NCAT Report 02-01

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DRAFT FINAL REPORT

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INTRODUCTION AND PROBLEM STATEMENT

The compaction of coarse-graded Superpave designed mixtures is sometimes more difficult than with some of the more fine-graded mixtures that had previously been designed using the Marshall procedure. One problem with compacting coarse-graded mixes has been the "tender zone," which sometimes occurs during compaction. The tender zone typically occurs within a temperature range of 245 to 180°F.

The problem of tender mixes is not new, it has been around for many years. There are many possible characteristics of a mixture which may lead to tenderness being exhibited during field compaction. Among these is the use of an excessive amount of rounded fine aggregates (natural sands), a low asphalt binder viscosity, a high asphalt binder content, a reduced filler content, the presence of internal moisture in the aggregate, etc. (*1*, *2*, *3*). All of the above-mentioned characteristics can alone, or in combination, cause a mix to exhibit tender behavior. With coarse-graded Superpave mixes, the tenderness typically occurs within a range of temperatures referred to previously as the "tender zone."

Some of the possible causes of the tender zone which have been expressed in the literature and by members of the HMA industry include the following:

1. Short term aging during mix design not being comparable to actual production

During the Superpave mix design procedure, mixtures are required to be short term aged. This short term aging period was established in an attempt to simulate the aging that an HMA mixture undergoes during production, transport, and laydown. However, the short-term aging procedure also allows time for the asphalt binder to be absorbed by the aggregates within a mix.

This short-term aging procedure calls for placing a loose mixture in a forced draft oven for two or four hours. If water absorption for the aggregates is less than 2.0 percent then the short term aging procedure is typically two hours in a forced draft oven set at the asphalt binder's compaction temperature. If water absorption is greater than 2.0 percent, the short term aging procedure is generally four hours at 135°C. In many cases the amount of binder absorption that occurs during the mix design procedure is greater than the binder absorption experienced during production, transport, and laydown. For instance, if a given mixture was aged for the four-hour period at 135°C (275°F), but the project was only 10 minutes from the asphalt plant (with no storage time), obviously the mixture would exhibit different absorption characteristics than that observed during mix design. A potential result of this short production/transportation time is that the mixture's aggregate may have not had sufficient time to fully absorb all of the binder that was absorbed during design. Without all of this absorption, the volume of effective asphalt in the mix at the time of placement is increased which makes the mix appear over-asphalted. Over-asphalted mixes can be prone to tenderness during compaction.

2. Presence of excessive internal moisture in the aggregate or underlying layers

In the most ideal case, the amount of internal aggregate moisture during HMA production would be near zero. However, this is often not the case. When the mixture is produced, this internal moisture attempts to escape from the aggregate particles. Moisture which leaves the aggregate particle after the particle is coated tends to strip the asphalt film from the aggregate.

During production, placement, and compaction, the internal moisture trapped within an aggregate will try to escape because of the elevated temperatures. Similar to the asphalt binder, this moisture escaping from the aggregate can act to lubricate the mixture by increasing the effective liquids content and by lowering the apparent viscosity of the asphalt binder. The net result is the mix acts as though it is over-asphalted during compaction which can lead to tenderness.

3. Decreased viscosity of the asphalt binder in the produced hot mix asphalt

A decrease in the asphalt viscosity from that expected may lead to a mixture which exhibits tenderness during compaction. A reduction in viscosity can be caused by increased temperatures, less mix aging, contamination, or inconsistent grade of supplied binder.

Decreased viscosity may relate to the amount of aging which is experienced in the field being less than that during the mix design procedure. Under Superpave, asphalt binders are required to meet a minimum stiffness requirement of 2.20 kPa when tested on the dynamic shear rheometer after rolling thin film oven (RTFO) conditioning or aging. If the aging during the mixing and placement operations is significantly less that expected then, the asphalt binder in the produced mix may have a viscosity that is too low, possibly resulting in a mixture which is more prone to tenderness.

4. A dust to effective asphalt ratio which is too low

The original dust to effective asphalt (D/A) ratio criteria used in Superpave was from 0.6 to 1.2. Many states are now specifying an increased limit for coarse-graded Superpave mixtures of up to 1.6 due to a feeling that the mixes should have more dust (minus 75:m) present in these coarser mixes to stiffen the binder and mixture. A coarse-graded mixture which has a low ratio will exhibit a lower mixture viscosity or stiffness than a mixture with a high ratio. The lower viscosity mixture is more likely to exhibit tenderness during compaction than a high viscosity (stiffer) mix.

5. Increased Asphalt Film Thicknesses and Temperature Differential Within the Lift

Additionally, a possible explanation of the “tender zone” may lie in the increased asphalt film thickness of the coarse-graded Superpave mixtures, along with the presence of a temperature differential within a given lift. With the coarse-graded mixtures, the aggregate surface area is reduced, yet the optimum asphalt content is approximately the same, thus yielding increased asphalt film thicknesses.

At the start of the breakdown rolling, the mix is in a loose enough state that the amount of aggregate interlock is minimal and the mix temperature is hot (small temperature differential) throughout the lift. As the breakdown rolling continues and the mix cools, the top and bottom portion of the lift become cooler than the middle portion of the lift. This results in the top and bottom of the lift having a greater stiffness than the middle portion. The top portion is now stiff enough to cause the mix to push in front of the roller and slip within the hotter middle portion of the layer.

Figure 1 shows the temperature at various locations within an example of a constructed pavement lift. In this example, a 1 inch lift was being placed with the temperature determined at the surface and bottom of the lift and at the 1/4 and 5/8 inch location within the lift. (*4*) A similar temperature differential would be expected for other typical lift thicknesses placed. As mentioned previously, the tender zone tends to occur when the breakdown rolling is nearing completion. Generally with the coarse-graded mixes this corresponds to approximately 5 to 10

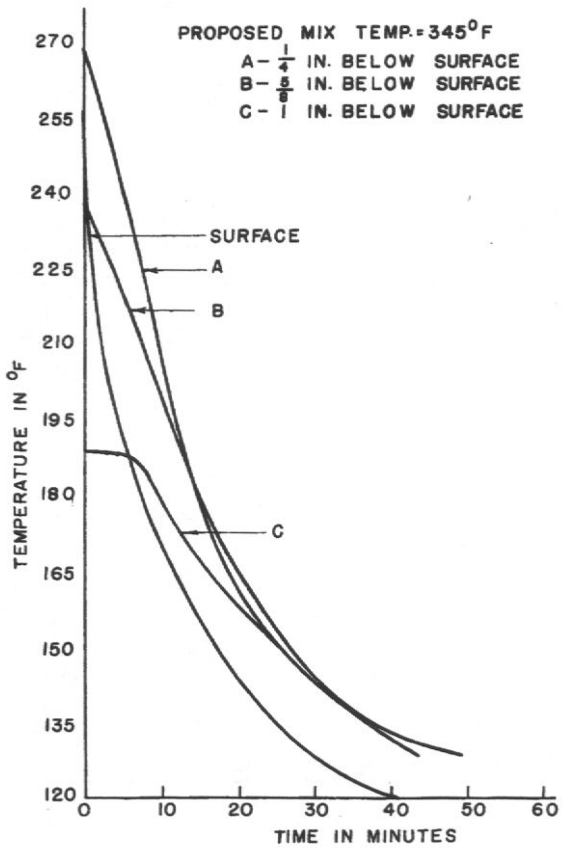

Figure 1. Differential Cooling Within Lift (*4*)

minutes after the initial mix placement. From Figure 1, the temperature at the surface and bottom of the lift is approximately 185 to 190°F; however, in the middle of the lift the temperature is substantially hotter, approximately 225°F. At this point the middle portion of the lift has less stiffness (hotter) than the top and bottom of the lift. The horizontal force component of the steel wheel roller tends to push the higher stiffness (cooler) portion of the lift past the lower stiffness portion located in the middle, as shown in Figure 2, causing shoving, checking, and lateral movement.

Some success has been obtained by using pneumatic rollers for intermediate compaction, in place of steel drum rollers. Pneumatic rollers, through kneading action, tend to have a compaction force in a more vertical direction than steel wheel rollers. Additionally, the kneading action of the tires acts to restrain the mat from lateral movement to a greater extent than does the steel wheel rollers. However, pneumatic rollers tend to pick up excessively so it is very important to ensure that this is not a problem.

When the middle portion of the lift reaches some lower temperature, the stiffness of this portion of the lift is sufficient to resist horizontal movement and tenderness is not present. However, the mix is still at a high enough temperature so that a small amount of compaction with the finish roller can be obtained. Compaction of the mat can now continue without the tenderness being encountered. In some cases, density has been obtained at temperatures down to approximately 140°F. Obviously, the temperature differential within the mat and also the rate of cooling is dependent upon the weather conditions, the lift thickness, and the overall mix temperature.

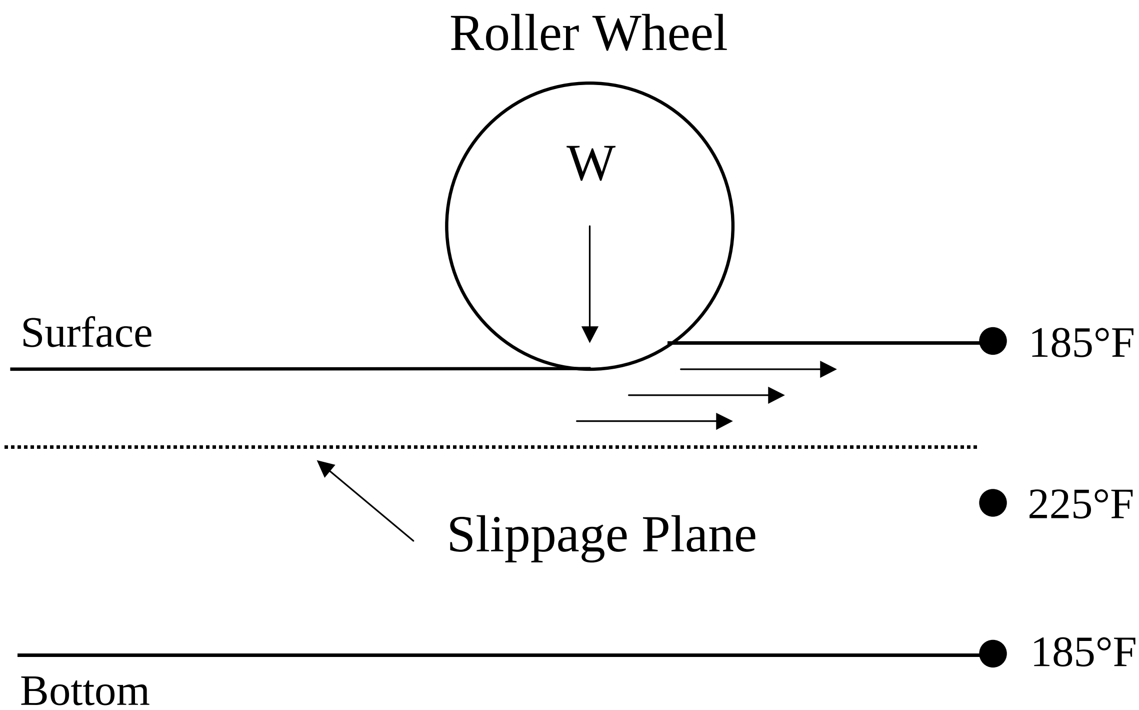

Figure 2. Roller Action on a Differentially Cooled Lift

OBJECTIVE

The objective of this study was to collect information concerning the production and placement of HMA pavements which had experienced problems with a tender zone during compaction and to determine the causes of these problems.

SCOPE AND TEST PLAN

A cooperative project, pertaining to the tender zone, between the National Asphalt Pavement Association (NAPA), the Federal Highway Administration (FHWA), and the National Center for Asphalt Technology (NCAT) was completed in 1999 and resulted in a final report (3) being issued in April 2000. This study was undertaken to determine the basic cause(s) of the tender zone, the best possible construction methods to work in and around the tender zone, and possible solutions to the elimination or reduction of the tender zone problem. The work consisted primarily of opinions of several experts, and had no mixture testing as a part of the study.

This project reported herein intended to build on the initial study by taking samples during construction and determining the appropriate properties of these samples. Both documentation and evaluation through mixture testing were included in the test plan. A representative of NCAT visited five HMA construction projects that were experiencing tender mix problems to document the project and collect samples for laboratory evaluation. The project was divided into two parts: (1) Documentation of Construction Observations and (2) Evaluation of Mixture Test Results.

Documentation of Construction Observations

Documentation of the mix design, production, transport, and laydown was conducted at each project. Items documented included the job mix formula information, plant information, roadway data, weather conditions, paving equipment, compaction methods (rolling patterns), and specific observations pertaining to the tender zone.

Evaluation of Mixture Test Results

Documentation of the project details was supplemented with a laboratory evaluation of the produced mixtures. This laboratory evaluation consisted of asphalt content, aggregate gradation, and mixture volumetric testing (theoretical maximum density and bulk specific gravity).

Additionally, a sample of the asphalt binder (approximately two gallons) was obtained from each project. With this sample, Superpave binder tests (verification of the performance grade) and steam distillation tests were conducted. Steam distillation of the binders was included to evaluate the light ends within the binders. The Superpave binder testing on both the original samples and steam distilled samples was performed to ensure that the asphalt cement being used conformed to the asphalt binder specifications set up for the project.

Some of the laboratory test results which may contribute to the occurrence of the tender zone are excess asphalt content, a low amount of minus 75 μm material, and/or asphalt stiffness. Other items which can be determined from the testing include the volumetric properties of the produced mixture. These volumetric properties (air voids, voids in the mineral aggregate, and voids filled with asphalt) may provide important insight into the reasons for the tender zone behavior in the field. For example, if the voids filled with asphalt, for a given sample is above the design range, then it may indicate that the asphalt content is too high resulting in a tender mix.

From the gyratory compaction printouts, it was determined whether or not a mixture showed any tendency toward tenderness during compaction. For example, some engineers believe that mixtures designed in the laboratory must not exceed some specified level of density at $N_{initial}$ in the gyratory compactor. The measured level for coarse-graded mixtures is normally well below the maximum specified density of 89 percent of G_{mm}. If the gyratory compacted samples show a high density at $N_{initial}$, this may be an indication that the mix is tender. Among the items which may cause high $N_{initial}$ density is a high asphalt content, low filler content, and aggregate moisture.

SITE REPORTS AND PRESENTATION OF RESULTS

A total of five projects were evaluated in this study. Brief site reports from each of the five tender zone projects evaluated are included in the following sections. The site reports include general project information, descriptions of the mix being placed, construction procedures, and the type and magnitude of mix tenderness shown. The mixture information (asphalt content, gradation, volumetrics, film thickness) obtained, along with each site report, is presented and analyzed to determine if there are possible reasons that could be identified to cause the tender zone in each project.

Alabama (Highway 157)

General Project Information
The project was evaluated on April 6, 2000 and consisted of a two-inch overlay of an asphalt pavement on the southbound travel lane of Highway 157 approximately 5 miles north of Moulton, Alabama in Lawrence County. Weather conditions were 70°F, sunny, with a 10 mph wind.

Mix Description
The mix consisted of a 12.5 mm nominal maximum size coarse-graded limestone/sand/slag blend designed at 106 gyrations (N_{design}) resulting in a design asphalt content of 4.9 percent. The binder used was a PG 67-22 (unmodified). No antistripping agent was used in the mix.

Construction Information
The project was located approximately 5 miles (7 minutes haul time) from the drum plant. No significant storage of the produced mix was observed at the plant. Complete project information is given in Table 1.

Tandem trucks fed the mix to a Roadtec RP30 paver. Breakdown rolling was conducted using a Caterpillar CB643C roller, shown in Figure 3, which started compaction immediately behind the paver at a surface temperature ranging from 285 to 290°F. Maximum amplitude and frequency were used during breakdown rolling with the roller making two passes.

The average surface temperature at the completion of the breakdown rolling was approximately 230°F. No intermediate rolling was performed due to movement of the mix in a surface temperature range from approximately 240 down to 135°F. The contractor did not use a pneumatic roller in the tender zone due to concerns about the pick-up of material (though with an unmodified binder pick-up is generally not a problem).

Finish rolling was started at approximately 135 to 140°F and was performed using a Hypac C764B roller operating in static mode. Typically two to three passes were made with the primary focus being to remove any roller marks. An increase in density of 1 to 2 percent was usually observed with the finish rolling. The target density of 94 percent of G_{mm} was consistently met or exceeded during the project according to the contractor.

Mix Tenderness Description
During the field observation only a small amount of tenderness was observed at approximately 235°F which corresponded to the latter part of the breakdown rolling. A small amount of lateral movement and pushing was observed, although not to a large degree, but did increase as the surface temperature decreased. The contractor stated that the degree of the tenderness seemed to change from day to day. This observation tends to suggest the possibility of a temperature gradient within the mix. During the hotter part of the day, the temperature gradient would not be as great as during the early morning.

Table 1. Project Information

Item	Project				
	Alabama Highway 157	Alabama Highway 78	Florida Interstate 10	Florida Highway 301	Mississippi Highway 49
N_{design} Gyrations	106	100	96	96	96
Coarse Aggregate	40% LMS (AL) 22% Slag	LMS	67% LMS (AL)	67% LMS (South FL)	80 % Gravel
Fine Aggregate	9% Sand 28% Slag Scrn. 1% Baghouse Fines	LMS Scrn.	33% LMS Scrn.	13% LMS Scrn.	9% Sand
RAP, %	None	15	None	20	10
Asphalt Grade	PG 67-22	PG 76-22	AC-30	AC-30	PG 76-22
Asphalt, %	4.9	4.5	6.5	7.0	6.2
Modifier Type	None	SBR, SBS	None	None	SBS
Liquid Anti-strip	None	None	0.75 %	0.75%	1.5% liquid, 1% Lime
Ambient Temp, F	65 - 70	60	90 - 95	85 - 90	80 - 85
Production Temperature, F	300	335	310	310	320
Tack Coat	AC-10	RS-1	RS-1	RS-1	RS-1
Paver Type	Roadtec RP-30	N/A	Blaw-Knox PF3200	Blaw-Knox PF3200	CAT AP1000 w/CAT WE601B
Breakdown Rolling	CAT CB634C 2 Passes Max. Amplitude and Frequency 295 - 230F	N/A	Ingersoll Rand DD130 ~ 2-3 Passes ~ Max. Amplitude and Frequency 290 - 225F	Ingersoll Rand DD110 2-3 Passes Max. Amplitude and Frequency 295 - 225F	Ingersoll Rand DD130 ~ 4-5 Passes ~ Med. Amplitude and Max Frequency 295 -245F
Intermediate Rolling	None	N/A	Ingersoll Rand DD110 2 Passes Max. Amplitude and Frequency 225 - 190F	Ingersoll Rand DD110 2-3 Passes Max. Amplitude and Frequency 225 - 190F	None
Finish Rolling	Hypac C764B 2 -3 Passes Static < 140F	N/A	CAT CB634C 2-3 Passes Static < 140F	Hypac C778B 3 Passes Static < 140F	Hypac C778B 3 Passes Vibratory > 150F, Static < 140F
Tender Zone Temp. Range	230 - 140	240 - 180	225 - 140	190 - 140	225 - 150

Note: All mixes are 12.5 mm nominal maximum size placed at a lift thickness of 50 mm except Hwy 78 which was a 19.0 mm NMS and placed 63 mm thick.
N/A - Not Available

Figure 3. Alabama Hwy 157 Construction

Alabama (Highway 78)

General Project Information

This project was visited on March 22, 2000 while production had been stopped due to construction problems. This night paving project consisted of a two-inch overlay of an asphalt pavement on the southbound lanes of Highway 78 near Jasper. Project information is provided in Table 1.

Mix Description

Prior to overlay, the mix consisted of a 12.5 mm nominal maximum size coarse-graded limestone blend with 15 percent RAP designed at a N_{design} of 100 gyrations. The design asphalt content was 4.5 percent. The binder used was a PG 76-22 modified originally with SBR. The contractor later switched to a SBS polymer. No antistripping agent was used in the mix.

The underlying pavement was severely cracked with full depth cracks, shown in Figure 4, down to the cement treated base material some 10 inches below the existing surface. It appeared that water had seeped from the cracks onto the surface As evidenced by water stains, on the existing pavement adjacent to cracks (Figure 5).

During construction the contractor routinely experienced a problem with the mix decreasing in density approximately 2 to 3 percent (according to nuclear gauge test results) after the breakdown rolling had been completed. This measured density loss typically occurred at a surface temperature below 235 to 245°F. According to the contractor, the mix seemed to slightly increase in volume at various locations which resulted in the de-compaction. This increase in volume and decompaction was not constant over the project which resulted in surface roughness. Profilometer testing after construction indicated that the pavement was getting rougher with time.

Figure 4. Close Up of Hwy 78 Cracking

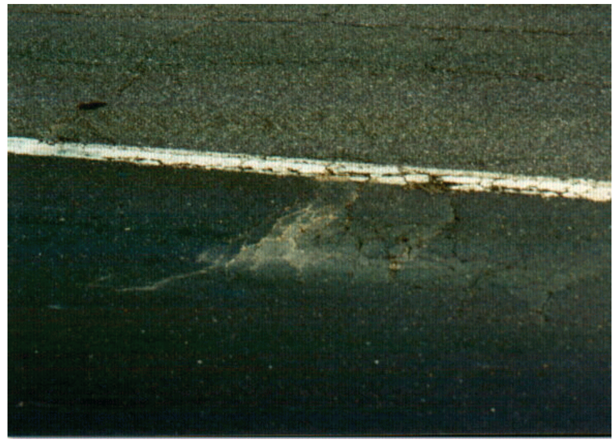

Figure 5. Water Stains on Hwy 78

Portions of the most severely cracked existing pavement had been patched to a depth of 4 to 6 inches prior to overlaying. The apparent volume increase and measured decompaction were not observed in these patched areas. This along with the water stains on the surface, indicated that the volume increase was likely caused by water in the underlying pavement structure being brought to the surface during construction. When the water reached the bottom of the new asphalt mix layer, the water was trapped and then turned to steam.

There is also a theory of the water from the rollers possibly causing mix tenderness. If that were the case for this project, the problem would have been seen on the entire project, not just in the non-patched areas. Additionally, in the two to three weeks prior to the beginning of construction a significant amount of rainfall fell at the project site. This could explain the abundance of water in the pavement structure. The very cracked condition of the existing pavement was also thought, by the contractor and Alabama Department of Transportation (ALDOT) personnel, to compound the tenderness problem by not providing adequate support for compaction.

As mentioned previously, there were two asphalt modifiers used on the job: SBR and SBS. SBR was originally used and then SBS was used to see whether the modifier type would decrease the amount of tenderness present. The contractor reported no significant difference in mix tenderness between the two modifiers.

A RS-1 emulsion was used for the tack coat, which was of concern since the project was being completed at night; however, the contractor reported that the emulsion had clearly broken prior to placement of the overlay. At the present time, ALDOT is in the process of barring the use of all emulsions for tack coat on night paving projects.

Florida (Interstate 10)

General Project Information

The project was evaluated on August 7, 1999 and consisted of a two-inch overlay of a rubblized concrete pavement. During the evaluation the contractor was paving the shoulder of westbound Interstate 10 approximately 5 miles east of Marianna in Jackson County. During the evaluation the weather conditions were 90 to 95°F, sunny, with a slight wind. Project information is provided in Table 1.

Mix Description

The mix consisted of a 12.5 mm nominal maximum size coarse-graded 100 percent limestone blend (80 percent Alabama limestone and 20 percent local limestone screenings) designed at a N_{design} of 96 gyrations which resulted in a design asphalt content of 6.5 percent. The binder used was an AC-30 (unmodified). A liquid anti-stripping agent was added at 0.75 percent of the binder by the binder manufacturer.

Construction Information
The haul distance from the drum plant to the project was approximately 7 miles (10 minutes). There was a minimal amount of mix storage at the plant; however, there were several instances where the mix remained in the truck for a long period of time (30 minutes) after arriving at the road.

A combination of conventional end dump trucks and horizontal flow trailers delivered the mix to a Blaw Knox PF3200 paver. The average surface temperature behind the paver ranged from 275 to 290°F. An Ingersoll Rand DD130, operating in maximum amplitude and frequency, was used for breakdown rolling and followed between 20 and 30 feet behind the paver. The rolling pattern observed was for the roller to make one pass toward the paver on the inside edge, then back along the same line, make another pass up along the opposite edge and then back along the same line. The contractor reported having to frequently change the rolling pattern to achieve density throughout the project. The average surface temperature at the completion of the breakdown rolling was approximately 225°F. At that time, the intermediate rolling began with an Ingersoll Rand DD110 roller utilizing the same rolling pattern as the breakdown roller in maximum amplitude and frequency. Intermediate rolling continued down to approximately 190°F. During the breakdown and intermediate rolling the mix held up well under the roller. However, at approximately 190°F surface temperature, the mix began to move more laterally and push substantially in front of the roller.

At approximately 135 to 145°F surface temperature finish rolling began with Caterpillar CB634C operating in static mode. The rolling pattern varied, but generally matched the patterns used by the intermediate roller. Throughout the project, an increase in density of 1 to 2 lbs/ft^3 was achieved with the finish roller. The contractor reported that achieving the target density of 94 percent of G_{mm} on the entire project had been very difficult.

Mix Tenderness Description
The beginning of the observed tenderness was seen during the latter part of the intermediate rolling at approximately 190°F surface temperature. The mix held up very well under the roller until this temperature. Any further rolling from approximately 190 to 140°F surface temperature, typically resulted in the mix moving substantially and a decrease in density. No effort was made by the contractor to use a rubber tired roller to compact the mix within the tender zone, primarily due to pick-up concerns.

Florida (Highway 301)

General Project Information
The project consisted of a two-inch overlay of an asphalt pavement on the passing lane of southbound Highway 301 near Hawthorne. The evaluation was conducted on August 26, 1999. Weather conditions were 85 to 95°F, sunny, with no wind. Project information is provided in Table 1.

Mix Description
Similar to the other Florida project, the mix consisted of a 12.5 mm nominal maximum size coarse-graded limestone blend designed at a N_{design} of 96 gyrations which resulted in a design asphalt content of 7.0 percent. Twenty percent RAP was used in the mix. The binder used was an

AC-30. A liquid antistripping agent was added at 0.75 percent by the binder manufacturer. An RS-1 emulsion was used as the tack coat.

Construction Information

The haul distance from the drum plant to the project was approximately 9 miles (15 minutes). There was minimal storage of the mix at the plant and little wait time at the roadway.

Horizontal flow trailers delivered the mix to a Blaw Knox PF3200 paver. The average mix surface temperature behind the paver ranged from 285 to 295/F. An Ingersoll Rand DD110 was used for breakdown rolling and followed closely behind the paver. All the breakdown rolling was completed using maximum amplitude and frequency settings, with the rolling pattern consisting of one pass up the right edge and then back along the same line (resulting in two passes). The pattern was duplicated along the left edge with a final pass made up the middle of the lane. Average surface temperature after breakdown rolling was 225 to 235/F. At this point the intermediate roller, another Ingersoll Rand DD110, used the same rolling pattern and settings as the breakdown roller. Intermediate rolling continued down to approximately 190/F surface temperature, where the mix began to exhibit the tenderness. Breakdown and intermediate rollers are shown in Figure 6.

The mix was allowed to cool down to approximately 135 to 140°F surface temperature before finish rolling could begin. A Hypac C778B roller was used and made sufficient passes to remove the roller marks from the pavement. According to the contractor, they had consistently received 100 percent pay for density throughout the project. The tender zone was viewed as part of the compaction procedure and was not thought to have a significant influence on the ability of the contractor to achieve compaction.

Figure 6. Florida Hwy 301 Construction

Mix Tenderness Description
As mentioned, the mix began to shown tenderness at about 190°F surface temperature. From this temperature down to 140°F surface temperature, the mix would show a lateral movement (1 inch) and pushing in front of the roller. No tenderness was seen at surface temperatures outside the 140 to 190°F range. The contractor did not try to use a rubber tired roller for compaction in the tender zone.

Mississippi (Highway 49)

General Project Information
The project was located in the travel lane of northbound U.S. Highway 49 near Mount Olive just north of the Covington County line. The project was evaluated on June 22, 1999 and the weather conditions were approximately 80°F with a slight wind and sunny. Project information is shown in Table 1.

Mix Description
The mix consisted of a 12.5 mm nominal maximum size coarse-graded blend designed at a N_{design} of 96 gyrations which resulted in a design asphalt content of 6.2 percent. Aggregates used in the blend consisted of 80 percent pit run crushed gravel, 9 percent sand, and 1 percent hydrated lime, along with 10 percent reclaimed asphalt pavement (RAP). The asphalt binder was a PG 76-22 that was modified with a styrene butadiene (SB) modifier. In addition to the hydrated lime, a liquid antistripping agent (Perma-Tac) was added by the manufacturer at a rate of 1.5 percent of the total weight of the asphalt. During design, the mix was short-term aged for 1.5 hours at the compaction temperature of 300°F.

Construction Information
The mix was produced approximately 3 miles from the project site. Mix storage at the drum plant was minimal during the project. The contractor utilized windrow paving techniques, shown in Figure 7, with horizontal flow trailers and end dump trucks used in conjunction with a Crafco Accupave windrow device to construct the windrow. A Caterpillar WE601B windrow elevator fed a Caterpillar AP1000 paver. An emulsified asphalt was used as the tack coat. The average mix surface temperature behind the paver was 295°F. The breakdown roller, an Ingersoll Rand DD130, followed immediately behind the paver. The contractor had varied the amplitude and frequency of the roller throughout the project to optimize compaction, but reported that a medium amplitude and a high frequency yielded the best results. The typical rolling pattern used during breakdown rolling was to make one pass up on the outside edge, then back along the outside edge, make another pass up along the opposite edge, and then back along the same line. All passes were in vibratory mode. Because of the occurrence of mix tenderness, no intermediate roller was used on the project. A Hypac C778B roller was used for finish rolling with no set pattern. Two to three passes were typically made in static mode at a mat temperature of approximately 150°F to take out the roller marks. If there was trouble achieving density, the contractor reported that vibration by the finish roller was used at the same temperature. An increase in density was observed when vibrating at surface temperatures above 150°F, but below 140°F the contractor reported a decrease in density. Some noticeable breakdown of material was observed when vibration was used with the finish roller.

Figure 7. Mississippi Hwy 49 Construction

Mix Tenderness Description

During the beginning of breakdown rolling at approximately 295°F surface temperature down to approximately 245°F, there appeared to be no tenderness in the mix. However, below approximately 245°F, the mix began to push laterally and in front of the roller. The degree of movement increased as the temperature decreased. The contractor reported that the same scenario had been seen throughout construction. At approximately 150 to 160°F, the tenderness in the mix decreased and the contractor was able to conduct finish rolling. No attempts were made to use a rubber-tired roller in the tender zone, due primarily to the contractor's past experience with material pick up.

The degree of tenderness seemed to increase throughout the day as the ambient temperature increased. A portion of the underlying material was concrete which seemed to increase the magnitude of the tenderness. As mentioned previously, the mix for the travel and passing lanes was the same, but with a modified asphalt used in the travel lane. The contractor reported that the tenderness was less when using the modified asphalt.

Laboratory Testing Results

Mixture Results

As mentioned previously, samples of the produced mix were obtained from each project and taken back to the lab for testing. Table 2 shows the design and production values for gradation, asphalt content, VMA, VFA, air voids, percent G_{mm} at $N_{initial}$, film thickness, and dust to effective asphalt ratio. (Note: All obtained samples had to be reheated for lab compaction, so the resulting volumetric property values may be slightly different from that of mixes that were not reheated.)

From Table 2, it can be seen that all the projects had asphalt contents which were within 0.3 percent of the job mix formula. This indicates that excessive total asphalt content was probably not the cause of the observed tenderness. For all projects, except the Alabama Highway 157 job, the calculated VMA was within 0.7 percent of design.

Table 2. Project Gradation and Volumetric Results

	Alabama Highway 157		Alabama Highway 78[1]	Florida Interstate 10		Florida Highway 301		Miss. Highway 49	
Sieve Size (mm)	Design	Actual	Actual	Design	Actual	Design	Actual	Design	Actual
25.0	-	-	100	-	-	-	-	-	-
19.0	100	100	95.6	100	100	100	100	100	100
12.5	96	93.8	80.4	91	94.1	98	96.9	96	97.2
9.5	79	75.0	63.1	79	87.3	89.9	91.9	89	91.7
4.75	45	41.6	34.3	45	48.0	55	58.4	61	65.2
2.36	32	30.0	25.7	28	24.4	28	28.3	41	42.1
1.18	25	22.9	20.8	20	20.0	22	22.3	29	29.9
0.6	19	17.3	14.9	15	16.4	18	18.3	22	22.6
0.3	11	11.0	7.7	10	12.4	12	14.4	13	14.5
0.15	6	6.5	5.2	4	8.5	7	9.7	8	9.7
0.075	3.4	4.3	3.9	3.5	6.3	4.8	6.3	6.1	7.8
Asphalt Content, %	4.9	4.9	4.3	6.5	6.3	7.0	7.3	6.2	6.3
VMA, %	14.5	16.2	13.2	14.0	13.4	14.8	14.8	14.1	14.7
Air Voids, %	4.0	6.4	5.3	4.0	4.9	4.0	5.3	4.0	4.3
%G_{mm} at $N_{initial}$	87.2	84.7	87.2	85.8	83.4	84.3	83.2	N/A	87.2
VFA, %	72.4	60.5	59.6	71.4	63.4	73.0	64.4	71	70.7
Film Thickness (:)	10.6	9.2	9.6	12.8	9.0	9.5	9.5	8.9	7.5
Dust / AC_{eff}	0.82	1.05	1.18	0.80	1.40	0.94	1.17	1.30	1.63

[1] Design Values for AL Highway 78 were not obtained.

The Alabama Highway 157 project showed an increase of 1.7 percent VMA. Air voids for the remaining projects also increased slightly from 0.3 to 1.3 percent above the design which may be the result of re-heating. Values of percent G_{mm} at $N_{initial}$ for all the projects were well below the 89 percent maximum value, both during design and production.

All of the projects had increases in the percent passing the 0.075 mm (No. 200) sieve from design to production. This increase in the dust fraction also led to production D/A ratios being higher than design values.

Film thicknesses were calculated using the MS-2 surface area factors and showed film thicknesses ranging from 8.9 to 12.8 microns for the design mixes. These film thicknesses are high primarily due to the low dust content and the overall coarseness of the aggregate blend. During production, the film thicknesses mostly decreased, primarily as a result of the increased dust content.

Results of Asphalt Binder Testing

The asphalt binder from four of the five projects was evaluated using the Superpave binder testing procedures. (Binder was unavailable from the Alabama Highway 78 project.) The binder was graded using the Superpave asphalt binder system in the as-received condition and also after steam distillation was conducted.

Steam distillation was conducted because the Superpave asphalt binder grading system does not directly identify asphalt binders which may have excessive light ends present. Many times a low viscosity asphalt binder may be used in certain climates to obtain the necessary Superpave low temperature grading, then modified to achieve the high temperature grading. During production these light ends can be released which may cause the mix to exhibit over-asphalted mix characteristics. Some believe that the steam distillation procedure better represents the production conditions during production in a drum plant than does the thin film oven conditioning test. (5)

The steam distillation procedure used consisted of placing a sample of the obtained asphalt binder in a flask and applying heat. Steam was then generated and diffused through the asphalt binder sample, resulting in the steam distillation of the asphalt binder. The viscosity or stiffness of an asphalt binder which has light ends present should increase after the completion of the steam stripping procedure.

The results of the asphalt binder testing are shown in Table 3. It appears that there is generally only a slight increase in the stiffness for each of the binders evaluated after the steam stripping procedure. The fact that only a slight increase was seen, seems to indicate that excessive light ends in the asphalt binders was not the cause of the tender zone in the observed cases.

Table 3. Asphalt Binder Testing Results Before and After Steam Stripping

Project ID	DSR, G*/sin* (kPa)		DSR (RTFO), G*/sin* (kPa)		DSR (RTFO + PAV), G*sin* (kPa)		BBR (RTFO + PAV)			
							S, (MPa)		m	
	Before	After	Before	After	Before	After	Before	After	Before	After
FL 301	1.597	1.602	3.661	3.489	2796	3099	158	149	0.344	0.338
FL I-10	1.762	2.062	3.878	3.914	2713	2627	141	145	0.373	0.363
MS 49	1.182	1.574	2.637	3.006	1148	1225	117	107	0.320	0.327
AL 157	1.553	1.621	3.798	3.902	1739	1698	48	52	0.341	0.344

OBSERVATIONS

Each paving project in which the tender zone occurred had its own set of weather, mix, and construction characteristics, which makes the determination of the cause(s) for the tender zone an extremely difficult task. The purpose of this study was to document projects in which the tender zone occurred to determine possible trends for its occurrence.

As has been reported, the tender zone generally occurred at approximately 230°F down to 140°F. It did not appear from the gradation, volumetric, or asphalt binder testing results that any one mix parameter could be singled out as identifying characteristics in mixes exhibiting the tender zone.

Based upon the observations during construction, two primary causes are put forth as possible reasons for the occurrence of mix tenderness in the five projects visited as part of this study. First, a common characteristic in four of the five projects visited (AL 157, FL I-10, FL 301, and MS 49) was that each had very short haul times and very little storage time. Construction observations for these four projects indicated that each had haul times less than 15 minutes with little or no storage time. The percent absorbed binder during mix design for these four projects ranged from 0.8 to 2.5 percent. Therefore, each of these projects utilized aggregates with absorptive characteristics. The combination of absorptive aggregates and the relatively short time between production and laydown likely resulted in the aggregates not absorbing all of the asphalt that was absorbed during mix design (short term aging procedure). Also, all of the mixes were coarse-graded and these types of mixes generally have low aggregate surface area. The net result is a mixture that behaves as if it is over-asphalted and likely resulted in the tenderness.

The second probable reason occurred during the Alabama Highway 78 project. This project was an overlay of a severely cracked asphalt pavement. The cracks were full depth down to a cement treated base material approximately 10 inches below. Because of the cracking, water had infiltrated the pavement. When the new mix was placed, the heat caused the water within the underlying pavement to move upward in the form of steam. This movement of the water upward resulted in some bulking of the placed mix during construction. Recall, that portions of the pavement were patched prior to placing the new mix. In the area of the patches, no bulking of the mix was noticed. For this project, tenderness within the mix was first noticed at around 245°F which is a common temperature for the tender zone. However, the field observations suggested that decompaction of the mix occurred after the breakdown rolling had been completed and prior to the intermediate roller. This was verified with nuclear density gauge measurements. When the water reached the bottom of the new asphalt mix layer, the water turned to steam resulting in the increase in volume of the mix.

During the introduction of this report, five possible causes for the tender zone were presented: 1) short term aging during mix design not being comparable to actual production; 2) presence of excessive internal moisture in the aggregate or underlying layers; 3) decreased viscosity of the produced asphalt; 4) dust to asphalt ratio which is too low; and 5) increased film thicknesses and temperature differential within the lift. Though none of the above possible causes can be excluded, the information gathered in this study suggest that two were prevalent within the five projects evaluated. First, the short term aging during mix design was not comparable to actual production which likely led to excessive effective asphalt in the mixes during compaction. As stated above, this occurred in four of the five projects evaluated. Secondly, the existence of excessive moisture in an underlying layer likely caused the tenderness in the fifth project.

RECOMMENDATIONS

Perhaps the most beneficial action which can be taken to aid in working with the tender zone is to pay close attention to the temperature of the mix during construction. Accurately knowing the temperature of the mat is crucial to being able to efficiently and adequately compact any mix, especially mixes that are expected to be tender. Generally, the mix should be placed at a temperature as low as possible but still be able to compact so that too much oxidation does not occur.

Past recommendations (3) have been made in regards to mix compaction on projects with the tender zone present. Among these recommendations was to achieve the desired density prior to the beginning of the tender zone. This may require a substantial effort by the contractor with more and heavier rollers, possibly used in an echelon pattern. Another recommendation is to compact the mix until the tender zone begins and then wait until the end of the zone to complete compaction. Many contractors have reported a gain of 1 to 2 percent in density at temperatures below 150°F. There is the possibility that a pneumatic roller can be used within the tender zone to achieve density without excessive movement of the mix. The use is greatly dependent upon the past experience of the contractor.

It is also recommended that further research be conducted to evaluate the concept of excessive effective asphalt content due to lack of time for complete binder absorption by a highly absorptive aggregate. Complete asphalt absorption may not take place until moisture is driven out from an absorptive aggregate. The resulting excessive effective asphalt binder can contribute to the tender mix problem. This research would entail measuring the Rice specific gravity and mixture moisture contents during various stages of construction (mix at plant, after various storage times, at paver, etc.) Previous research by Kandhal and Koehler (6) and Musselman et.al (7) has suggested that the volume of effective asphalt in a plant produced mix decreases with time. A study of this nature may lead to various recommended mix storage times prior to placement based upon aggregate absorptive characteristics.

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