Technical Paper T-134

TEMPERATURE SEGREGATION/ Temperature Differential Damage

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INTRODUCTION

Due to the extreme high traffic loads in the United States, it has become more essential to build better, longer lasting pavements. The pavement needs to be more durable, withstand heavier loads, and require fewer repairs. Hot mix asphalt is smoother, more flexible, quieter, lasts longer and requires less disruption to traffic when being repaired. Hot mix asphalt has been the pavement of choice over the last four decades and mix designers have continued to improve the durability, rut resistance, and resistance to fatigue cracking.

With the aid of the advanced equipment available to asphalt paving contractors today, these improved mixes can be placed to provide a much smoother profile than in the past. Smoother roads lead to longer lasting roads and reduce the maintenance cost, fuel consumption and tire wear of automobiles and trucks. Smoother roads also lead to less driver fatigue and thus to a much safer road system.

SEGREGATION

Over the past two decades, as higher tonnages of mix have been produced and placed, the two most common problems in premature failure of hot mix asphalt roads is segregation and failure at the longitudinal joints. A number of papers have been written on segregation. The first was Astec's Technical Bulletin T-117 which has been revised a number of times to include new data. The National Asphalt Pavement Association has sold over 40,000 copies of this paper and recently the American Association of State Highway & Transportation Officials (AASHTO) published a revised copy of Astec's bulletin.

The key word necessary to produce a long life hot mix asphalt is uniformity or consistency. Uniformity in gradation, asphalt content and air voids.

Identifying segregation historically has been done by visual observation as the mix is placed on the road. Where large aggregate is used for base and binder materials, the segregated spots can be easily identified. On finer surface mixes, however, apparent segregation spots often cannot be visually noticed as the mix is placed and may not show up until six to twelve months later. Since the surface mix is the top lift and the one most susceptible to traffic and weather conditions, any segregation of the surface mix, just like the segregration in other layers, leads to a shortening of the pavement life and premature failure. Various states have studied the surface segregation problem, but tests have often shown the particles to not vary in size significantly, with even with the apparent segregated spots passing all the gradation tests.

These authors, along with Dr. Ray Brown of NCAT and members of the NCAT staff have searched for ways to nondestructively determine segregation. Devices such as microwaves, nuclear asphalt gauges, nuclear density gauges and others have been used, each having some success.

TEMPERATURE DIFFERENTIAL DAMAGE/ TEMPERATURE SEGREGATION

Recently Astec Industries' staff began using a highly accurate infrared camera to evaluate its possible use for detecting aggregate segregation. As the infrared camera was used to look at the mix being discharged from the truck bed, it became obvious that the temperature differential across the bed was significantly greater than ever anticipated. Temperature differential as much as 80° F (27° C) occurred on mixes that had been hauled as little as 10-15 miles (16-24 km) at mix temperatures of 290° F (143° C). Some areas of the mat were as low as 210° F (99° C).

Mr. Steve Read, a graduate student at the University of Washington, first recognized this phenomenon in the summer of 1996 while conducting studies of segregation problems in paving operation for his master's thesis. The thesis entitled "Construction Related Temperature Differential Damage In Asphalt Concrete Pavements" was done under the direction of his advisor, Dr. Joe Mahoney and in coordination with Washington State Department of Transportation. Mr. Read was commissioned by the WSDOT to study the phenomenon that has been known as truck fans, spot segregation, end of load segregation and recently as cyclic segregation. The purpose of this study was to determine the cause and potential solution to the problem of cyclic segregation in asphalt pavements in Washington State. In Mr. Read's thesis he states, "When a pavement rehabilitation project is afflicted by this phenomenon, the expected life of the overlay can be reduced to roughly half of the 12 to 15 years that the Washington State Department of Transportation normally expects. There has been no way to be able to predict which projects will be affected by cyclic segregation and the problem has proven to be particularly insidious in that it may not manifest itself during construction but will show up in a project as long as two years after completion."

In Chapter 4 of his thesis Read states, "While the approach to this study concentrated on what was thought to be a problem with segregated mix, it became apparent as data collection progressed that the phenomenon that was being observed was not aggregate segregation. The problem that had been termed 'cyclic segregation' turned out to be related to a differential in temperature of the HMA mass in the trucks developed in transport from the HMA manufacturing facility to the job site. This phenomenon has since been named 'temperature differential damage.' This title seemed appropriate in that the mechanism that causes the problem is related to temperature differentials in the loads of HMA prior to placement and the damage to the project occurs during construction; the other problems (e.g. stripping, lower compaction, raveling, etc.) are merely symptoms of damage that has already occurred to the HMA matrix during the construction process. The mechanism by which temperature differential damage occurs begins when a truck load of HMA is dumped into the paver. If the load is exhibiting temperature differentials, the very cool material that is along the sides of the load is extruded out towards the sides of the paver's hopper. When the truck is emptied and the pile in the hopper is run down, this cool material falls inward to lay on top of the material over the slat conveyors. When the next truck arrives and dumps into the paver, this cool mix is subsequently conveyed back to the auger chamber and screeded out. The screed is unable to consolidate the colder mix and open, segregated appearing areas (temperature differential damage) show in the mat. As this mechanism can work for each load placed, the cyclic nature of the phenomenon becomes apparent."

Although Mr. Read did not have an infrared camera to use, he accurately identified the problem and its cause.

Through the use of an infrared camera, along with the ability of the camera to not only take videos but also to capture photographs of specific areas, and, through the use of a software program which can plot the profile, it became obvious that significant temperature differentials were occurring. Figure 1 and Figure 2 show the differential temperature as mix is being dumped from a truck bed, along with the spot temperatures.

Figure 1

Figure 3 and Figure 4 show the mix in the paver hopper along with the spot temperatures across the hopper of the paver. It is obvious that the colder material is somewhat stagnant in the wings of the paver hopper. If these wings are dumped, a sufficient amount of cold material will be placed in the mat which results in a temperature differential damaged area.

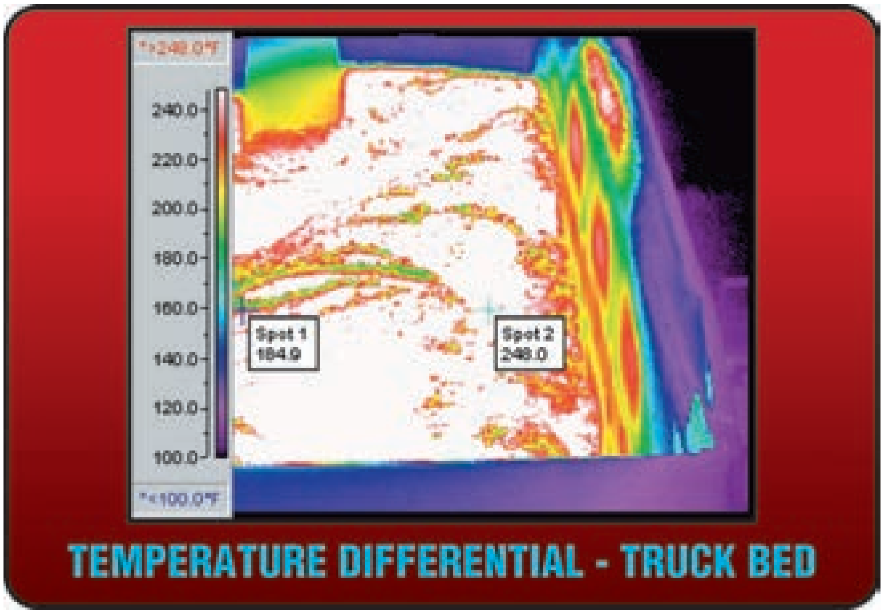


Figure 2

Figure 5 and Figure 6 show the mat behind the paver along with the spot temperatures. As can be seen, these cold spots are at sufficiently low temperatures, so that it will be impossible to achieve compaction in these areas. After Dr. Joe Mahoney became aware of the infrared camera, he and the Washington Department of Transportation asked Herb Jakob with Astec Industries to bring

Figure 3

Hot mix in a paver hopper

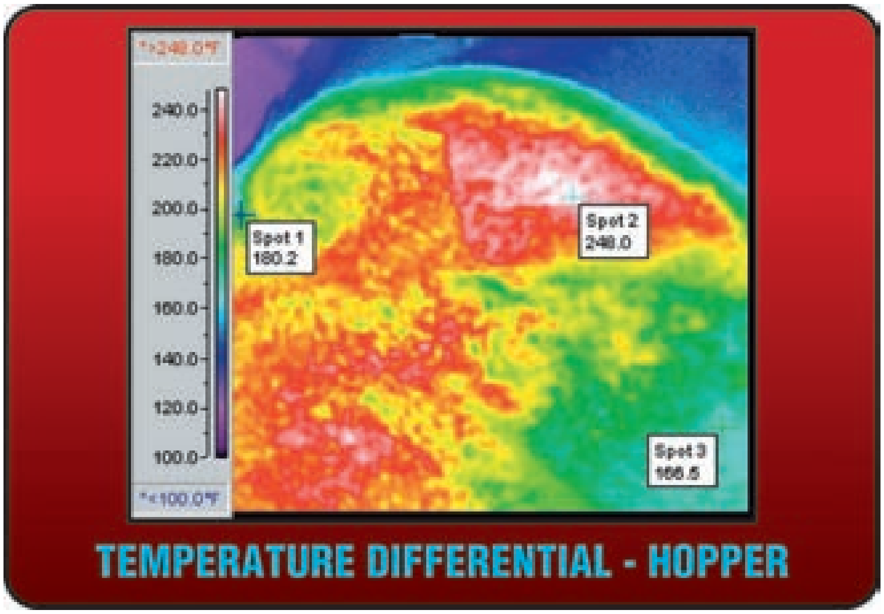


Figure 4

Temperature profile and spot temperatures of hot mix in a paver hopper

Figure 5

Truck dumping into paver and the mat behind the paver

Figure 6

Temperature profile and spot temperatures of mat behind paver without remixing

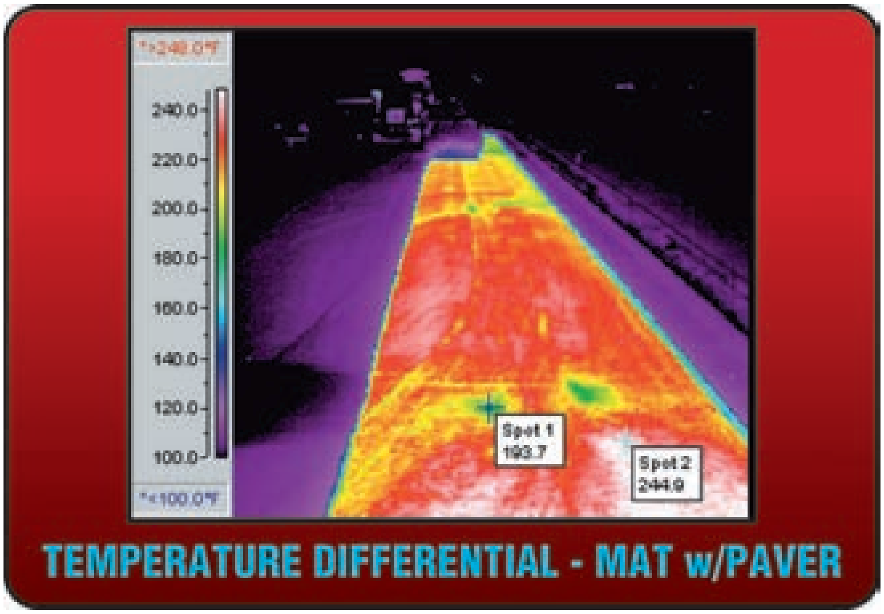


Figure 7

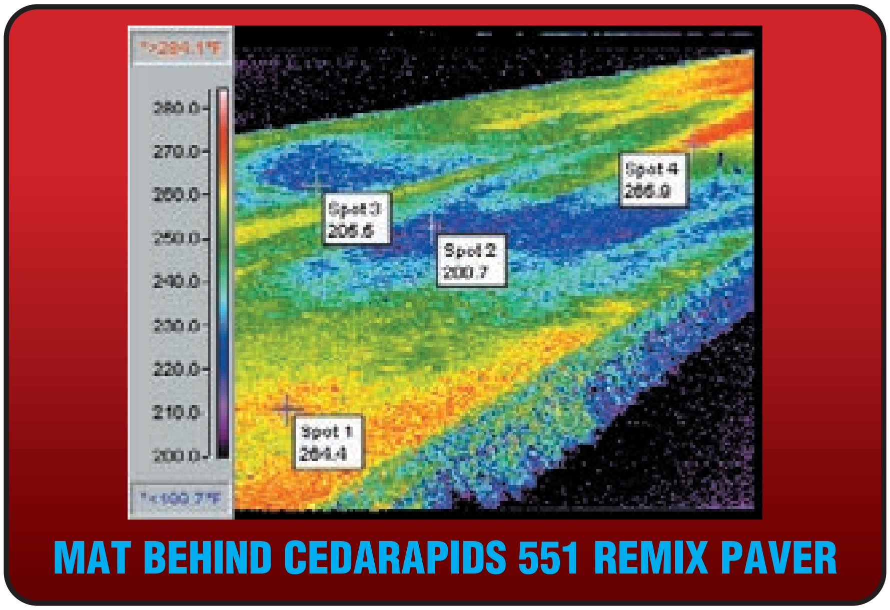
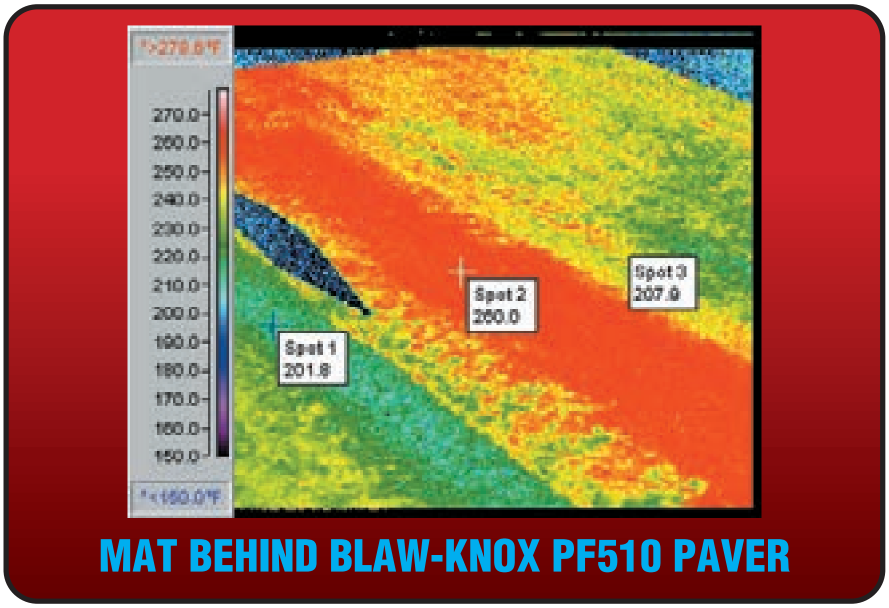
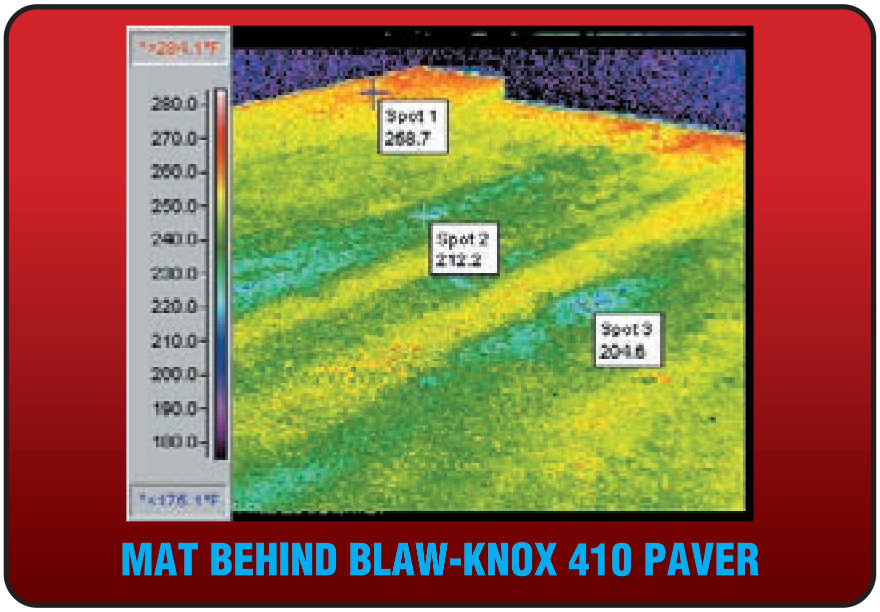


Figure 8



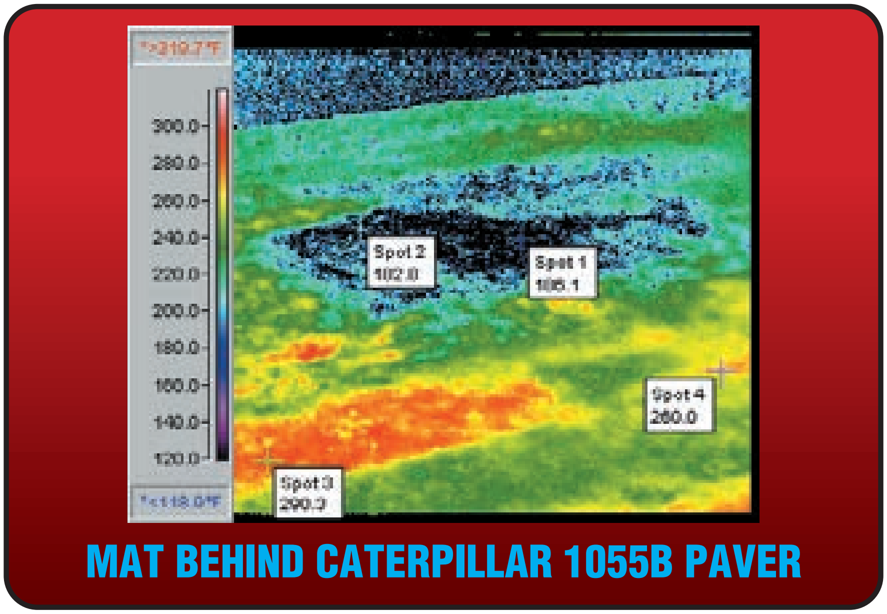


MAT BEHIND BLAW-KNOX 410 PAVER

Figure 9

the camera to Washington to study a number of jobs during the summer of 1998. Figure 7 shows the job south of Blaine, Washington where the mix was hauled approximately 55 miles (89 km). The material was dumped through a Cedarapids 551 Remix paver. Utilizing the infrared camera, the cold or nonuniform spots were marked directly behind the paver. After the compaction was complete, nuclear density tests were run in the uniform and nonuniform areas. In addition to the density tests, cores were taken to determine the air voids and gradation in each of these areas. Table 1 (see page 22) shows the results of this study.

Figure 8 shows infrared pictures of a second job in Spokane, Washington where the material was placed through a Blaw-Knox PF 510 paver with a 6 mile (10 km) haul. Table 2 (see page 22) shows the results of the densities and air voids in the uniform and nonuniform areas. Figure 9 shows the infrared of a job in Colfax, Washington. This mix was hauled 1/10 miles (0.2 km) and placed through a Blaw-Knox 410 paver. Table 3 (see page 23) shows the density and air void results in the uniform and nonuniform areas. Figure 10 shows the infrared of a job on State Route 99 in Seattle, Washington. The haul time on this was 20 minutes and the mix was placed through a Caterpillar 1055B paver. Table 4 (see page 23) shows the air voids and densities from this job. As can be seen from these results, the density and air voids are significantly affected by the reduced temperature in the cold areas.



MAT BEHIND CATERPILLAR 1055B PAVER

Figure 10

The National Center for Asphalt Technology has studied segregation on 19 projects in Georgia, which had open textures, low densities, and areas susceptible to raveling, cracking, and moisture damage. Some of the significant quotes of that report are as follows:

- “Regardless of the source of segregation, it was always highlighted at the end of truck loads.

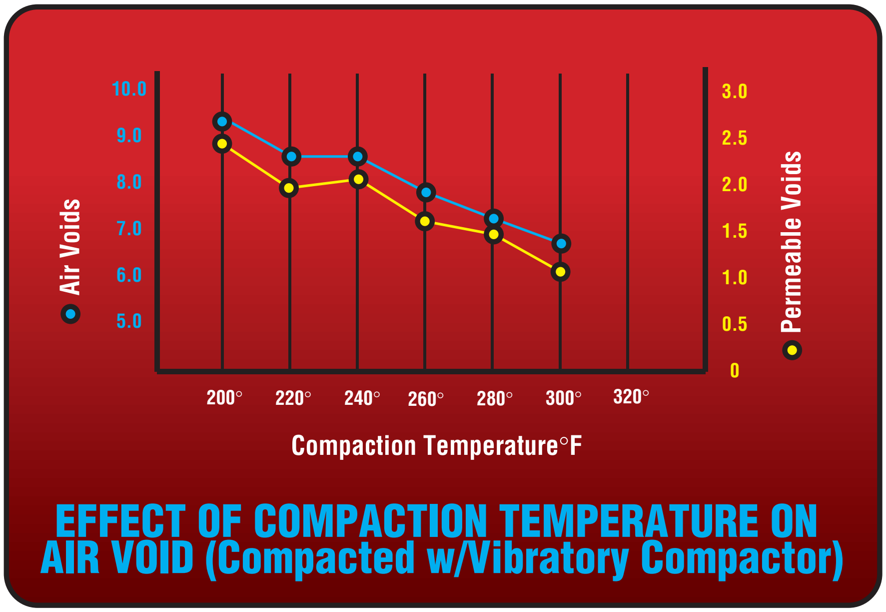
If this one problem could be solved, segregation would no longer be a major problem."

- "Many times segregation is difficult to see during construction and when it is observed, it is not always a simple matter to correct."

- A conclusion in the Brown et al report is - "Segregated areas are generally 8-15% coarser on the #8 sieve than nonsegregated areas; the air voids are typically 3-5% higher and asphalt content is often 1-2% lower."

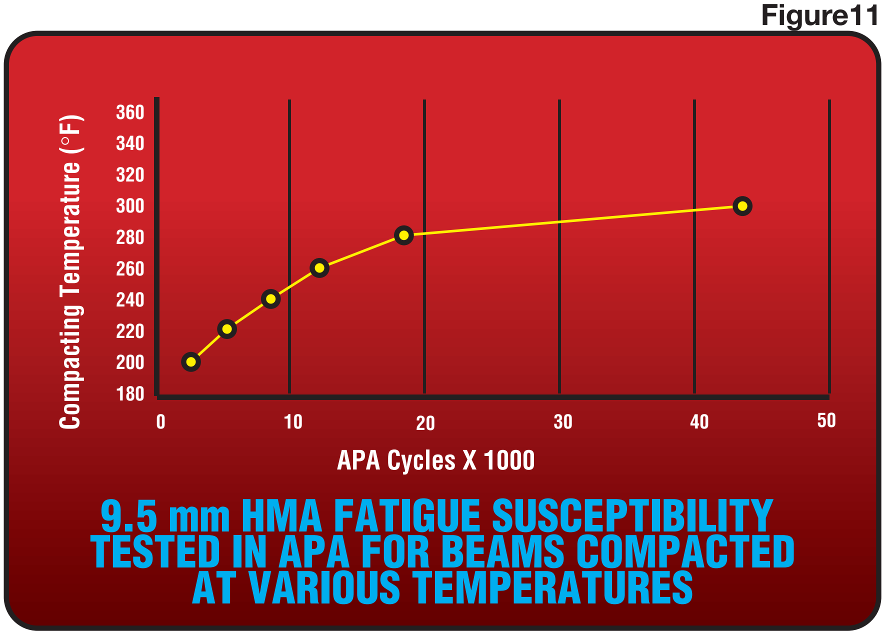
- A recommendation in the report is - "It is recommended that a nuclear gauge be considered for use in identifying segregated areas since one will likely be on the project for density measurements. Based on the results of this study, any segregated area that has a density 4 to 5 PSF lower than the adjacent nonsegregated area will have a significant reduction in mix properties and; therefore, should be removed and replaced."

It should be noted in the Washington study that gradations were taken and none of the cold areas exceeded the 8 to 15% coarser on the #8 sieve. In general the gradation was very similar to that of the uniform areas. However, the density and air voids would both exceed those recommended in the NCAT study.



EFFECT OF COMPACTION TEMPERATURE ON AIR VOID (Compacted w/Vibratory Compactor)

Figure11



9.5 mm HMA FATIGUE SUSCEPTIBILITY TESTED IN APA FOR BEAMS COMPACTED AT VARIOUS TEMPERATURES

Figure 12

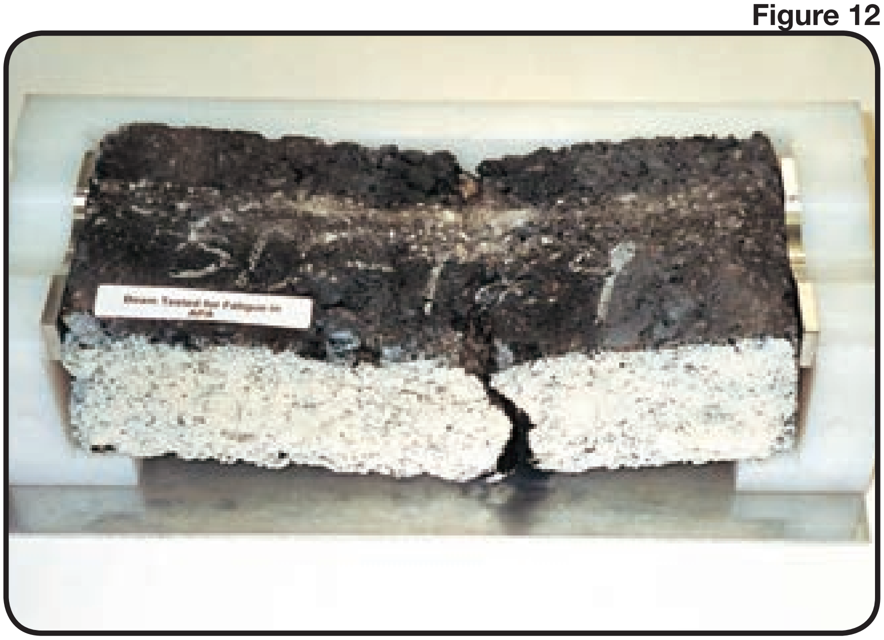


Figure 13

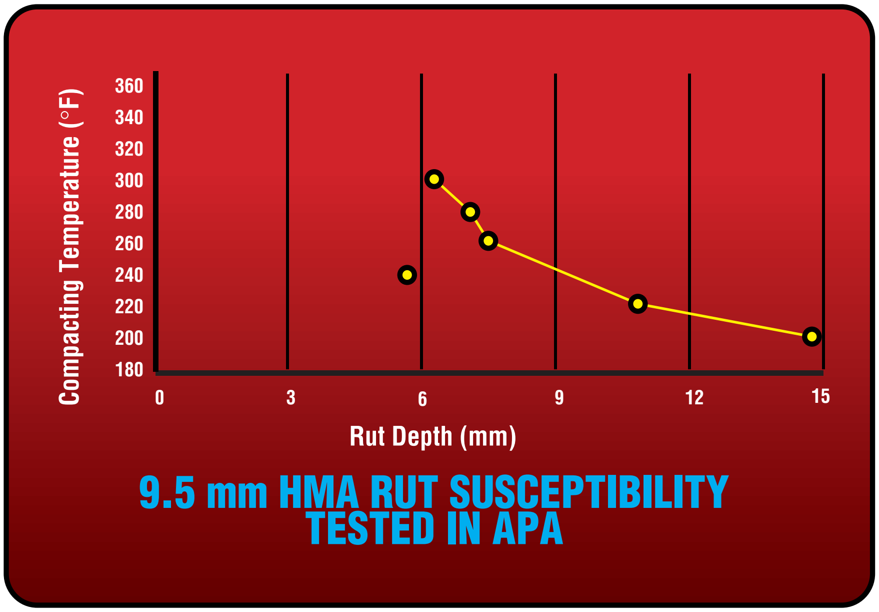


Figure 14

Table 5: SUPERPAVE BEAM PROPERTIES TESTED IN APA

Compacted at (°F)	Air Voids (%)		Rutting (mm)	Fatigue (# of Cycles)
	Rut Testing	Fatigue Testing		
300	6.7	6.8	6.38	46,718
290	7.1	7.4	6.26	20,956
280	7.0	7.5	6.06	19,690
260	7.6	8.0	7.47	13,198
240	8.5	8.4	9.50	8,010
220	8.2	8.6	10.72	4,578
200	9.1	9.5	14.84	4,250

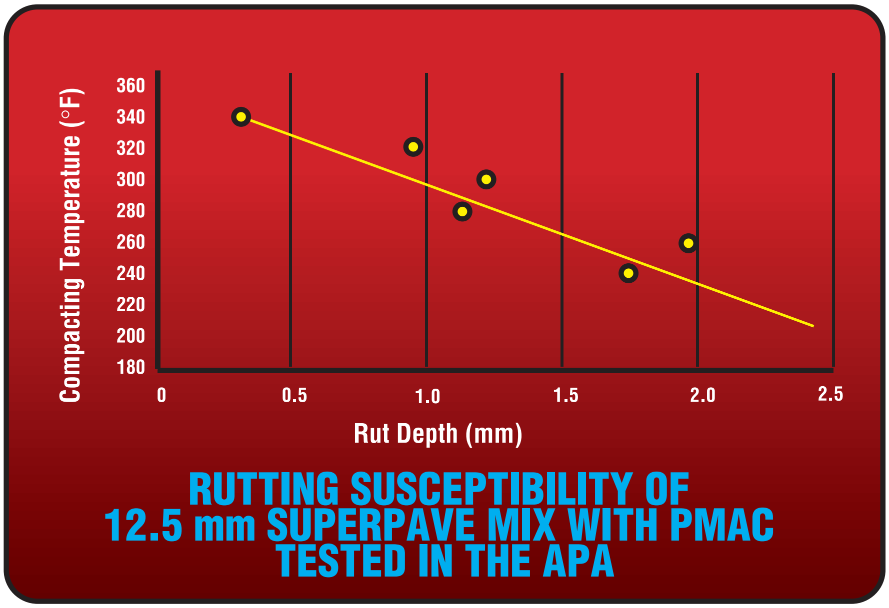


Figure 15

In an attempt to determine the severity of the damage caused by the cold spots, Mr. Ron Collins of Pavement Technology utilizing the PTI vibratory compactor and asphalt pavement analyzer compacted a typical Georgia mix at 300°, 290°, 280°, 260°, 240°, 220°, and 200° F (149°, 143°, 138°, 127°, 116°, 104°, and 93° C). The vibratory compactor was used to compact the mix at 300° (149°C) to approximately 7% air voids. The time required to compact (approximately 17 seconds) and the down pressure, amplitude and frequency of vibration were all held the same as the temperature of the mix was dropped.

Figure 11 shows the effect on air voids as the temperature is dropped. As can be seen, the air voids drop from approximately 6.8% when compacted at 300° (149°C) to 9.3% when compacted at 200° (93°C). Each of the beams produced from this study was placed in the asphalt pavement analyzer and a fatigue test was run until the beams failed. One such beam is shown in Figure 13. As can be seen from Figure 12, the cycles required to failure decreased significantly as the air voids increased in the pavement. The mix compacted at 220° (104°C) would have approximately 10-12% of the life of the mix compacted at 300° (149°C).

Figure 14 and Table 5 shows the effect of compaction temperatures on rutting and fatigue for a 9 1/2 mm dense graded HMA and Figure 15 and Table 6 shows the rutting susceptibility of a 12 1/2 mm superpave mix with polymer modified asphalt with variations in compaction temperature. Figure 16 shows pictorially the difference in the rutting that occurs as temperatures vary.

Earlier in the paper it was stated that based on the Washington study, the life of the pavement would be reduced by 50% due to cyclic segregation. Based on this laboratory data, it is seen that this estimate is probably conservative.

The cold spots in the mat will result in nonuniform density in the pavement, which will lead to high air voids and roughness. Secondly, the high air voids that occur in this area will allow water to infiltrate the mix which will freeze in the wintertime and break up the pavement, resulting in a pothole. It is important to note that the above phenomena will act exactly like a segregated spot with coarse particles concentrated, resulting in the birth of a pothole. However, in this case, instead of particle segregation, the root cause is temperature segregation. While examining these phenomena and realizing the causes, it is apparent that the asphalt paving contractor does not control many of the causes of differential cooling.

CAUSES OF TEMPERATURE DIFFERENTIAL DAMAGE

Even when mix is produced correctly at the plant, is then properly stored in a silo and then correctly loaded into a truck, a

Table 6: SUPERPAVE BEAM PROPERTIES TESTED IN APA

Compacted at (°F)	Air Voids (%)		Rutting (mm)	Fatigue (# of Cycles)
	Rut Testing	Fatigue Testing		
340	7.4	7.4	0.53	300,000*
330	8.6	7.4	0.88	226,962
320	8.6	8.3	0.89	175,972
300	9.5	9.5	1.13	172,390
280	9.3	10.3	0.91	79,146
260	8.7	9.4	2.00	71,094
240	9.5	9.8	1.55	51,798

* Cycling discontinued

Figure 16

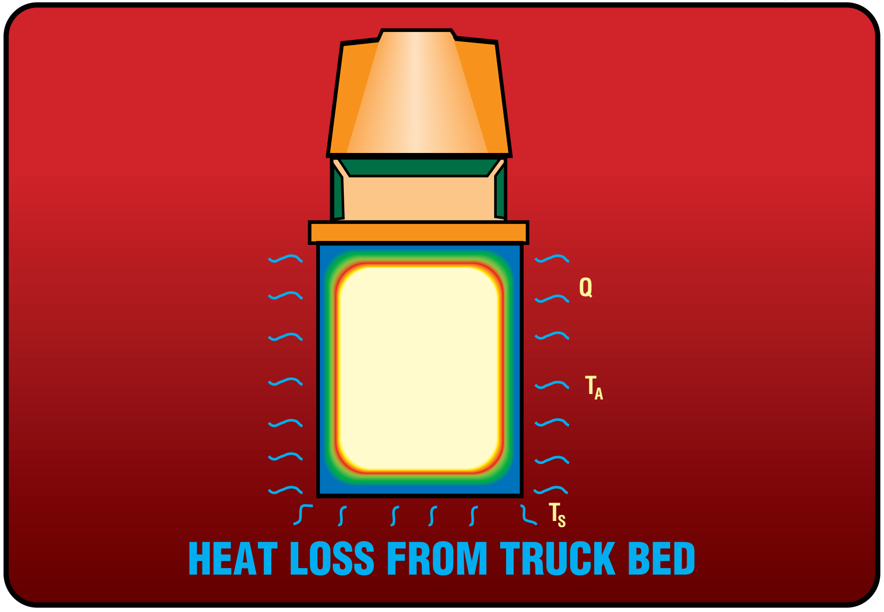


Figure 17

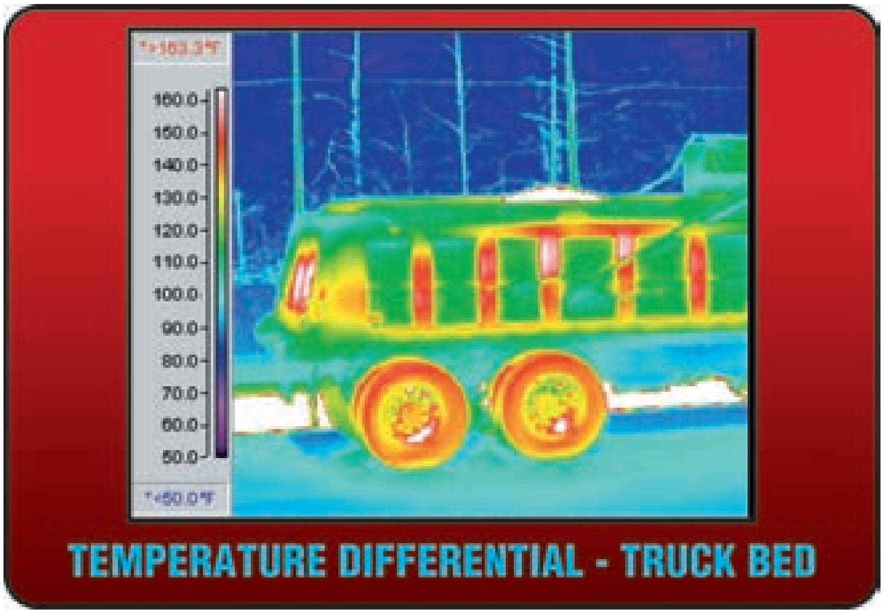


Figure 18

$$Q = UA(T_S - T_A)$$

Q = amount of heat loss from a substance; U = overall heat transfer coefficient;
A = area of heat transfer; T_S = temperature at the surface; T_A = ambient temperature

EQUATION FOR HEAT LOSS FROM A SUBSTANCE

Figure 19

Figure 20

poor quality pavement can be produced because of temperature segregation.

As the mix is dropped into the truck, as shown in Figure 17, heat loss immediately begins to occur around the perimeter of the truck (Figure 18). It should be noted that the truck in Figure 18 is insulated on the sides. Notice the higher temperature at the uninsulated tailgate. Mix in this area will be the first out and will join with the cold mix for the sides of the previous load. Figure 19 shows the equation for heat loss from a substance where “Q” is the amount of heat loss in a given time, “U” is the overall heat transfer coefficient, “A” is the area of heat transfer, “T_S” is the temperature at the surface, and “T_A” is the ambient temperature surrounding it.

It is obvious that with higher mix temperatures, more temperature differential and more heat loss will occur in the mix. Also greater heat loss will occur when the ambient air temperature is lower. Asphalt and aggregates tend to have relatively low thermal conductivities, resulting in high percentages of cooling around the extremities of a truck bed where the heat loss is occurring. Heat is slowly conducted from the heart or center of the mix out to the edge but due to the low thermal conductivity, high temperature differentials between the edge and the center of the truck occurs as shown in Figure 20 and Figure 21. Basically the mix tends to insulate itself.

A number of factors will influence the amount of heat loss and the amount of temperature differential within the truck.

These factors are as follows:
1) Mix temperature when loaded into truck
2) Ambient air temperature
3) Is the truck bed insulated
4) Size of truck bed in relation to tons of mix hauled
5) Length of haul
6) Speed of travel
7) Waiting time at paver
8) If the mix is covered
9) Traffic delays

As can be observed from the above list of variables, the asphalt paving contractor does not control many of these variables. The new polymer modified mixes, superpave mixes, the SMA mixes and other rut resistant mixes require higher laydown temperatures than the conventional mixes of the past. To be able to compact these stiffer mixes, they have to be produced and loaded into trucks at a higher temperature resulting in a greater temperature difference between the mix and outside air and thus more temperature differential damage. Long haul distances and additional traffic delays can require further temperature increases at the plant giving the same results.

EFFECTS ON COMPACTION & SMOOTHNESS

Many articles have been written on the proper way of operating rollers in order to achieve compaction. Figure 22 and Figure

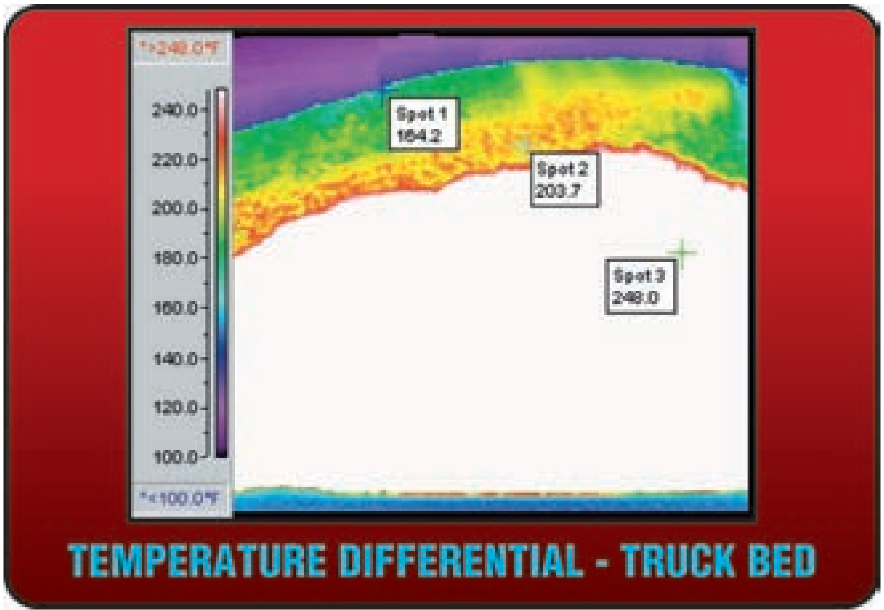


Figure 21

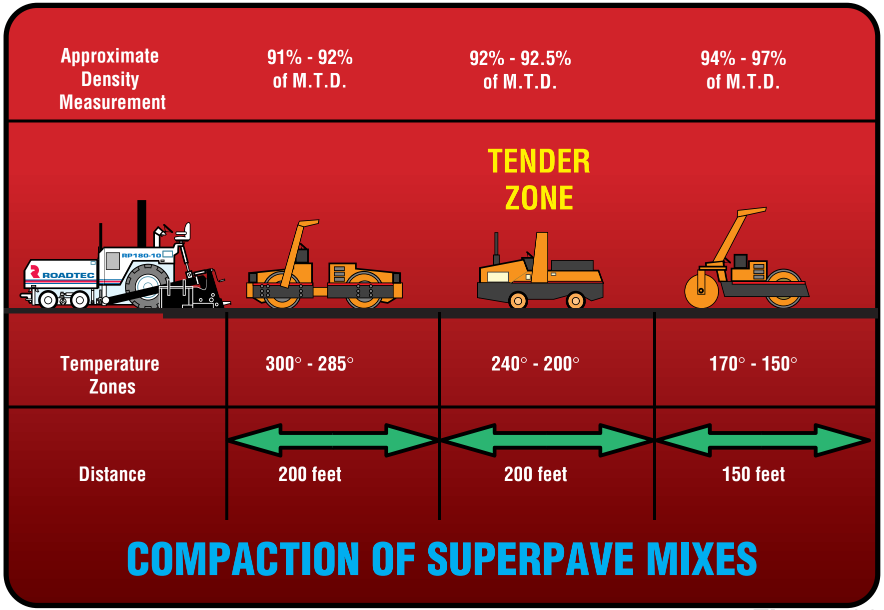


Figure 22

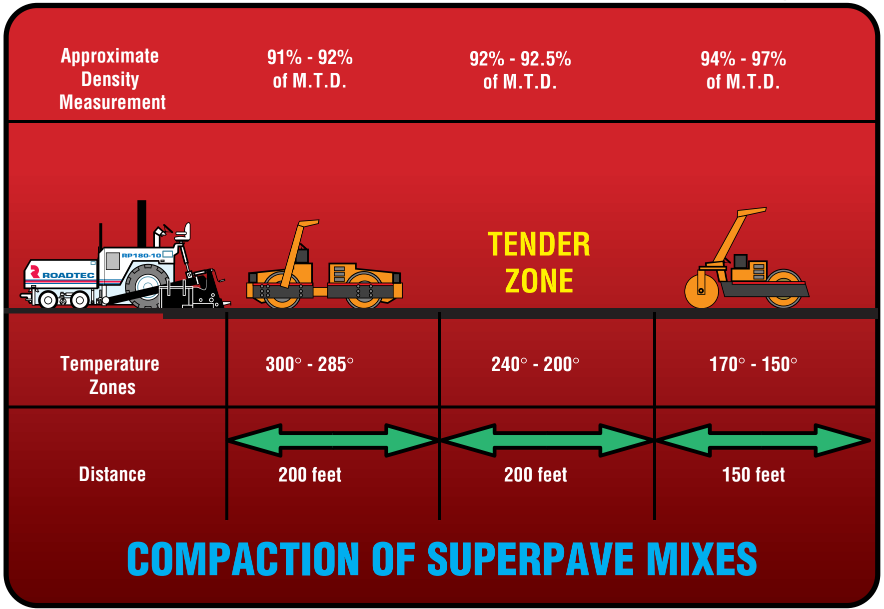


Figure 23

23 show different rolling patterns for the new superpave mix as suggested by Compaction America. These patterns have proven to be very useful in stiff type mixes that occur with superpave. However as shown from the previous paragraphs, the temperature within the rolling zones are not uniform and even if the rolling patterns are followed, uniform density will not necessarily be achieved.

Rolling patterns are laid out to try to give each square foot of pavement the same compactive effort so that a uniform density with the proper air voids can be achieved. Since the compactability of a mix varies with the temperature of the mix, temperature variations in the mat will cause nonuniform densities in the finished pavement.

Figure 24

Uniform density occurs when all parts of the mat are compressed or compacted the same amount, i.e., when placing a 2.0” (51 mm) mat, 2.5” (64 mm) is placed at the front of the paver screed and the screed and rollers compress or compact the material to 2.0” (51 mm). If the mix is cold in certain areas, one of two things will occur during compaction. The mix located in the cold spot will not compress the full amount causing the paver screed to rise or fall, thus leaving a rough place in the pavement, or cracking will occur due to extreme heavy load caused by the cold area supporting the entire roller. In either case, the result is a substandard pavement that will be short-lived.

Figure 25

Pavement smoothness is affected when nonuniform densities occur. Temperature segregation and aggregate particle size both can seriously affect pavement smoothness. Paver screeds will rise and fall as mix temperatures and the associated mix stiffness changes.

SOLUTIONS

This leads to the conclusion that some type of remixing must be performed immediately prior to placing the mix to achieve a uniform temperature. Read studied various transfer devices to determine their effect on temperature differential damage. These were a windrow pickup device (Figure 24 and Figure 25), a Blaw-Knox transfer machine, and a Roadtec Shuttle Buggy® material transfer vehicle.

While concluding that the windrow pickup device reduced the amount of differential temperature segregation, he noted that keeping the exact amount of mix in the windrow uniformly was difficult. It was also apparent that excess or deficiencies in the windrow would lead to mix being stored for longer or shorter times in the paver hopper, contributing to temperature segregation. Also, belly dump trailers usually dump from the center first with the cold material on the sides being discharged last, leading to concentrations of cold material at the end of each load. While the mat was improved, the temperature segregation was not eliminated.

Figure 26

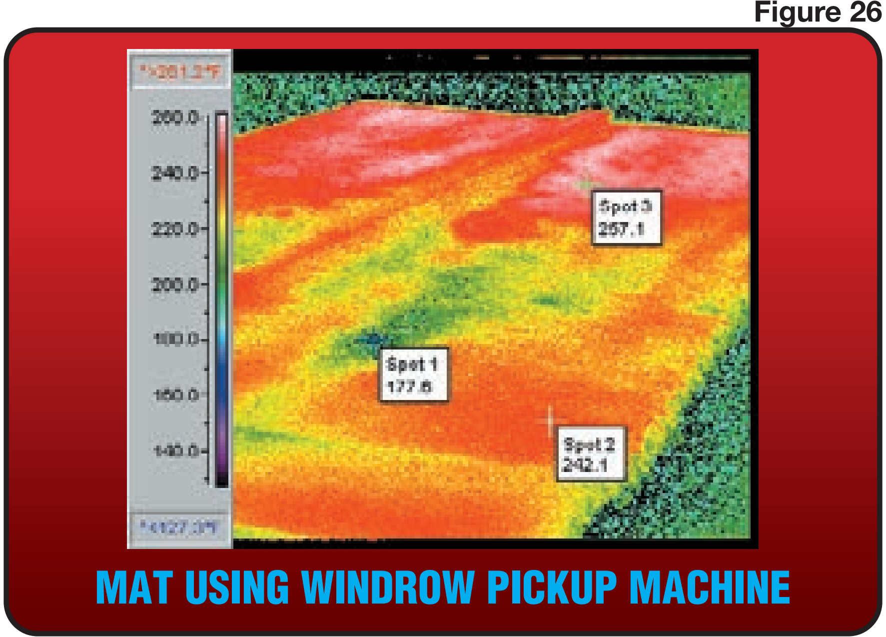


Figure 27

Figure 28

Figure 26 shows a windrow placing device often used in Mississippi which is intended to remix the material in the windrow prior to it being picked up by the pickup machine. As can be seen from the infrared photograph (Figure 27) taken behind this machine, the remixing for temperature is minimal when using this machine. When this photograph was taken, the mix had been hauled 10 miles (16 km).

Figure 28 shows the Cedarapids MS-3 on a job in Nova Scotia and Figure 29 shows the infrared photograph behind it. The MS-3 is basically a material transfer machine allowing more storage in the paver but does little remixing as can be seen from the infrared. Figure 30 shows the Cedarapids remix paver and Figure 31 shows the augers inside of the remix paver. Figure 32 shows the infrared behind this machine after a 55- mile (89 km) haul. As can be seen, little remixing for temperature occurs when utilizing this device.

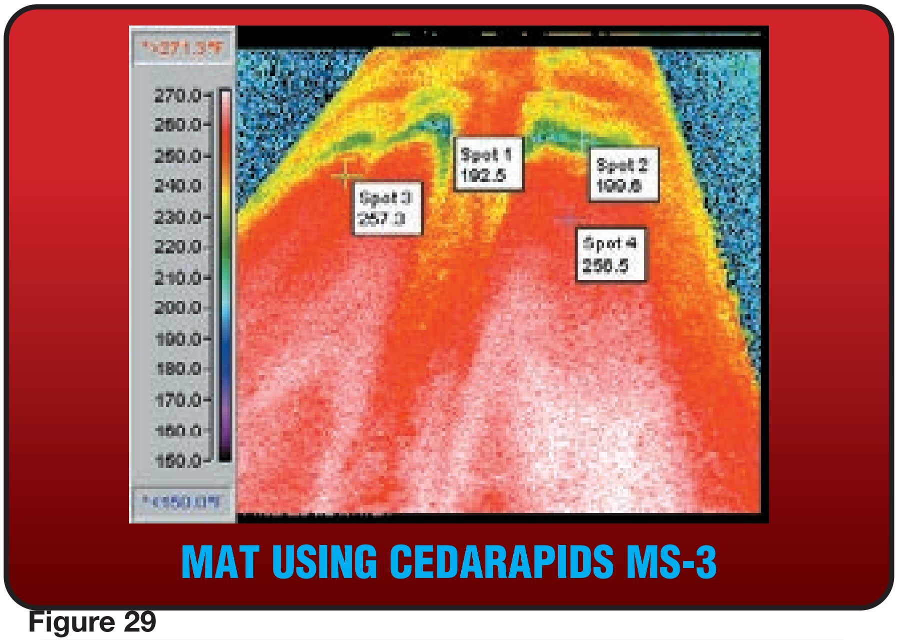


Figure 29

Figure 30

Figure 31

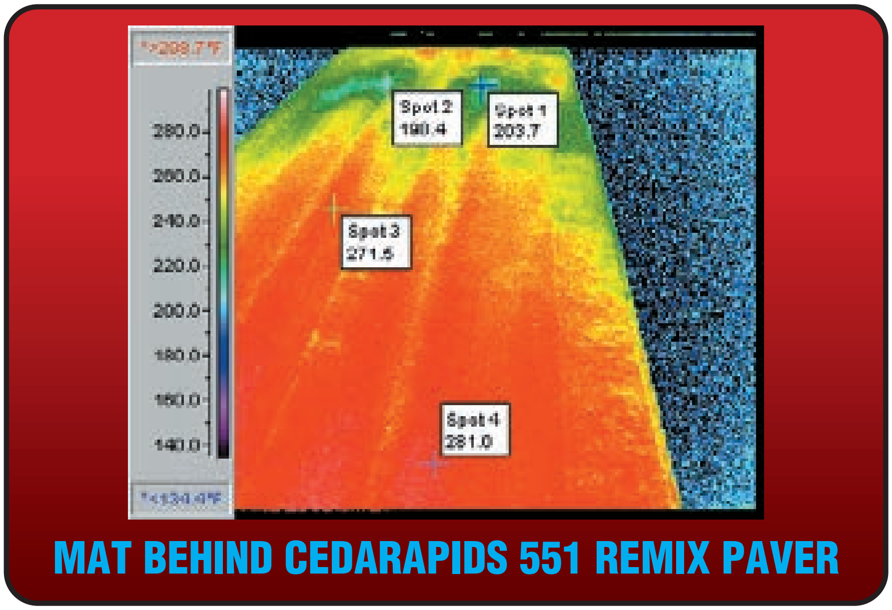


Figure 32

Figure 33

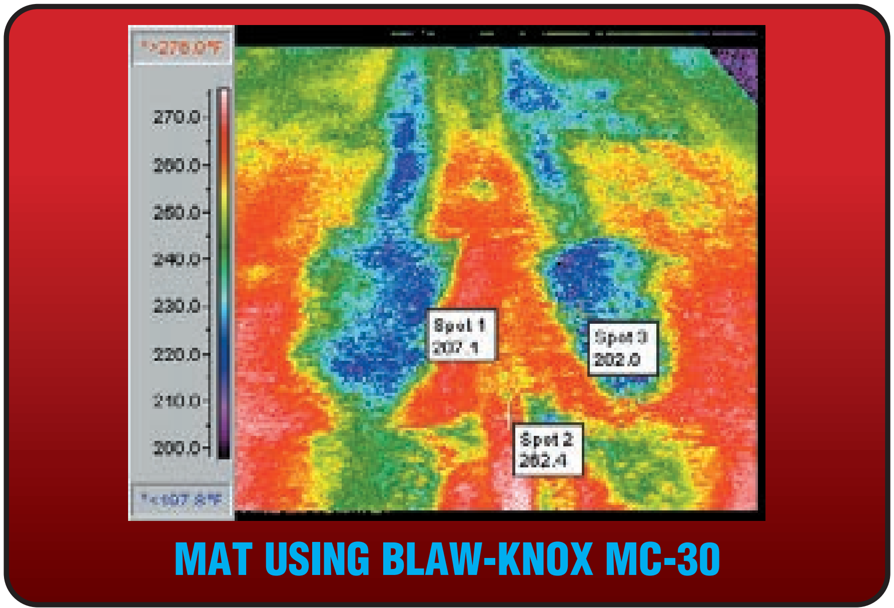
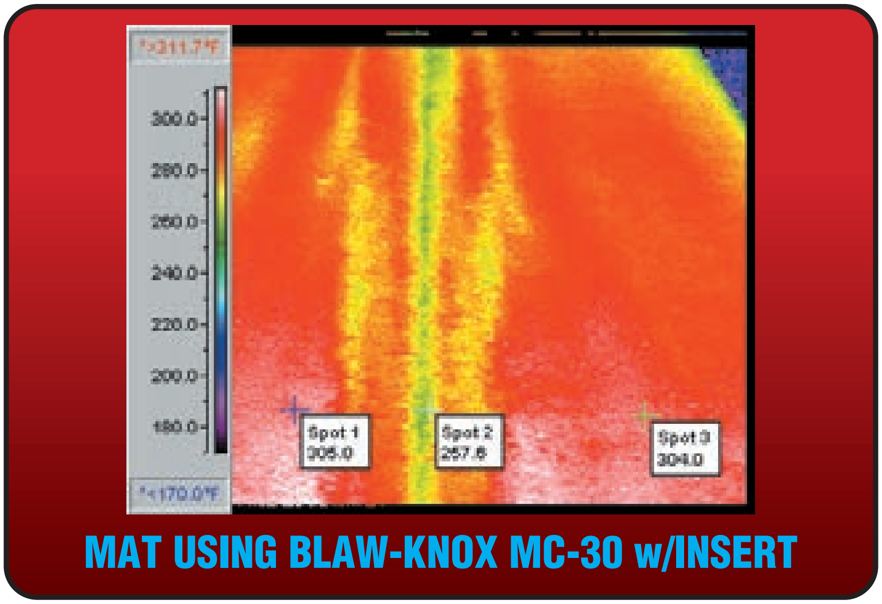


Figure 34

Figure 35

Figure 36



MAT USING BLAW-KNOX MC-30 w/INSERT

Figure 37

Figure 33 shows the Blaw-Knox transfer machine, which is basically a belt transfer machine that has minimal remixing. While this machine improves the mat, it still demonstrates the same amount of temperature segregation, as seen in Figure 34. Figure 35 shows an improvement on this machine with an insert (as seen in Figure 36) containing a mixer in the bottom of the paver hopper. Figure 37 shows the infrared temperature of the mat behind this combination. While improved, there is still significant temperature differentials.

Figure 38 shows the Roadtec material transfer vehicle. This machine has triple pitch augers (as shown in Figure 40) in the bottom of the storage hopper. The machine will store approximately 25 metric tons or 30 short tons. When augers are used as shown in Figure 39, no remixing occurs since all of the mix is fed in from the inlet end of the auger. This results in all of the material being conveyed from the outside of the hopper with the center emptying last. By changing the pitch of the auger, as shown in Figure 40, new material can enter the flights as the flights spread out or the pitch changes. Since the pitch changes twice on each side of the hopper, mix from six different areas across the hopper (transversely to the direction of the paver) is remixed or reblended, with the cold or coarse material being reblended with the hot or finer material from the quarter points and the center of the machine.

Figure 38

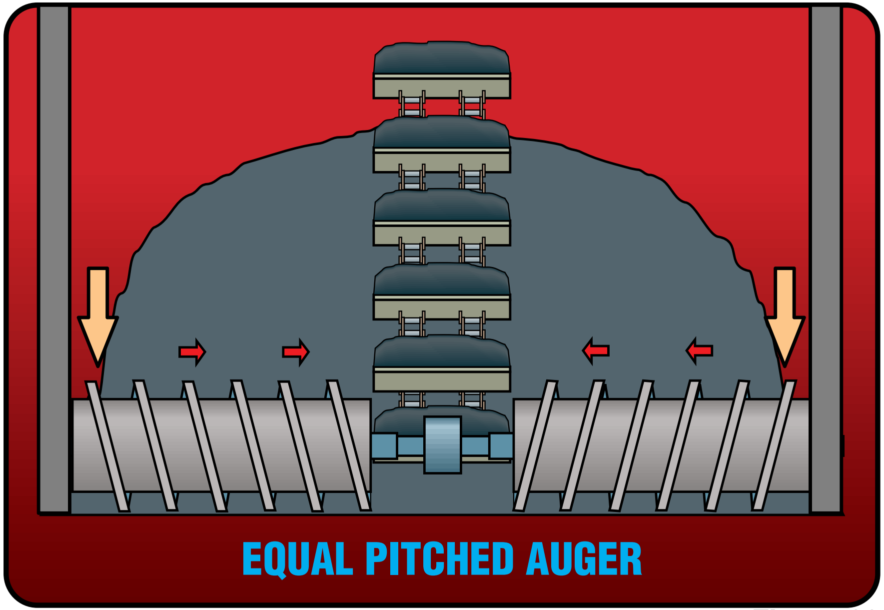


Figure 39

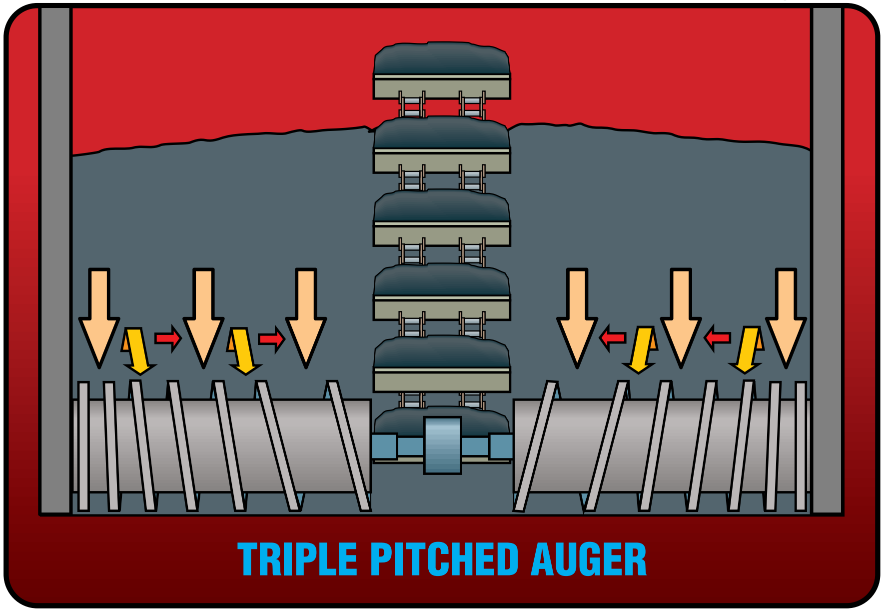


Figure 40

Figures 41, 42, and 43 show three infrared photographs behind the Roadtec Shuttle Buggy. As can be seen, when compared with the other transfer machines, the temperature differential behind this machine is less than 10°F in all cases.

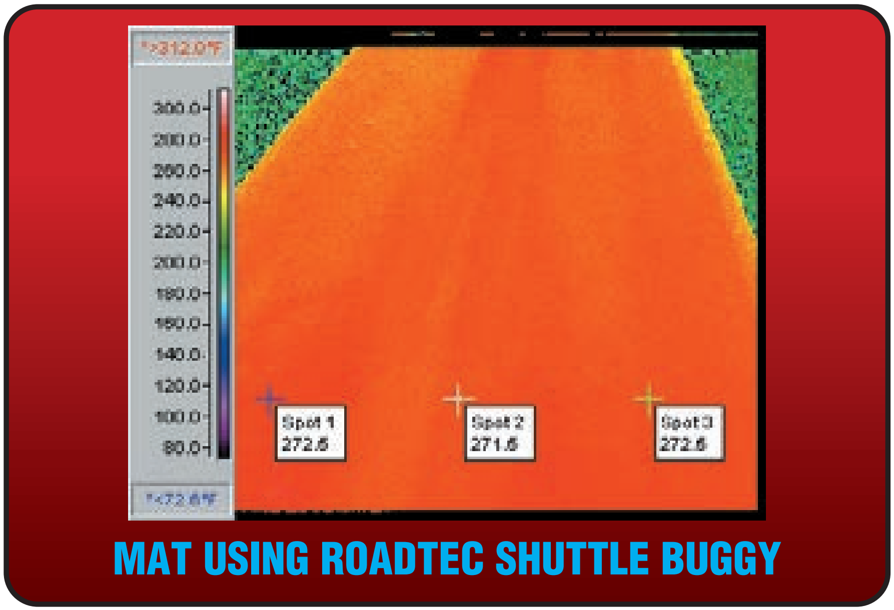


Figure 41

This photo was taken on Route 210 in Eastville, Nova Scotia in June of 1998.

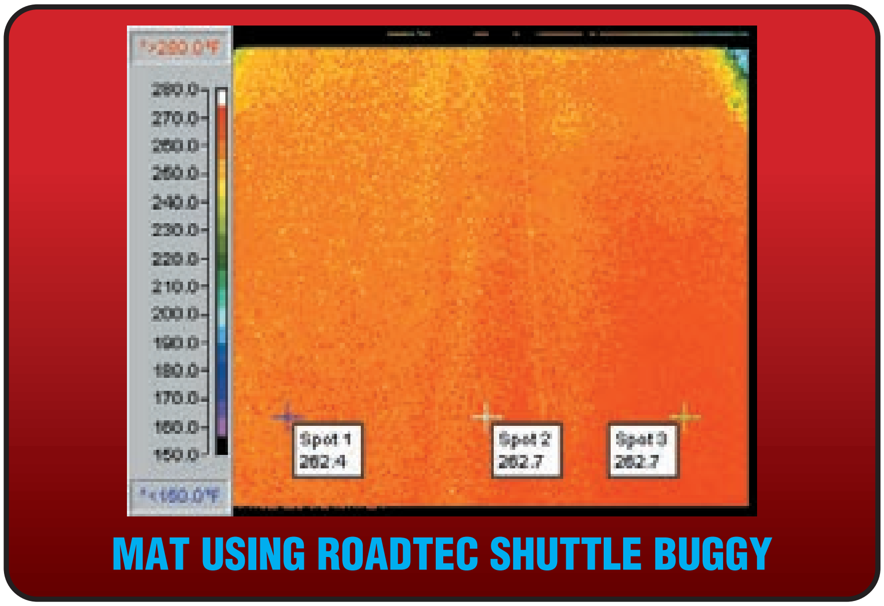


Figure 42

This photo was taken on I-S South in Everett, Washington in June of 1998.

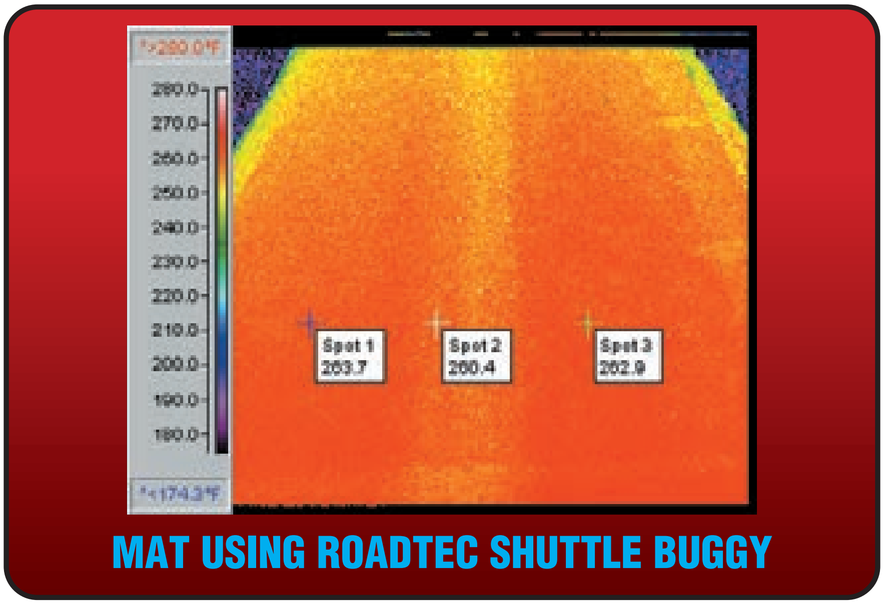


Figure 43

This photo was taken on Route 336 in Newcombville, Nova Scotia in June of 1998.

This phenomenon was first recognized approximately three years ago when a contractor in Arkansas who was laying thin lifts of asphalt in February observed that while using the Roadtec Shuttle Buggy, his smoothness increased significantly and his pay for density went from 80% to 100%. His observation was that the machine remixes for temperature and, in his opinion, it was more important than remixing for segregation. Figure 44 shows the section of road placed without the Shuttle Buggy. Figure 45 shows the section placed with the Shuttle Buggy. Frankly, at that time, the significance of the amount of temperature segregation occurring was not realized.

Figure 44

Figure 45


Figure 46

Figure 47


Figure 48

Again in early 1997 a contractor in Australia hauled mix 150 miles one way (241 km), resulting in a 176° F (80° C) temperature on the outside of the truck; on the top the mix was 205° F (96° C), but in the center of the load the mix was still 305° F (152° C). After remixing through the Roadtec material transfer vehicle, the temperature discharge from the machine was 284° F (140° C) *see Figure 46, Figure 47 and Figure 48.* The result pavement was uniform in density and very smooth.

From this it becomes apparent that unless an extremely short haul in good weather occurs, some type of remixing directly prior to placing the mix into the paver should occur in order to achieve a uniform consistent mix in the mat. When belly dump trucks are used and windrow paving occurs, a Shuttle Buggy with a windrow pickup head gives the advantage of having storage and remixing. By incorporating the augers and screed on the rear of the machine, the Shuttle Buggy becomes a paver. This integrated machine accomplishes the same job as the paver and pickup machine and insures a uniform temperature in the mat behind the paver. Such a device is shown in Figure 49.

CONCLUSION

Figure 49

Through the use of the infrared camera, it has become apparent that temperature variations in mix discharged from trucks have been much greater than previously thought and although undetected, has been a significant problem for many years. When looking at infrared photographs, it is apparent that random variations in density, which are quite common place, are caused by the concentration of cold material in the mat. It is also apparent that these cold spots will eventually lead to a deteriorated spot in the pavement or a pothole. As mixes become harsher, such as the new superpave and SMA mixes, mix temperatures have often been increased significantly to overcome these random density problems. All of this leads to the conclusion that some type of remixing must occur directly prior to placing the mat. While HMA can be produced uniformly at the asphalt plant, with each step in the process being performed correctly, as the mix is hauled to the job, heat loss is inevitable. The many variables affecting the time between the truck leaving the plant and arriving at the job site results in variable mix temperatures on the outside of the truck bed and leads to an uncontrollable situation for the contractor.

Test results have shown that there is insufficient remixing in paving machines to eliminate this phenomenon. Therefore, to produce a long lasting smooth pavement with consistent density and thus consistent air voids, some type of device that uniformly remixes the material directly prior to placement is essential. Companies and entrepreneurs over the next few years will most likely develop a number of devices to accomplish remixing. Whether a device does an adequate job can easily be determined by utilizing an accurate infrared camera. The camera eliminates the guesswork by exposing the temperature variations as they occur.

By remixing prior to placement, we will achieve smoother longer lasting roads without premature failures in certain areas of the road. This will result in more economical, longer lasting pavements with less disruption to the public and a smoother ride for all.

Table 1: I-5 (Blaine) Temperature, Density, and Air Voids

Sample Identifier (1)	Probe Temp. (C°)	Rice Density (kg/m^3)		Nuclear Density (kg/m^3)	Bulk Density (kg/m^3	Nuclear Density Diff. (N-C) (kg/m^3)	% Air Voids Based on Nuclear Density(3)	Increase in Air Voids (%) (C-N)
		Box	Core					
3N	141	2506	2511	2205	2071	138	12.0	6.8
4C	113	2546	2497	2067	2056		18.8	
5N	141	2519	2498	2202	2120	101	12.6	4.4
6C	112	2532	2521	2102	2133		17.0	
7N	124	2514	2500	2176	2107	90	13.4	4.0
8C	93	2529	2534	2087	-		17.5	
9C	101	2521	2521	2176	2186		13.7	
10N	119	2511	2516	2117	2122	80	15.7	3.5
11C	107	2521	2506	2037	2109		19.2	
12C	109	2510	-	2083	-	54	17.0	2.1
13N	147	2511	-	2138	-		14.9	
14N	141	2505	-	2170	-	72	13.4	3.5
15C	121	2522	-	2098	-		16.8	
16N	121	2521	2503	2260	2274		10.4	
Truck-Front		2534						
Truck-Middle		2522						
Truck-Rear		2521						

Table 2: SR 2 (Spokane) Temperature, Density, and Air Voids

Sample Identifier (1)	Probe Temp. (C°)	Rice Density (kg/m^3)		Nuclear Density (kg/m^3)	Bulk Density (kg/m^3)	Nuclear Density Diff. (N-C) (kg/m^3)	% Air Voids Based on Nuclear Density(3)	Increase in Air Voids (%) (C-N)
		Box	Core					
1C	99	2498	2474	2199	2309	109	12.0	3.7
2N	127	2518	2492	2308	2378		8.3	
3C	84	2482	2433	2175	2218	67	12.4	2.2
4N	106	2495	2481	2242	2276		10.1	
5C	92	2510	2486	2135	2191	82	14.9	3.3
6N	134	2510	2487	2216	2260		11.7	
7C	105	2505	2482	2237	2224	29	10.7	1.6
8N	111	2494	2486	2266	2295		9.1	

Table 3: SR 195 (Colfax) Temperature, Density, and Air Voids

Sample Identifier (1)	Probe Temp. (C°)	Rice Density (kg/m³)		Nuclear Density (kg/m³)	Bulk Density (kg/m³)	Nuclear Density Diff. (N-C) (kg/m³)	% Air Voids Based on Nuclear Density(3)	Increase in Air Voids (%) (C-N)
		Box	Core					
1C	100	2659	2662	2385	2349		10.3	
2N	130	2651	2654	2526	2513	111	4.7	4.9
3C	128	2673	2657	2415	2421		9.7	
4C	104	2654	2688	2280	2337	205	14.1	7.8
5N	132	2652	2654	2486	2433		6.3	

Table 4: SR 99 (Seattle) Temperature, Density, and Air Voids

Sample Identifier (1)	Probe Temp. (C°)	Rice Density (kg/m³)		Nuclear Density (kg/m³)	Bulk Density (kg/m³)	Nuclear Density Diff. (N-C) (kg/m³)	% Air Voids Based on Nuclear Density(3)	Increase in Air Voids (%) (C-N)
		Box	Core					
1C	110	2514	2470	-	2348	35	6.6	1.6
2N	149	2510	2474	-	2383		5.0	
3C	103	2526	2487	-	2327		7.9	
Truck-Front		2516						
Truck-Middle		2511						
Truck-Rear		2492						

(1) Sample identifier
- 1...3 = sample number
- N or C = (N)ormal-temperature or (C)ool spot sample

(2) “Temp. Diff.” = N - C
(3) % Air Voids calculation based on nuclear density and “Box” Rice density.

Information supplied by Dr. Joe Mahoney of the University of Washington.

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