves complete removal and replacement of the existing pavement structure and may include new and/or recycled materials.

Pavement Rehabilitation – Structural enhancements that extend the service life of an existing pavement and/or improve its load carrying capability. Rehabilitation techniques include restoration treatments and structural overlays.

Performance Period – The period of time that an initially constructed or rehabilitated pavement structure will perform before reaching its terminal serviceability.

Plant Mix – *See Hot Mix Asphalt*.

Point Bearing – Concentration of compressive stresses in small areas. This may occur when a partial-depth patch in portland cement concrete pavement is made without the compressible insert. Also, slab expansion in hot weather forces an adjacent slab to bear directly against a small partial-depth patch and causes the patch to fail by delaminating and popping out of place.

Polishing – Wearing away of the surface binder, causing exposure of the coarse aggregate particles. A polished pavement surface is smooth and has reduced skid resistance.

Portland Cement Concrete (PCC) Pavement – A pavement constructed of portland cement concrete with or without reinforcement. Conventional PCC pavements include JPCP, JRCP, and CRCP.

Potholes – Potholes are created by collapse of the pavement surface. This is caused by water ingress into the pavement layers reducing stiffness and increasing flexing. Loss of HMA surface fines and matrix will lead to a reduction in integrity of the top pavement layer and formation of a hole. Loss of surface material in the HMA pavement requires a patch to restore pavement rideability. Potholes are typically bowl shaped holes of various sizes.

Preformed Compression Sealant – An extruded joint sealing material for PCC pavement that is manufactured ready for installation and is supplied in rolls. Preformed sealants incorporate an internal web design so that the material, when compressed and inserted into the sealant reservoir, remains in compression against the sides of the joint.

Present Serviceability Index (PSI) – A subjective rating of the pavement condition made by a group of individuals riding over the pavement. This may also be determined during a condition survey.

Present Worth – *See Net Present Value*.

Preventive Maintenance - A planned treatment on a road in good condition that is intended to preserve the system retard future deterioration, prolong service life and delay the need for rehabilitation.

Pumping – Ejection of fine-grained material and water from beneath the pavement through joints, cracks, or the pavment edge, caused by the deflection of the pavement under traffic loadings.

Punch Out – A localized area of a continuously reinforced concrete pavement bounded by two transverse cracks and a longitudinal crack. Aggregate interlock decreases over time and eventually is lost, which leads to steel rupture and allows the pieces to be punched into the subbase and subgrade.

Racked-In Seal – An application of a small aggregate to a fresh chip seal, with or without a flush coat of binder, for the purpose of increasing shear resistance in fresh chip seals and is especially useful in intersections.

Raveling – Aggregate loss from the pavement surface. This may be caused by the wearing away of the pavement surface, dislodging of aggregate particles, shrinkage or insufficient adhesive and cohesive strength of the asphalt binder. Loss of cohesion may be caused by aging or incomplete cure of an emulsion.

Reactive Maintenance – Maintenance applied to restore a pavement to an acceptable level of service due to unforeseen conditions. Activities such as pothole repairs, performed to correct random or isolated localized pavement distresses or failures, are considered reactive. Similar to Corrective Maintenance.

Recycling Agents – Organic materials with specific chemical and physical characteristics that are used in pavement recycling to address binder deficiencies and to restore aged asphalt material to desired specifications. Such materials include heavy lube oil fractions or aromatic oil extracts that soften the asphalt and increase its flexibility. Some recycling agents may contain asphalt as well as polymers to improve binder rheology.

Reflection Cracking – Cracking that appears on the surface of a pavement above joints and cracks in the underlying pavement layer due to horizontal and vertical movement at these joints and cracks. Reflection cracking is caused by a build-up of strain below the surface layer caused by movement at cracks or joints. These strains, if not alleviated (relieved), cause crack initiation in the surface layer. This crack may then propagate to the surface. The rate is dependent on the physical characteristics and geometric properties of the pavement surface layer.

Rejuvenating Agent – Similar to recycling agents in material composition, these products are added to existing aged or oxidized HMA pavements to restore pavement surface flexibility and to retard cracking.

Reservoir – The part of a portland cement concrete pavement joint that normally holds a sealant material, usually formed by a widening saw cut above the initial saw cut. Reservoirs may also be found in HMA pavements where joints are sawed and sealed above existing PCC pavements.

Retrofit Dowel Bars– Dowels that are installed into slots cut into the surface of an existing concrete pavement to restore load transfer.

Rideability – Ride quality of a pavement as perceived by its users or quantified by longitudinal profile.

Router – A mechanical device, with a rotary cutting system, that is used to widen, cut, and clean cracks in pavements prior to sealing.

Routine Maintenance – Maintenance work that is planned and performed on a regular basis to maintain and preserve the condition of the highway system or to respond to specific conditions and events that restore the highway system to an adequate level of service. Examples include crack sealing, fog sealing, and repair of localized failed areas of pavement.

Rubberized Asphalt Concrete (RAC) – Similar to HMA but having a minimum 15% crumb rubber additive in the binder.

Rubberized Asphalt Sealant – A sealant, generally hot applied, that is composed of asphalt cement, various types of rubber or polymer modifiers, and other compounding ingredients used for pavement crack and joint sealing.

Rutting – Longitudinal surface depressions in the wheel path of an HMA pavement, caused by cumulative plastic deformation of the HMA mix, inadequate compaction, or abrasion from studded tires (such abrasion can also be observed on PCC pavements). There may also be associated transverse displacement.

Sandblasting – A procedure in which sand particles are blown with compressed air at a pavement surface to abrade and clean the surface. Sandblasting is a construction step in partial-depth patching and joint resealing.

Sand Seal – An application of asphalt binder, normally an emulsion, covered with a fine aggregate. It is a technique to improve skid resistance and to seal the pavement surface on low volume roadways.

Sandwich Seal – An application of a dry aggregate to a bleeding surface followed by an application of an emulsion binder and a smaller aggregate for the purpose of alleviating the bleeding surface.

Scrub Seal – An application of a polymer modified asphalt emulsion to the pavement surface followed by the broom scrubbing of the emulsion into cracks and voids, then the application of an even coat of sand or small aggregate, and a second brooming of the aggregate and asphalt mixture. This seal is then rolled with a pneumatic tire roller.

Sealant – A material that has adhesive and cohesive properties to seal joints or cracks [generally less than 76 mm (3 in) in width].

Sealant Reservoir – *See Reservoir*.

Sealing – The process of placing sealant material in prepared joints or cracks to minimize intrusion of water and incompressible materials. This term is also used to describe the application of pavement surface treatments.

Sealing Compound – *See Joint Sealant*.

Segregation – Separation of aggregate components present in asphalt or portland cement concrete mixes by particle size. Segregation may occur anytime there is movement of the material.

Serviceability – Ability of a pavement to provide a safe and comfortable ride to its users. The term commonly used to describe the functional capacity of the pavement.

Settlement – A depression at the pavement surface that is caused by deformation or erosion of underlying materials.

Shoving – Localized displacement of an HMA pavement surface, often caused by high shear stresses associated with vehicle acceleration to deceleration.

Silicone Sealant – A type of joint or crack sealant compound consisting of polymers of polysiloxane structures that cures through a chemical reaction when exposed to air.

Skid Resistance – An indication of the frictional characteristics of a pavement surface.

Slab Stabilization – Process of injecting grout or bituminous materials beneath PCC pavements to fill voids without raising the pavement.

Slippage Cracking - Cracking associated with the horizontal displacement of a localized area of an HMA pavement surface mainly due to a poor bond between layers of bituminous pavement.

Slurry – Dispersion of solid materials in a water carrier that forms a smooth and evenly distributed mixture. A slurry is a dispersion of a solid in a liquid forming an unstable suspension of particles. The technical name is sol or colloidal sol.

Slurry Seal – Slurry seal is most commonly made with a quick setting emulsion in California (CQS-1h or LMCQS-1h) which passes the ASTM (T59) slow setting specification with the exception of the cement-mixing test, well graded fine aggregate, mineral filler, and water. In California, polymer in latex form is usually added to the slurry. It is used to fill fine non-active cracks and seal areas of old or raveling pavements, to restore a uniform surface texture, to seal the surface to prevent moisture and air intrusion into the pavement, and to improve skid resistance.

Spalling, Compression – Cracking, breaking, chipping, or fraying of slab edges within 0.6 meters (2 ft) of a transverse crack.

Spalling, Sliver – Chipping of concrete edge along a joint sealant usually within 12 mm (0.5in) of the joint edge.

Spalling, Surface – Cracking, breaking, chipping, or fraying of slab surface, usually within a confined area less than 0.5 square meters (0.6 yd^2).

Stone Matrix Asphalt (SMA) – A mixture of asphalt binder, stabilizer material, mineral filler, and gap-graded aggregate that provides high stone on stone contact. The high level of mineral filler forms a mortar with the binder to enhance flexibility. Fibers are often added to prevent drain down during transportation of the mix to the job site; SMAs are used as a rut resistant wearing course.

Stress-Absorbing Membrane Interlayer (SAMI) – A thin layer that is placed between an underlying pavement and an HMA overlay for the purpose of dissipating strain and stresses at a joint or crack in the underlying pavement before they create stresses in the overlay. SAMIs normally consist of a spray application of asphalt rubber as the stress-relieving material, followed by a layer of aggregate chips.

Structural Condition – The condition of a pavement as it pertains to its ability to support the anticipated loadings.

Structural Overlay – An increase in the pavement load carrying capacity by adding additional pavement layers.

Surface Texture – The microscopic and macroscopic characteristics of the pavement surface that contribute to surface friction and noise.

Surface Treatment – Any application applied to an asphalt pavement surface to restore or protect the surface characteristics. Surface treatments include a spray application of asphalt (cement, cutback, or emulsion) and may or may not include the application of aggregate cover. Surface treatments are typically less than 25 mm (1 in) thick. They may also be referred to as surface seals, seal coats or chip seals. Slurry seals, thin bonded wearing course and thin overlays are also considered surface treatments.

Swell - A hump in the pavement surface that may occur over a small area or as a longer, gradual wave; either type of swell can be accompanied by surface cracking.

Terminal Serviceability – The lowest acceptable serviceability rating before resurfacing or reconstruction becomes necessary for the particular class of highway.

Thin Overlay – A single lift HMA overlay with a thickness of 38 mm (1.5 in) or less.

Transverse Crack – A discontinuity in a pavement surface that is generally oriented perpendicular to the pavement centerline. In HMA pavements, transverse cracks often form as a result of thermal movements of the pavement or reflection from underlying layers. In PCC pavements, transverse cracks may be caused by fatigue, loss of support, or thermal movements.

Treatment Life – The period of time during which a treatment application remains effective. Treatment life is contrasted with Life Extension.

Two-Component Sealant – A sealant supplied in two components which must be mixed at a specified ratio prior to application in order to cure to final properties.

Ultra Thin Overlay – An HMA overlay over an existing HMA or PCC pavement and is less than 25 mm (1 in) in thickness. May also be called a thin bonded wearing course.

Unbonded Overlay – Increase in the pavement structure of an existing concrete or composite pavement by addition of jointed plain, jointed reinforced or continuously reinforced concrete pavement placed on a separator layer (usually an asphalt layer) designed to prevent bonding to the existing pavement.

User Costs – Costs incurred by highway users traveling on the facility, and the excess costs incurred by those who cannot use the facility because of either agency or self-imposed detour requirements. User costs typically are comprised of vehicle operating costs (VOC), crash costs, and user delay costs.

Warranty – Contractual agreement between an approved contractor/vendor and the agency soliciting bids, which uses specific performance measures to protect the agency from responsibility for repair of premature distress caused by deficiencies in material and/or workmanship.

Waterblasting – The use of a high-pressure water stream 58,000 to 69,000 kPa (8,500 to 10,000 psi) to clean PCC. It may be used in PCC joint resealing to remove sawing debris or in patching to produce a clean surface prior to placement of the sealer or patch material. This is also referred to as hydroblasting.

Whip-Off – The loss of excess aggregate due to traffic or sweeping immediately after construction of a chip seal.

Ultra-Thin White (UTW) Topping – A thin [50 to 100 mm (2 to 4 in)] PCC overlay of an existing HMA pavement. UTW is a functional overlay that provides a stable surface that is resistant to deformation from static, slow moving, and turning loads.

Working Crack – A crack in a pavement that undergoes significant deflection and thermal opening and closing movements greater than 2 mm (1/16 in), typically oriented transverse to the pavement centerline.