CHAPTER 10 THIN MAINTENANCE OVERLAYS

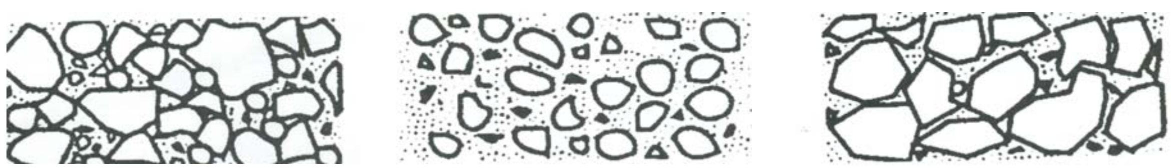
10.1 OVERVIEW

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 (Caltrans, 2007). 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 1½ inches (37.5 mm) in thickness. In Caltrans, thin blankets are 1.2 inch (30 mm) thick.

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

- Dense Graded Thin Blankets (HMA-A and HMA-B)
- Open Graded (OGFC, RHMA-O, and RHMA-O-HB)
- Gap Graded Mixes (RHMA-G)

The different mixes are defined based on their aggregate grading, binder content, and voids content. Figure 10-1 illustrates, in general, the differences in aggregate structure for these mix types.



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

Figure 10-1 Stone Matrices Created by Different Gradings (Austroads, 2000)

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

10.2 DENSE-GRADED OVERLAYS

10.2.1 Dense-Graded Mixes

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. An appropriate asphalt grade should be selected based on the climatic region and anticipated distress mode. Asphalts could be modified to adjust properties for these conditions. For example, modified asphalts may be used if it is anticipated that thermal cracking may occur due to a single severe temperature drop (Asphalt Institute, 1998) and/or during cooler (night) paving conditions. Now PG asphalts are used with these mixes and the graded is selected based on the climatic region and anticipated distress 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 (Caltrans, 2007). It should be noted that for thin overlays of 1 to $1^1/_2$ in (25 to 37 mm) the stone size was previously limited to a maximum of one-half the thickness of the layer, but this was changed to one-third in the new section 39 specifications. Table 10-1 shows the required aggregate physical requirements as specified in the Standard Specifications.

Table 10-1 Aggregate Quality Requirements (Caltrans, 2007)

Quality Characteristic	Test Method	HMA Type			
		A	B	RHMA-G	OGFC
Percent of crushed particles	CT 205				
Coarse aggregate (% min.)					
One fractured face		90	25	--	90
Two fractured faces		75	--	90	75
Fine aggregate (% min)					
(Passing No. 4 sieve and retained on No. 8 sieve.)		70	20	70	90
Los Angeles Rattler (% Max.)	CT 211				
Loss at 100 Rev.		12	--	12	12
Loss at 500 Rev.		45	50	40	40
Sand equivalent [a] (min.)	CT 217	47	42	47	--
Fine aggregate angularity (% min.) [b]	AASHTO T 304 Method A	45	45	45	--
Flat and elongated particles (% max. @ 5:1)	ASTM D 4791	10	10	10	10
K_c factor (max.)	CT 303	1.7	1.7	1.7	--
K_f factor (max.)	CT 303	1.7	1.7	1.7	--

Notes:

a Reported value must be the average of 3 tests from a single sample.

b. The Engineer waives this specification if HMA contains less than 10 percent of nonmanufactured sand by weight of total aggregate.

10.2.2 Dense-Graded Overlays 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.

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 asphalt binders can be used to address low temperature cracking and reflective cracking.

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).
- 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 properly, it will tend to be less cohesive and ravel or delaminate.

Job Selection

Thin blanket overlays should only be used on sound pavements where minor defects are 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.

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 (Hicks, 2000). 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 3 provides a simplified framework of selecting cost effective treatments.

10.2.3 Dense-Graded Overlays 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 (Caltrans, 2007, Asphalt Institute, 1998, Army Corps of Engineers, 1991, Asphalt Institute, 1988) 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 determination of an 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 10-2 shows the required properties of the mixture as specified in the Standard Specifications (Caltrans, 2007).

Table 10-2 Hot Mix Asphalt for Job Mix Formula (Caltrans, 2007)

Quality Characteristic	Test Method	HMA Type		
		A	B	RHMA-G
Air voids content (%)	CT 367[a]	4.0	4.0	Special Provisions
Voids in mineral aggregate (% min.)	LP-2			
No. 4 grading		17	17	--
3/8" grading		15	15	--
1/2" grading		14	14	18 – 23[b]
3/4" grading		13	13	18 – 23[b]
Voids filled with asphalt (%)	LP-3	65 - 75	65 - 75	Note d
Dust proportion	LP-4			
No. 4 and 3/8" gradings		0.9 – 2.0	0.9 – 2.0	Note d
1/2" and 3/4" gradings		0.6 – 1.3	0.6 – 1.3	
Stabilometer value [c](min.)	CT 366			
No. 4 and 3/8" gradings		30	30	--
1/2" and 3/4" gradings		37	35	23

Notes:

a. Calculate the air voids content of each specimen using California Test 309 and Lab Procedure LP-1. Modify California Test 367, Paragraph C5, to use the exact air voids content specified in the selection of OBC.
b. Voids in mineral aggregate for RHMA-G must be within this range.
c. Modify California Test 304, Part 2.B.2.c: "After compaction in the compactor, cool to 140 degrees ± 5 degrees F by allowing the briquettes to cool at room temperature for 0.5-hour, then place the briquettes in the oven at 140 degrees F for a minimum of 2 hours and not more than 3 hours."
d. Report this value in the JMF submittal.

10.2.4 Dense-Graded Overlays Material Requirements

Dense graded 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., PG 64-10, PG 64-16, 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 2 has more information on materials requirements. Information on the use of rubber-modified mixtures can be found in the Caltrans Asphalt Rubber Usage Guide (Caltrans, 2006).

10.2.5 Dense-Graded Asphalt Concrete (DGAC) Overlay Construction

Safety

Standard Caltrans safety and traffic control procedures must be followed. These procedures are detailed in Caltrans references (1999 and 2003).

Manufacture

Aggregates and binder are mixed using either a batch plant or drum mixing plant (Caltrans, 2007). References including the Asphalt Institute (1998) and Army Corps of Engineers (1991) 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 2) to allow full coating of the aggregates during the actual mixing process.

Storage

Currently DGAC should not be stored in silos for periods greater than 18 hours. Material with hardened lumps cannot be used. The Standard Specifications (Caltrans, 2007) details storage silo requirements as does References Asphalt Institute, 1998 and Army Corps of Engineers, 1991.

Hauling

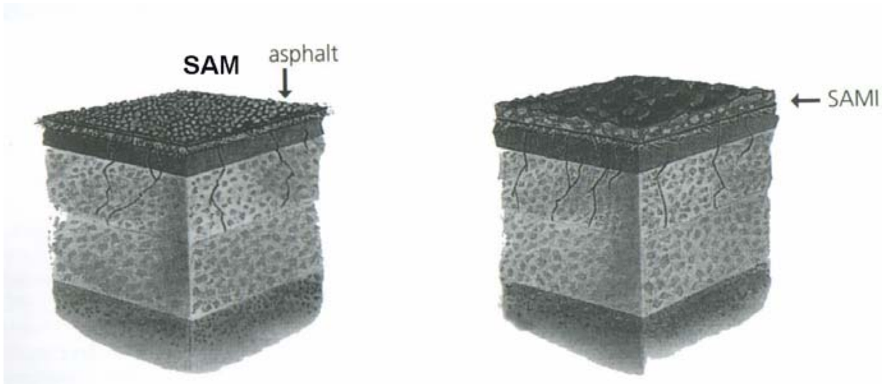
Standard hauling equipment (i.e., end dump vehicles, bottom dump vehicles, or live bottom dump vehicles) may be used for the construction of dense graded thin overlays. U.S. Army Corps of Engineering (1991) contains further information regarding these types of vehicles. Tarping is advised to prevent 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.

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 potholes patched. Crack sealing and patching practices were covered in Chapters 4 and 5, respectively.

In some cases a SAM or SAMI (Figure 10-2) 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 10-2 SAM Seal and SAMI (Austroads, 2000)

Tack Coat

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 (Asphalt Institute, 1998).

Good tack coat practice must be followed. The Standard Specifications Section 39-4.02 (Caltrans, 2007) 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 5). A tack coat should be applied in one application at the residual rate determined by the Section 39-1.09C (Caltrans, 2007).

Laydown

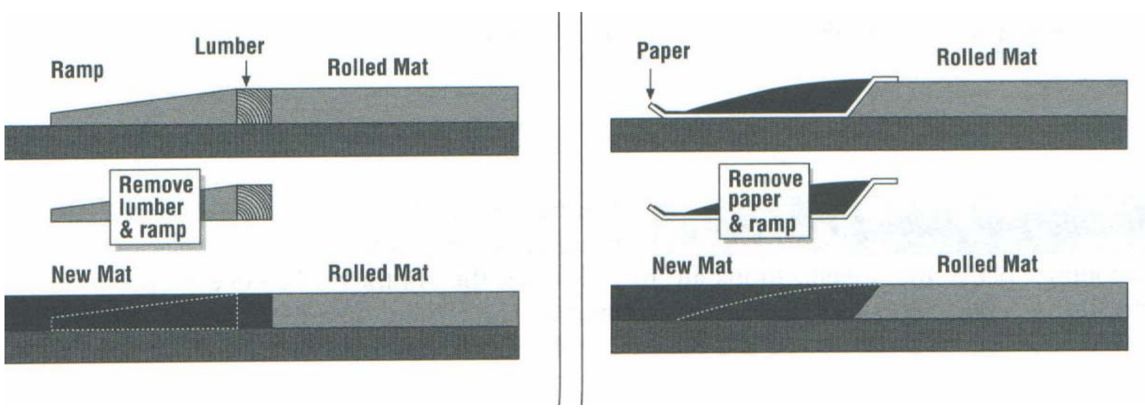
Dense graded mixes may be windrowed ahead of the paver and picked up with a pick up device (loader) and deposited in the paver hopper. The length of the windrow must be as short as possible to ensure excessive cooling does not occur. If conditions are good (i.e., little or no wind and higher temperatures), this is usually about 160 ft (50 m) maximum (Hicks, 2000). If conditions are poorer than this, the length of the windrow should be kept less than 160 ft (50 m). Table 10-3 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 10-3 Recommended Application Temperatures (Caltrans, 2007)

BINDER TYPE	**MINIMUM AIR TEMPERATURE, °F**	**MINIMUM SURFACE TEMPERATURE, °F**	**MINIMUM BREAKDOWN ROLLING TEMPERATURE, °F**	**MINIMUM FINISHING TEMPERATURE, °F**
CONVENTIONAL (UNMODIFIED)	55	60	250	150
PG-PM	50	55	240	140

**These are minimum temperatures. It is recommended that spreading and compacting be performed at temperatures above these minimums, but not to exceed 325ºF.*

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 10-3a. Conversely, if traffic is allowed to travel over the joint, it will be necessary to construct a tapered joint as illustrated in Figure 10-3b. References Asphalt Institute (1998) and U.S. Army Corps of Engineering (1991) provide detailed guidance for constructing transverse joints.



a) Butt Joint b) Tapered Joint

Figure 10-3 Transverse Joint Formation (Asphalt Institute, 1998)

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 2 in (50 mm) to create a vertical face, or an overlapping joint can be constructed.

Whenever a joint is created by "cutting back the joint," a 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 10-4 illustrates a technique of rolling from cold side. In this method, rolling in the first pass was done in the static mode with a major portion of the roller wheel on the cold side with about 6 inches (152 mm) of the roller wheel on the hot side of the joint. This technique is believed to produce a "pinching" effect on the joint. The second backward pass was made in the vibratory mode with roller on the hot side with about 6 inch overlap on the cold side. However, timing in this type of rolling is critical. When the roller is operated on the cold side, the hot side undergoes cooling which can make it difficult to achieve the desired compaction level (Kandahl, et al, 2002).

If the mix along the joint is clean, a tack coat is not normally needed prior to placement of the adjacent lane of pavement. Static or vibratory rollers with low amplitude setting should be used.

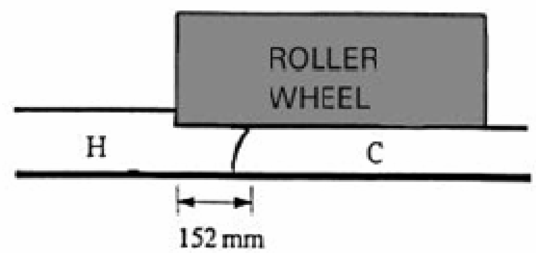
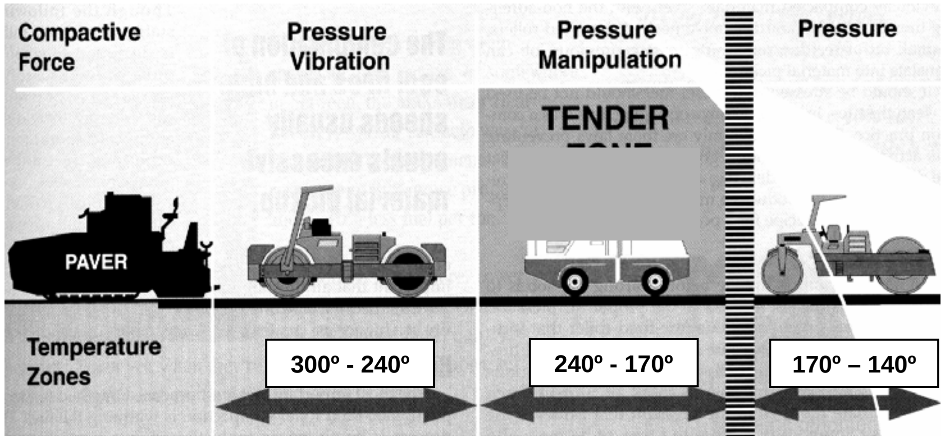


Figure 10-4 Formation of Longitudinal Joints

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 10-5 (Lender, 2001). The actual temperatures would vary some based on binder type.



(Temperatures given in °F)

Figure 10-5 Rolling Regimes

Acceptance

Dense graded asphalt pavements are usually accepted based on aggregate grading, binder content, and density of the in-place mixture. Acceptance criteria for method specifications are presented in Table 10-4.

Table 10-4 Acceptance – Method (Caltrans, 2007)

Quality Characteristic	Test Method	HMA Type			
		A	B	RHMA-G	OGFC
Aggregate gradation [a]	CT 202	JMF ± Tolerance [b]	JMF ± Tolerance [b]	JMF ± Tolerance [b]	JMF ± Tolerance [b]
Sand equivalent (min.) [c]	CT 217	47	42	47	--
Asphalt binder content	CT 379 or 382	JMF ± 0.45%	JMF ± 0.45%	JMF ± 0.5%	JMF +0.50 -0.70
HMA moisture content (max.)	CT 370	1.0%	1.0%	1.0%	1.0%
Stabilometer value[c, d, e] (min.)	CT 366				
No. 4 and 3/8" gradings		30	30	--	--
1/2" and 3/4" gradings		37	35	23	--
Percent of crushed particles	CT 205				
Coarse aggregate (% min.)					
One fractured face		90	25	--	90
Two fractured faces		75	--	90	75
Fine aggregate (% min)					
(Passing No. 4 sieve and retained on No. 8 sieve.)		70	20	70	90
Los Angeles Rattler (% max.)	CT 211				
Loss at 100 rev.		12	--	12	12
Loss at 500 rev.		45	50	40	40

a. The Engineer determines combined aggregate gradations containing RAP under Laboratory Procedure LP-9.
b. The tolerances must comply with the allowable tolerances in Section 39-1.02E, "Aggregate."
c. The Engineer reports the average of 3 tests from a single split sample.
d. The Engineer prepares and tests a set of 3 briquettes for each stability determination. If the stability range is more than 12 points, the Engineer prepares and tests new briquettes.
e. Modify California Test 304, Part 2.B.2.c: "After compaction in the mechanical compactor, cool to 60 degrees C ±3 degrees C by allowing the briquettes to cool at room temperature for 0.5 hour, then place the briquettes in the oven at 60 degrees C for a minimum of 2 hours and not more than 3 hours."

Caltrans Standard Specifications does specify density on pavement lifts less than 1 ½". Compaction on thin lift overlays are based on the method specification 39-3.03.

Post Treatments

Dense graded materials usually require no post-laydown treatments.

10.3 OPEN-GRADED OVERLAYS

10.3.1 Open-Graded Mixes

Open Graded Friction Course (OGFC), also referred to as Open Graded Asphalt Concrete (OGFC), is a surface course with an aggregate gradation that provides an open void structure as compared with conventional dense graded asphalt concrete (Hicks, 2000, AEMA, 1998). Air void content typically ranges between 15 to 25% in OGFC mixtures (Hicks, 2000, Kandahl, 1998, Mallick, 2000) resulting in a highly permeable mixture relative to HMA (which normally is relatively impermeable). The porous nature of OGFC 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 OGFC mixtures is a significant reduction in splash and spray relative to HMA mixtures and PCC pavements. Other benefits include a reduction in tire noise and an increase in the frictional characteristics relative to HMA mixtures. The addition of modifiers such as polymers and asphalt rubber can 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 Caltrans Standard Specifications. Table 10-5 shows the required characteristics of such aggregates as specified in the Standard Specifications. The mixture requirements are based on a drain down test and are discussed in Section 10.3.4.

Table 10-5 Aggregate Quality Requirements (Caltrans, 2007)

Quality Characteristic	Test Method	HMA Type
		OGFC
Percent of crushed particles	CT 205	
Coarse aggregate (% min.)		
One fractured face		90
Two fractured faces		75
Fine aggregate (% min)		
(Passing No. 4 sieve and retained on No. 8 sieve.)		90
Los Angeles Rattler (% Max.)	CT 211	
Loss at 100 Rev.		12
Loss at 500 Rev.		40
Sand equivalent [a] (min.)	CT 217	--
Fine aggregate angularity (% min.) [b]	AASHTO T 304 Method A	--
Flat and elongated particles (% max. @ 5:1)	ASTM D 4791	10
K_c factor (max.)	CT 303	--
K_f factor (max.)	CT 303	--

Notes:

a Reported value must be the average of 3 tests from a single sample.

b. The Engineer waives this specification if HMA contains less than 10 percent of nonmanufactured sand by weight of total aggregate.

10.3.2 Open-Graded Overlays Performance

OGFC 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.

Distresses/Conditions Addressed

Conventional open graded thin overlays should only be placed on structurally sound pavements, 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 (Kandahl, 1998, Mallick, 2000):

- 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, OGFC mixes may also enhance resistance to reflective cracking. In addition, modified systems such as asphalt rubber and PG-PM binders can be used to address low temperature cracking and reflective cracking. Also, because durability is a function of film thickness (Shell, 1999), the use of modifiers (e.g. asphalt rubber) that increase in-service viscosity allow thicker films resulting in higher resistance to oxidation and raveling (Kandahl, 1998, Mallick, 2000). The void structure also allows absorption of free surface asphalt to mitigate bleeding pavements.

Principal Distress Modes

OGFC overlays exhibit the following distress modes (Hicks, 2000, Austroads, 2000, Kandahl, 1998):

- Permanent deformation due to heavy traffic loading in conjunction with 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. The performance of OGFC thin overlays is based on maintaining the void structure.

10.3.3 Open-Graded Overlays Job Selection

Where Should OGFC be Used?

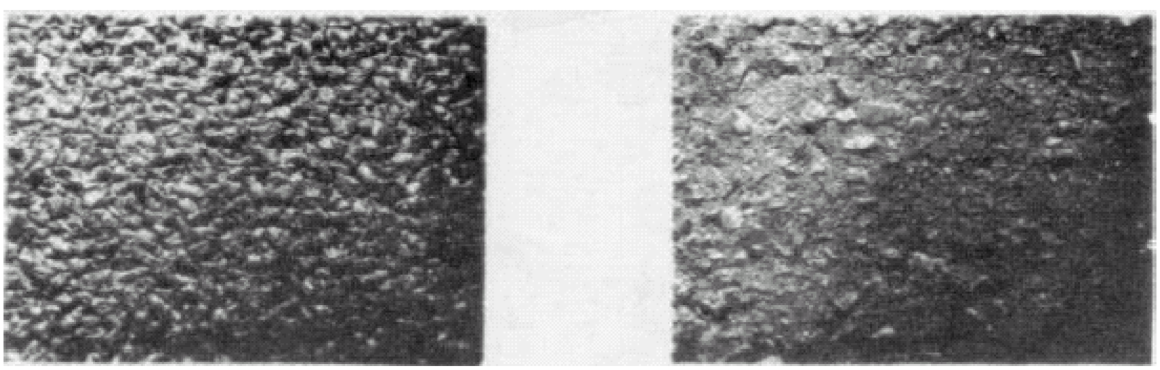
- In California, OGFC is generally used in new construction, major rehabilitation projects, and also in maintenance overlays. OGFC is used as a wearing course (i.e., surface treatment over HMA pavements and occasionally on portland cement concrete (PCC) pavements). OGFC is generally used on the traveled way and extending 1 ft (0.3 m) on the shoulder (AEMA, 1998). In maintenance applications, the distress mode of the existing pavement must be determined and addressed.
- Open graded overlays should be placed on structurally sound pavements.
- RHMA-O or RHMA-O-HB can be used to address the possibility of reflective cracking due to the existing pavement surface.

When Should OGFC be Used?

Consider using OGFC as a surface treatment when the following conditions exist:

- **Wet Weather Accidents:** Consider the use of OGFC 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 OGFC to minimize wet weather accident occurrences.

- **Skid Resistance:** When frictional properties of the pavement surface are suspect, a friction test should be conducted to determine the existing coefficient of friction of the pavement surface (CT 342). Figure 9-6 shows typical surface textures of OGFC compared with HMA.



Typical Open Graded Typical Dense Graded

Figure 10-6 Typical Texture

- **Wet-night Visibility:** Another consideration for the use of OGFC is when the TASAS Report reveals a high percentile confidence level for wet weather and nighttime accident occurrences. OGFC 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, OGFC may be especially helpful to assist in the draining of water from the pavement surface.

- **Noise:** OGFC has also been reported to reduce road noise (Kandahl, 1998, Mallick, 2000, Caltrans, 2001, FHWA, 1995, FHWA, 1990). 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 OGFC (Caltrans, 2001). The life expectancy of the noise benefit varies with the mix and binder type.

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

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

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

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

Where and When Should OGFC Not be Used?

OGFC should not be used on:

- **Unstable Pavements:** OGFC should not be used on any pavement that exhibits substantial cracking, rutting, bleeding, or depressions. The extent of pavement distress precluding the use of OGFC 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 conventional OGFC due to potential for scuffing. These areas may include parking areas, intersections, ramp terminals, or curbed sections. However, OGFC with modified binders has been successfully utilized in these areas.

- **Curb and Gutter/Dense Graded:** OGFC should not be placed adjacent to curb and gutter or HMA 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 OGFC.

- **Fuel or Oil Spill Areas:** OGFC 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 OGFC as a bathtub effect may be created. If OGFC were to be used as the final course, a leveling course would be required first.

Special Maintenance Requirements of OGFC

Permeability must be maintained to ensure water flow is unimpeded**.** Maintenance on roadways surfaced with OGFC should avoid any activities that may obstruct the lateral flow of water through the OGFC. These activities may include crack sealing or patching a small failed area with HMA thus creating a 'dam' where water may be retained or stored and contribute to further failure of the OGFC surfacing. When large areas of patching are involved, OGFC should be replaced with OGFC. 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. OGFC has different thermal and icing properties compared with HMA. Thermal conductivity is up to 70% less according to National Asphalt Pavement Association (NAPA, 2002). It will act as an insulating layer and accumulate ice and frost faster than HMA.

General maintenance of OGFC to prevent clogging is important in some areas. Water hoses, high-pressure cleaners, and specialized cleaning vehicles may be used for this purpose.

Service Life and Costs

OGFC overlays have been shown to last 2 to 10 years, but more commonly 4 to 6 years (Hicks, 2000). 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 3 (Framework for Treatment Selection) provides a simplified method of comparing cost effectiveness of different treatments.

10.3.4 Open-Graded Overlays Mix Design and Specifications

Caltrans uses CT 368 to design OGFC 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. When utilizing a modified binder, the OBC is determined by measuring the drain down using the appropriate unmodified binder for the project location. 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.

Materials Requirements

More detailed information on the materials requirements for binders and aggregates is covered in Chapter 2. The special requirements of OGFC 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 OGFC mixtures must be more resistant to the effects of aging than those used for HMA 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 10-5 and the gradings were shown in Table 10-6. It has been found that coarser gradings give a more open void structure (Hicks, 2000, Mallick, 2000). These tend to give good stone on stone contact and deformation resistance and the voids are less susceptible to becoming clogged.

Binders for OGFC include PG 64-10, PG 64-16, PG 64-28, PG 70-10, and Asphalt Rubber (Caltrans, 2007). Modified systems such as asphalt rubber can be used to address low temperature cracking, reflective cracking and night paving. Polymer modified binders (PG PM) may be used to address low temperature cracking and to overcome problems of lower temperature paving conditions (e.g., night paving). Binder requirements are shown in Table 10-7. The void structure allows absorption of free surface asphalt to overcome bleeding pavements. Since durability is a function of film thickness (Shell, 1999), the use of modifiers that increase in-service viscosity allow for thicker films and higher resistance to oxidation and raveling (Lender, 2001). All modifiers appear to improve the abrasion resistance of the mixes (Mallick, 2000).

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 (Smith, 1993; Schuler, 1994). 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.

Table 10-6 Aggregate Gradation Requirements (Caltrans, 2007)

1–inch OGFC

Sieve Sizes	Target Value Limits	Allowable Tolerance
1 1/2"	100	—
1"	99 - 100	TV ±5
3/4"	85 - 96	TV ±5
1/2"	55 - 71	TV ±6
No. 4	10 - 25	TV ±7
No. 8	6 - 16	TV ±5
No. 200	1 - 6	TV ±2

1/2–inch OGFC

Sieve Sizes	Target Value Limits	Allowable Tolerance
3/4"	100	—
1/2"	95 - 100	TV ±6
3/8"	78 - 89	TV ±6
No. 4	28 - 37	TV ±7
No. 8	7 - 18	TV ±5
No. 30	0 - 10	TV ±4
No. 200	0 - 3	TV ±2

3/8–inch OGFC

Sieve Sizes	Target Value Limits	Allowable Tolerance
1/2"	100	—
3/8"	90 - 100	TV ±6
No. 4	29 - 36	TV ±7
No. 8	7 - 18	TV ±6
No. 30	0 - 10	TV ±5
No. 200	0 - 3	TV ±2

Mix Requirements

Table 10-7 shows binder materials typically used by Caltrans.

Table 10-7 Asphalt Binder Selection (Caltrans, 2007)

<table>
<tr><th rowspan="2">Binder

Climatic Region</th><th colspan="2">Conventional Asphalt</th><th>Rubberized Asphalt</th></tr>
<tr><th>PG</th><th>PG Polymer Modified[1]</th><th>PG</th></tr>
<tr><td>South Coast
Central Coast
Inland Valleys</td><td>64-10</td><td rowspan="5">58-34PM</td><td rowspan="3">64-16</td></tr>
<tr><td>North Coast</td><td>64-16</td></tr>
<tr><td>Low Mountain
South Mountain</td><td></td></tr>
<tr><td>High Mountain
High Desert</td><td>64-28</td><td>58-22</td></tr>
<tr><td>Desert</td><td>70-10</td><td>64-16</td></tr>
</table>

Note: [1] For low temperature placement

10.3.5 Open-Graded Overlays Construction

Manufacturing and construction methods are similar to those for dense graded materials. The methods must address the following important issues (Hicks, 2000).

Safety

Standard Caltrans safety and traffic control procedures must be followed. These procedures are detailed in Caltrans references (1999 and 2003).

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 (Caltrans, 2007). 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.

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. See Caltrans Standard Specifications Section 39 for details (Caltrans, 2007).

Hauling

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 10-3 are met.

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 OGFC. 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 OGFC surface will require removal of the existing OGFC prior to placing new OGFC. 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 Coat

Good tack coat practices must be followed correctly. (Caltrans, 2007; Caltrans, 2006b). OGFC 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.

Laydown

During laydown, standard Caltrans safety and traffic control procedures must be followed. These procedures are detailed in the Caltrans reference (1999). Traffic is not allowed on OGFC until final rolling has been completed.

Paving guidelines shown in Table 10-8 are applicable to the laydown of the OGFC mix.

Table 10-8 Laydown Guidelines

ANTICIPATED AMBIENT TEMPERATURE	GUIDELINES*
> 70ºF	OGFC may be placed using windrow and pick up machines. The length of the windrow should be usually limited to 164 ft. There should be little or no wind
55ºF – 70ºF	OGFC should be placed by end-dumping into the paving machine, not by windrowing. Keep rollers within 49 ft of paving machine. Tarp trucks for hauls >30 minutes. Mix in hopper to be 194-248ºF.
50ºF – 55ºF	In addition to above rules, PG-PM (polymer modified) asphalt binder should be used. Asphalt rubber binders may also be used. Maximum mixing temperature can be raised to 325 ºF. Mix temperature in hopper to be 275ºF.
< 50ºF	OGFC should not be placed.

**Ensure all Standard Specifications and SSPs (Caltrans, 2007) 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). Rolling temperatures are shown in Table 10-9. The entire mat placed by the paving machine must be rolled before it cools. It would be prudent, however, to insure that the roller rolls to the edge only and does not "hang over" an unsupported edge, causing excess weight concentrated on the edge which could collapse the void structure. It should be noted that the recommended weight of rollers for OGAC is steel rollers having a weight of 126-172 pounds per linear inch of compactive force (Caltrans, 2007). They shall be used only in the static mode and limited to two complete coverages. The static weight of the rollers was not used due to the varying widths of rollers available.

Table 10-9 Application Temperatures (Caltrans 2007)

Binder Type	Minimum Air Temperature, ºF	Min Surface Temperature, ºF	Minimum Breakdown Rolling Temperature, ºF	Minimum Finishing Temperature, ºF
Conventional (Unmodified)	55	60	ASAP (240)	200
PG-PM	50	50	240	180
Asphalt Rubber	55	60	280	250

Sampling and Acceptance

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

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 1 to 2 lbs/yd^2 after rolling is complete (Caltrans, 2007).

10.4 GAP-GRADED OVERLAYS

Gap graded mixtures currently placed in California are, in general, solely Rubberized Asphalt Concrete (RAC) Type G which uses asphalt rubber binders (Caltrans, 2007). However, MB type G mixtures have been used in pilot projects. This section covers only the RAC-G asphalt rubber mixes.

10.4.1 Gap-Graded Mixes

A gap graded mixture consists of an aggregate grading that has a missing fraction. The Type G gradings are shown in Table 10-10. 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 (Hicks, 2000). The binder content may be 7 to 9% by weight with asphalt rubber binders.

Table 10-10 Rubberized Hot Mix Asphalt - Gap Graded (Caltrans, 2007)

3/4" RHMA-G

Sieve Sizes	Target Value Limits	Allowable Tolerance
1"	100	—
3/4"	95 - 100	TV ±5
1/2"	83 - 87	TV ±6
3/8"	65 - 70	TV ±6
No. 4	28 - 42	TV ±7
No. 8	14 - 22	TV ±5
No. 200	0 - 6	TV ±2

1/2" RHMA-G

Sieve Sizes	Target Value Limits	Allowable Tolerance
3/4"	100	—
1/2"	90 - 100	TV ±6
3/8"	83 - 87	TV ±6
No. 4	28 - 42	TV ±7
No. 8	14 - 22	TV ±5
No. 200	0 - 6	TV ±2

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.

10.4.2 Gap-Graded Overlays Performance

Distresses/Conditions Addressed

Thin gap graded thin overlays should be placed on structurally sound pavements. They can be used to mitigate the following distresses present in an existing pavement:

- Raveling
- Oxidation
- Reflection cracking
- Minor surface irregularities
- 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.

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, only asphalt rubber modified binders are used in these mixes.

10.4.3 Gap-Graded Overlays Job Selection

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).

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.

Service Life and Costs

Costs of Type G mixes are higher than OGFC. Caltrans has not performed any LCCA on these mixes.

10.4.4 Open-Graded Overlays Design and Specifications

The design of Type G mixtures is similar to that for dense graded mixtures as indicated in SSP 39-400 (Caltrans, 2007) 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 (Caltrans, 2007).
- Laboratory mixing is done from 300 to 325°F (149 to 163ºC) and compaction from 290 to 300°F (143 to 149ºC)
- 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) (Asphalt Institute, 1988).

Asphalt rubber materials requirements are provided in Chapter 2. The aggregate for Type G rubberized asphalt concrete shall conform to the grading contained in SSP 39-400 (Caltrans, 2007) and shall meet the quality provisions specified for Type A asphalt concrete in Section 39-2.02, "Aggregate," of the Standard Specifications (Caltrans, 2007).

10.4.5 Gap-Graded Overlays Construction

Construction methods for Type G mixtures are similar to those for dense graded materials as detailed in Section 10.2.5. The following are important issues (Hicks, 2000).

Safety

Standard Caltrans safety and traffic control procedures must be followed. These procedures are detailed in Caltrans references (1999 and 2003).

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 2 and Caltrans, 2007).

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.

Storage

In general, Type G mixes should not be stored for more than two hours due to stability limitations in the asphalt rubber binder.

Hauling

Standard hauling equipment (i.e., end dump vehicles) may be used for the construction of Type G overlays. Caltrans reference (2003) 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.

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.

Tack Coat

Good tack coat practice must be followed. The Standard Specifications (Caltrans, 2007) and Caltrans Tack Coat Guidelines (Caltrans, 2006b) specify 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.

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 160 ft (50 m) maximum (Hicks, 2000). If conditions are poorer than this, the length of the windrow should be kept shorter than 160 ft (50 m). Table 10-11 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 10-11 Recommended Application Temperatures (Caltrans, 2007)

MATERIAL	MINIMUM AIR TEMPERATURE, °F	MINIMUM MIX LAYDOWN TEMPERATURE, °F	MINIMUM BREAKDOWN ROLLING TEMPERATURE, °F	MINIMUM FINISHING TEMPERATURE, °F
Asphalt Rubber	55 to 65	290	260	203
	≥ 65	280	250	203

These are minimum temperatures. It is recommended that spreading and compacting be performed at temperatures above these minimums, but not to exceed 325ºF.

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 (See section 10.2.5 Laydown).

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 8 to 9 tons (7,000 to 8,000 kg). Rolling temperatures are shown in Table 10-11.

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.

Acceptance

Type G mixes are usually accepted based on grading, binder content, and visual inspection.

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 (Caltrans, 2007) is applied after final rolling at 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.

10.5 TROUBLESHOOTING AND FIELD CONSIDERATIONS

10.5.1 Troubleshooting Guide

This section provides information to assist maintenance personnel with troubleshooting problems associated with placing any of the thin HMA overlays. Table 10-12 presents a troubleshooting guide that associates common problems to their potential causes, whereas Table 10-13 lists some commonly encountered problems and their recommended solutions.

Table 10-12 Troubleshooting Guide

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				✔													
Incorrect Nulling of Screed												✔					
Screed Starting Blocks Too Short												✔					
Screed Extensions Installed Incorrectly					✔	✔											
Vibrators Running Too Slow						✔				✔							

Table 10-12 Troubleshooting Guide (Continued)

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
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			✔			✔		✔		✔							
Trucks Bumping Finisher		✔					✔										
Truck Holding Brakes		✔					✔										
Improper Base Preparation	✔	✔				✔				✔			✔	✔		✔	✔
Improper Rolling Operation	✔										✔	✔	✔	✔		✔	✔
Reversing or Turning Too Fast of Rollers		✔												✔		✔	✔
Parking Roller on Hot Mat		✔														✔	✔
Improper Mix Design (Agg)	✔		✔			✔			✔				✔	✔	✔		✔
Improper Mix Design (Asphalt)	✔		✔			✔			✔				✔	✔	✔		✔
Mix Segregation	✔	✔	✔			✔			✔								
Moisture in Mix			✔										✔	✔	✔		✔
Variation of Mix Temperature	✔	✔	✔			✔		✔					✔	✔	✔	✔	✔
Cold Mix Temperature			✔	✔	✔	✔		✔		✔	✔	✔					✔

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 10-13 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 10-13 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. • The dumping of hopper wings when paving with bottom dumps **SOLUTIONS** • Ensure thickness is at least three times that of largest stone size, mix design is correct, and the paver is properly set up • Ensure mix temperature is correct • Not dump the wings or, alternatively, place insert plates in the hopper eliminating the wing area
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 10-13 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 (No. 16 - No. 30 [1.18mm - 600 µm 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

Table 10-13 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

10.5.2 Field Considerations

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 at least 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 RESPONSIBILITIES	
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?

<table>
<tr><th colspan="2">PROJECT INSPECTION RESPONSIBILITIES</th></tr>
<tr><td>LAYDOWN OF RAC TYPE G MIX</td><td>

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?

</td></tr>
<tr><td>LAYDOWN OF OPEN GRADED MIX</td><td>

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?

</td></tr>
</table>

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 RESPONSIBILITIES	
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–24 mph (40 kph) 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.

10.6 REFERENCES

Asphalt Emulsion Manufactures Association, 1998. *Recommended Performance Guidelines*, Annapolis, Maryland, 1998.

Asphalt Institute, 1988. *Mix Design Methods For Asphalt Concrete*, Series MS-2, Lexington, Kentucky,1988.

Asphalt Institute, 1998. *HMA Construction*, Series MS-22, 2nd Edition, Lexington, Kentucky, 1998

Austroads, 1998. *Guide to the Selection of Road Surfacings*, Publication AP-G63/03, Sydney, Australia, 2000.

California Department of Transportation, 1999. *Caltrans Code of Safe Operating Practices*, Sacramento, California, 1999.

California Department of Transportation, 2001. *I-80 Davis OGFC Pavement Noise Study*, Sacramento, California, 2001.

California Department of Transportation, 2006. Open Graded Friction Course Usage Guide, Caltrans, Sacramento, California, Fed. 8, 2006.

California Department of Transportation, 2006. *Asphalt Rubber Usage Guide*, Sacramento, California, 2006.

California Department of Transportation, 2006a. *Highway Design Manual*, Chapter 630 Flexible Pavements, Sacramento, California, June, 2006

California Department of Transportation, 2006b. *Tack Coat Guidelines*, Sacramento, California, July, 2006.

California Department of Transportation, 2007. *Standard Specifications*, Section 39 Hot Mix Asphalt, Sacramento, California, 2007.

Federal Highway Administration, U.S. Department of Transportation, 1990. *Open graded friction courses*, Technical Advisory T5040.31, Washington, D.C., December 26, 1990.

Federal Highway Administration, U.S. Department of Transportation, Office of Environment and Planning, Noise and Air Quality Branch, 1995. *Highway Traffic Noise Analysis and Abatement Policy and Guidance*, Washington, D.C. June 1995

Hicks, R.G, Fee, F, Moulthrop, J.S, 2000. *Experiences With Thin and Ultra Thin HMA Pavements in the United States*, Australian Asphalt Pavement Association International Conference, Sydney, Australia, 2000.

Kandahl, P.S., Mallick, R.B., 1998. *Open Graded Asphalt Friction Course State of the Practice*, National Center for Asphalt Technology Report 98-7, Auburn, Alabama, 1998.

Kandahl, et al, 2002. *Evaluation of Eight Longitudinal Joint Construction Techniques for Asphalt Pavements in Pennsylvania*, NCAT Report 02-03, Feb. 2002.

Lender, S., 2001. *Establish Perfect Roller Patterns For Bonus Quality Mats*, Asphalt Contractor, November 2001.

Mallick, R.B., Kandahl, P.S., Cooley, L.A., Watson, D.E., 2000. *Design Construction and Performance of New Generation Open Graded Friction Courses*, Journal, AAPT, Vol. 69, 2000.

National Asphalt Pavement Association, 2002. *Design Construction and Maintenance of Open Graded Asphalt Friction Courses* IS-115, Maryland, 2002.

Schuler, S., Hanson D.L., 1994. *Improving Durability Of Open Graded Mixes*, Transportation Research Board Record, 1994.

Shell, 1999. *Shell Bitumen Handbook*, United Kingdom, 1999.

Smith, H.A., 1993. *Performance Characteristics of Open Graded Friction Courses*, NCHRP Synthesis of Highway Practice # 180, Washington, D.C., 1993.

U.S. Army Corps of Engineering, 1991. *Hot Mix Paving Handbook*, July 1991.

Various Authors, 1990. *Porous Asphalt Pavements*, Transportation Research Board Record 1265, 1990.