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Longitudinal Pavement Joint Performance: A Field Study of Infrared Heated and Notched Wedge Joint Construction

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This report presents the findings of a field study in Maine, constructed during summer 2012 using two different joint technologies and an infrared heater. MaineDOT has previously used an infrared heater and notch-wedge apparatus to improve longitudinal joint density on a trial basis. The goal of infrared joint heaters is to increase the temperature of the existing HMA material being paved against, in turn reducing the viscosity of the material and allowing the material to be compacted by the rollers. In contrast, the notch-wedge apparatus is designed to construct a precompacted, tapered mat edge with an adjustable vertical "notch" at the top and bottom of the lift.

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Introduction

Longitudinal joints are created when two adjacent lanes of pavement are placed at different times. Typically, the longitudinal joint is weak area in a pavement where cracking and raveling will occur within a few years of construction. The likely cause of the premature failure is lower material density at the joint. Under typical construction practices, the initial pavement lane has an unconfined edge that is not fully compacted because it is not restrained by an adjacent material. When the adjoining mat is placed the initial edge has cooled and cannot be compacted any further, creating a cold joint with lower density. The reduced density at the joint allows water to penetrate into the pavement, causing further degradation, raveling, and cracking.

Various methods have been used by highway agencies to improve the quality of a longitudinal joint, including the different procedures for rolling the joint, constructing wedge joints, cutting the joint, using a restrained edge, reheating the joint, and using joint adhesives. The objective of these various methods is to increase the pavement density at the joint, therefore improving durability and service life. Numerous studies performed across the country have shown that these technologies can improve density and durability at the longitudinal joint.

A recent study in New Hampshire (Daniel & Real, 2006) evaluated the use of an infrared joint heater used on the base, binder, and surface courses of a full-depth hot mix asphalt (HMA) pavement. The sections using the infrared joint heater were found to have significantly improved density and strength values over control sections. Measurements of permeability in the joints also showed measurable difference between the methods. Also, field surveys of the joints conducted a year after construction showed that sections that used the infrared joint heater were found to have significantly less cracking than the control sections. Other studies(Fleckenstein, Allen, & Schultz, 2002) have shown similar results for the improvement of joint durability with the proper use of an infrared joint heater.

The standard practice of constructing longitudinal joints in Maine in recent years has been to use the vertical edge approach. Using this method the first lane is paved a minimum of 3” and a maximum of 6” over the proposed centerline and then the pavement is milled or cut back to the propose centerline before placing the adjacent lane. A low modulus joint sealer is typically applied to the vertical face being matched immediately prior to the pavement of the adjacent pavement. This method creates a clean vertical edge in which to pave up against that should be densified adequately. However, on thicker lift thicknesses the vertical edge created using this method creates safety concerns for traffic if the edge is left to traffic for a period of time. Even with this practice, the MaineDOT continues to observe premature failure of its HMA pavements at the longitudinal joint.

This paper presents the findings of a field study in Maine, constructed during summer 2012 using two different joint technologies and an infrared heater. MaineDOT has previously used an infrared heater and notch-wedge apparatus to improve longitudinal joint density on a trial basis. The goal of infrared joint heaters is to increase the temperature of the existing HMA material being paved against, in turn reducing the viscosity of the material and allowing the material to be compacted by the rollers. In contrast, the notch-wedge apparatus is designed to construct a precompacted, tapered mat edge with an adjustable vertical “notch” at the top and bottom of the lift. A schematic of typical notch-wedge longitudinal joint construction is shown below in Figure 1.

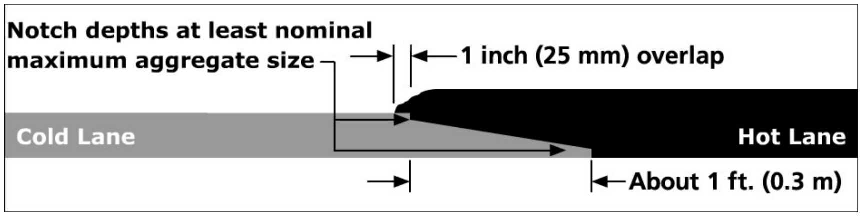


Figure 1 – Schematic of a typical notch-wedge joint

The goal of this research is to compare these two methods to the current state of practice for the Department to observe if a significant increase in density is possible. The factors affecting the performance of the longitudinal joint treatments were also examined as well as the relative temperature of the HMA material at the joint in each method. The resulting density values from each treatment are compared statistically to observe which treatment provided the best compaction. Further recommendations are made for the Department to move forward to improve the service life of longitudinal joint in the state of Maine.

PROJECT DESCRIPTION / STUDY METHODOLOGY

The Bangor-Plymouth pavement preservation project served as the site for the field trial of the longitudinal joint treatments. The project is located on Interstate 95 Southbound from the southern joint of Bridge No. 5971 in Bangor and extending southerly for 21.09 miles to Exit 161 in Plymouth. The location is shown in green on the location map. The paving project was identified by Project Numbers 16784.20, 18293.00, 19199.00, & 19200.00.

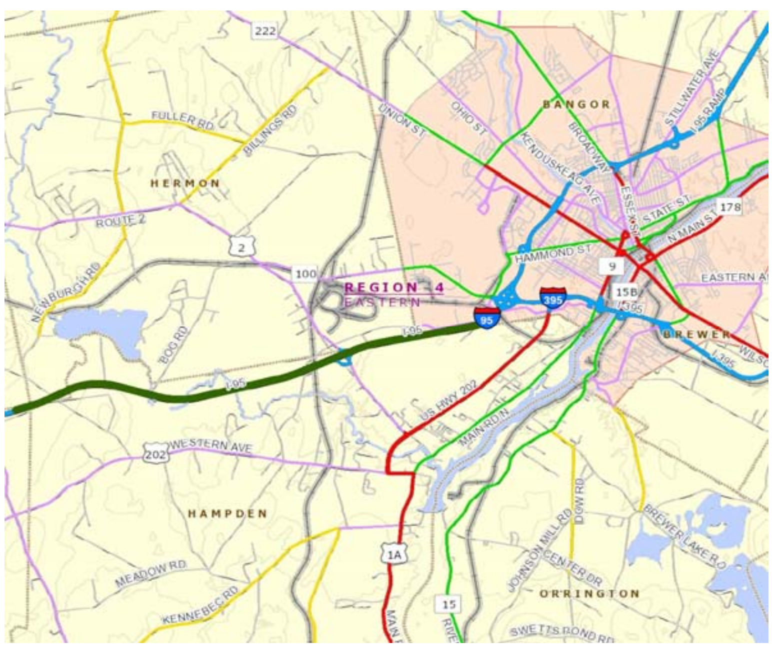


Figure 2 - Location Map

The work in the project consisted of pavement milling and HMA overlays of the roadway. The test sections of the longitudinal joint treatments were performed on the 1 ¾" thick, 12.5 mm nominal size HMA surface course. The travel lane HMA was paved using a PG 70-28 polymer modified binder while the passing lane was paved using an unmodified PG 64-28 binder.
A Typical Section is shown in Figure 3.

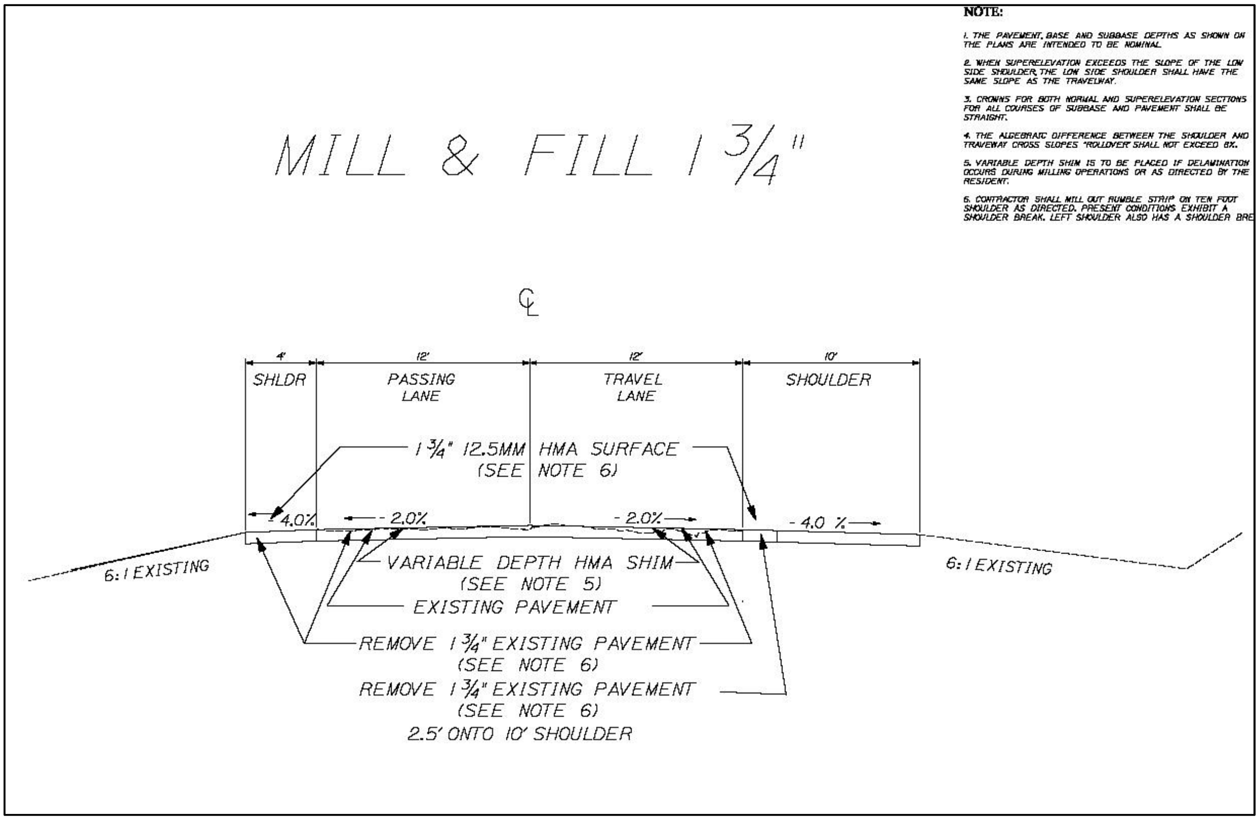


Figure 3 - Typical Section

Three different longitudinal joint treatments were used in this study: (1) the trimmed vertical edge, (2) a notch-wedge, and (3) a notch-wedge reheated using the infrared joint heater. Shorter control sections were paved using the trimmed vertical edge and the notch wedge apparatus, while the remainder of the project was paved using the notch wedge apparatus in conjunction with the infrared joint heater. The trimmed vertical edge control section is located from station 3462+00 to station 3340+40 (12,160 ft length). A low modulus joint sealer was applied to the vertical face of the joint before the adjoining lane was paved. Two notch-wedge control sections were utilized and they are located from station 3627+12 to station 3558+90 (6,822 ft length) and from station 2926+09 to station 2739+83 (18,626 ft length). A six inch notch-wedge was used, and was not further compacted by the rollers after paving. When the notch-wedge apparatus was used without the infrared joint heater, a double tack application was applied to the joint. The infrared joint heater was used with the notch-wedge apparatus for the remainder of the project. Pavement core sample locations were generated randomly with sublots of 2000 ft sections. At each sample location, a pavement core was taken from the longitudinal joint and from a random location in the mat. The mat location will be used as a measure of total compactive effort at the location in an effort to remove bias. The pavement density on the joint was calculated using the maximum specific gravity of the HMA mix in both lanes (the modified and unmodified mix). Thermal imaging technology was also utilized during construction to observe the amount of heating retained from the joint heater.

PAVING OPERATIONS

The paving for this project was completed with a Caterpillar AP1055D paver. A Roadtec SB 2500 Material Transfer Vehicle (MTV) was used on the project to transfer mix from the haul trucks to the paver, as is required on all interstate projects in Maine. The breakdown roller was a Caterpillar 54D roller, the intermediate roller was Ingersoll Pneumatic PT 240R roller, and the two finish rollers were both Caterpillar 534 XW rollers. The entire paving train, including the infrared joint heater when used, is shown below in Figure 4. When the first lane (passing lane) was constructed, the breakdown roller made its first pass 4-8” off the unconfined edge and then made its return pass over the joint (or 4-8” over the joint when the notch-wedge was used). The pneumatic roller then passed along the joint 4-6 times, with varying distances from the joint. The finish rollers used the same pattern as the breakdown roller, but with the return pass slightly (2”) farther over the joint. When the second lane (travel lane) was paved, the breakdown roller made its first pass 4-8” off centerline and then made its return pass over centerline by 4-8”. The pneumatic roller then made a pass close to the joint for two passes, and then on the joint for two passes. The finish rollers then did one pass 6-8” off of centerline and then two passes on top of centerline (last one in static).

Figure 4 - Paving train (including infrared joint heater)

For the majority of the project, when a stretch of the passing lane was paved, the adjoining travel lane section would be paved the next day.

Infrared Heating Equipment

The infrared heater apparatus was operated nearly 200 ft ahead of the paving operation due to space limitations for the MTV and the haul trucks. The infrared joint heater was mounted on a truck. It was electrically powered and consisted of three low-level radiant energy heaters or microwave emitting infrared-type heaters. The infrared equipment was thermostatically controlled to provide a uniform and consistent temperature increase through the layer. The infrared heater vehicle used on the project is shown below in Figure 5.

Figure 5 - Image of the infrared joint heater with three reheater assemblies used on the project

RESULTS

Cores six inches in diameter were taken from the centerline joint and the travel lane in the random locations identified by the study. A total of 38 locations were identified in this study, with one core sampled from the joint and one core sampled from the mat in each location. All cores were cut by the Contractor for the project under the standard procedures for Quality Assurance coring the Department uses. The MaineDOT Central Laboratory performed all density measurements for the cores. The complete density results for the trimmed vertical joint section, the notch-wedge section, and the notch-wedge with infrared section are shown below in Table 1, Table 2, and

Station (Feet)	Mat			Centerline (CL)		Diff. in Density (Mat - CL)
	Left Offset (Feet)	Specific Gravity (Gmb)	Density	Specific Gravity (Gmb)	Density	
2725+93	10.4	2.312	94.4%	2.351	96.0%	-1.6%
2759+01	8.3	2.296	93.4%	2.275	92.6%	0.8%
2783+72	10.9	2.260	91.9%	2.265	92.1%	-0.2%
2805+20	3.5	2.256	91.9%	2.236	91.1%	0.8%
2811+12	9.3	2.285	93.1%	2.311	94.1%	-1.0%
2842+94	10.6	2.302	93.8%	2.247	91.5%	2.3%
2848+19	10.4	2.317	94.4%	2.263	92.2%	2.2%
2869+96	8.6	2.292	93.6%	2.294	93.7%	-0.1%
2893+45	1.0	2.336	95.4%	2.305	94.1%	1.3%
2922+13	10.6	2.315	94.5%	2.373	96.9%	-2.4%
3580+23	10.7	2.315	95.7%	2.314	94.9%	0.8%
3602+93	4.9	2.274	92.4%	2.192	89.2%	3.2%
Average:			93.7%		93.2%	0.5%

Table 3 respectively. The station of each coring location is noted as well as the bulk specific gravity and density values of both the centerline and mat core.

Table 1 - Density results for the vertical edge section

Station (Meters)	Mat: Left Offset (Meters)	Mat: Specific Gravity (G_{mb})	Mat: Density	Centerline (CL): Specific Gravity (G_{mb})	Centerline (CL): Density	Diff. in Density (Mat - CL)
3355+64	4.6	2.317	94.2%	2.245	91.3%	2.9%
3374+92	2.5	2.313	94.0%	2.272	92.4%	1.6%
3398+31	8.4	2.326	94.6%	2.244	91.2%	3.4%
3426+48	8.8	2.342	95.6%	2.276	92.9%	2.7%
3449+37	3.7	2.343	95.7%	2.304	94.1%	1.6%
3454+58	5.1	2.341	95.6%	2.289	93.5%	2.1%
Average:			95.0%		92.6%	2.4%

Table 2 - Density results for notch-wedge joint section

Station (Feet)	Mat: Left Offset (Feet)	Mat: Specific Gravity (G_{mb})	Mat: Density	Centerline (CL): Specific Gravity (G_{mb})	Centerline (CL): Density	Diff. in Density (Mat - CL)
2725+93	10.4	2.312	94.4%	2.351	96.0%	-1.6%
2759+01	8.3	2.296	93.4%	2.275	92.6%	0.8%
2783+72	10.9	2.260	91.9%	2.265	92.1%	-0.2%
2805+20	3.5	2.256	91.9%	2.236	91.1%	0.8%
2811+12	9.3	2.285	93.1%	2.311	94.1%	-1.0%
2842+94	10.6	2.302	93.8%	2.247	91.5%	2.3%
2848+19	10.4	2.317	94.4%	2.263	92.2%	2.2%
2869+96	8.6	2.292	93.6%	2.294	93.7%	-0.1%
2893+45	1.0	2.336	95.4%	2.305	94.1%	1.3%
2922+13	10.6	2.315	94.5%	2.373	96.9%	-2.4%
3580+23	10.7	2.315	95.7%	2.314	94.9%	0.8%
3602+93	4.9	2.274	92.4%	2.192	89.2%	3.2%
Average:			93.7%		93.2%	0.5%

Table 3 - Density results for notch-wedge with infrared reheating section

Station (Feet)	Mat			Centerline (CL)		Diff. in Density (Mat - CL)
	Left Offset (Feet)	Specific Gravity (G_{mb})	Density	Specific Gravity (G_{mb})	Density	
24+94	5.9	2.335	94.6%	2.270	92.0%	2.6%
71+95	8.1	2.360	96.1%	2.265	92.2%	3.9%
2929+35	5.7	2.297	93.3%	2.227	90.5%	2.8%
2974+57	7.3	2.880	93.0%	2.267	92.1%	0.9%
3003+25	7.7	2.345	95.3%	2.264	92.0%	3.3%
3060+20	4.5	2.276	92.7%	2.263	92.2%	0.5%
3098+89	2.8	2.278	92.3%	2.246	91.0%	1.3%
3129+71	2.5	2.280	92.4%	2.265	91.8%	0.6%
3162+30	3.8	2.305	93.3%	2.251	91.1%	2.2%
3201+11	8.3	2.319	93.8%	2.270	91.9%	1.9%
3250+32	3.1	2.261	91.9%	2.302	93.6%	-1.7%
3261+92	9.1	2.293	92.8%	2.312	93.6%	-0.8%
3496+15	11.4	2.283	93.6%	2.260	92.6%	1.0%
3511+21	5.7	2.299	94.2%	2.297	94.1%	0.1%
3526+37	1.7	2.320	95.1%	2.287	93.7%	1.4%
3541+13	1.2	2.313	94.8%	2.310	94.7%	0.1%
3550+53	8.9	2.270	93.0%	2.294	94.0%	-1.0%
3638+17	3.9	2.298	93.2%	2.245	91.0%	2.2%
3656+17	2.3	2.347	95.2%	2.315	93.9%	1.3%
Average:			93.7%		92.5%	1.2%

The core density data for all three treatments is summarized below in Table 4. A vast majority of the centerline densities in the study were greater than 90%, which is not common at the longitudinal joint. Agencies that use centerline joint density specifications typically specify a minimum density of 91%. A total of 31 of the centerline cores had densities greater than 91%. By simple inspection of the data, it is clear that the trimmed vertical edge with joint sealer treatment performed the worst out of the three sections. The difference between the centerline and mat cores for the vertical edge was 2.5%, compared to only 0.5% and 1.2% for the notch-wedge and infrared treatments. Although the centerline density values for the vertical edge and infrared sections were similar, inspection of the mat densities show that the mix was more compacted in the vertical edge sections. The mat densities for all three treatments were similar, with the average value in the vertical edge section being 95% and 93.7% in the other two sections. The notch-wedge section had the highest average centerline core densities out of the three treatments. The notch-wedge centerline cores were found to be considerably more variable than the other treatments, though the coefficients of variation (COV) values for all the treatments/sections are quite low.

Table 4 - Summary of Density Results for each Treatment

Treatment	Location	# Cores	Avg.	Std. Dev.	COV
Vertical Edge	Joint	6	92.6%	1.2%	1.3%
	Mat	6	95.0%	0.8%	0.8%
Notch-Wedge	Joint	12	93.2%	2.2%	2.3%
	Mat	12	93.7%	1.2%	1.3%
Notch-Wedge w/Infrared	Joint	19	92.5%	1.2%	1.3%
	Mat	19	93.7%	1.2%	1.3%

TEMPERATURE ANALYSIS

The Department used an infrared thermal camera in order to measure the temperature difference of the HMA material between the different treatments. A FLIR T620 thermal camera was used to take infrared images of the centerline longitudinal joint before and after it was reheated (if applicable) as well as before and after it was paved against. The camera takes temperature readings of the surface of the material, and not the interior of the HMA. The typical surface temperature of the existing HMA being paved up against without any reheating was between 100°F and 120°F depending on the time of the day the images were taken. Figure 6 below shows an existing HMA notch-wedge joint before it is paved up against.

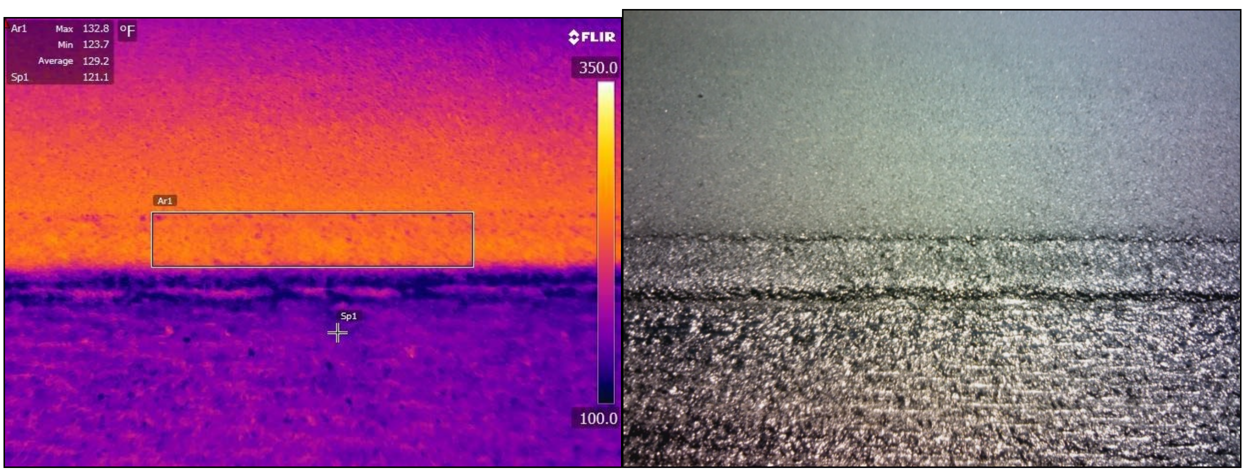
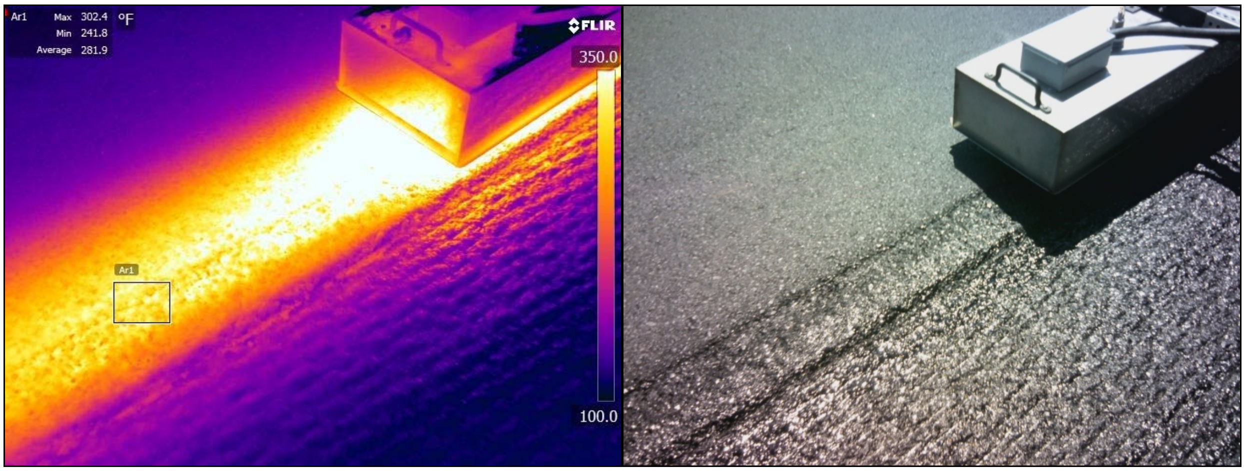
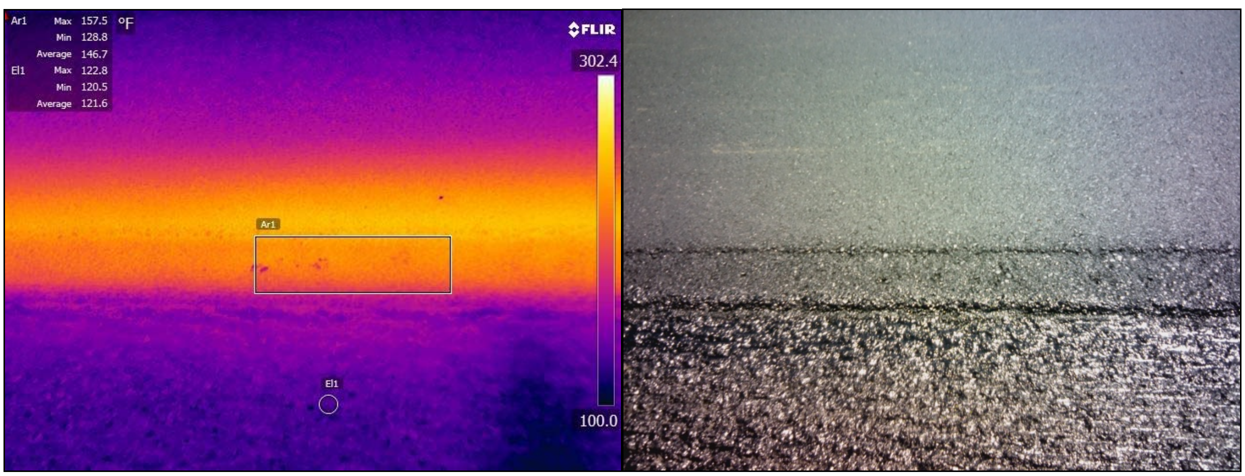


Figure 6 - Infrared and regular image of a notch-wedge joint before reheating

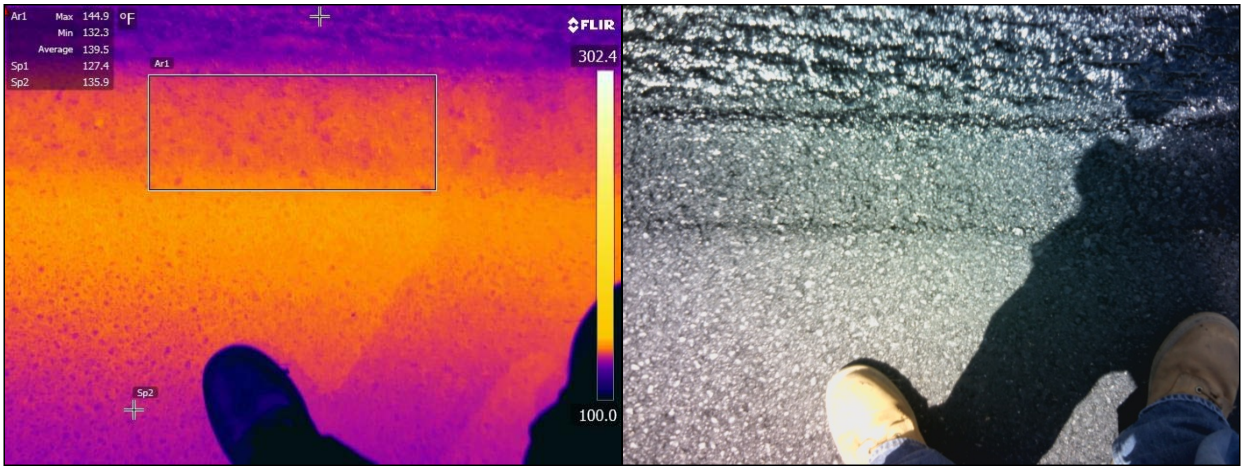
The primary objective of the infrared images was to measure how much heat the HMA joint retains after the reheating compared the surrounding HMA. In order to measure this, a random location was identified where infrared images would be taken before and after the infrared reheater was applied, with images to track the temperature over time until it was paved up against. The temperature analysis was conducted at station 3535+00 on July 7, 2012. As part of the paving train, the infrared joint heater passed over the location first at 1:15 p.m. as seen in Figure 7. The infrared joint heater was set up to heat the HMA joint up to a surface temperature of approximately 300°F through its three individual heaters on the side of the truck, as per the specification in the contract. The infrared image in Figure 7 (a) shows that the HMA joint surface immediately after reheating is approximately 282°F. Figure 7 (b) shows that the surface temperature of the joint was an average of 147°F nearly 12 minutes after the location had been reheated, a reduction of nearly 140°F from the original surface temperature. However, the surface temperature of the joint is still an average of 25°F warmer than the surrounding HMA. The infrared image in Figure 7 (c) shows that nearly 30 minutes after the joint is reheated, it still has a surface temperature of 140°F. The infrared joint heater was effective in increasing the temperature of the HMA joint, although the surface temperature dropped rather quickly from its initial temperature of over 280°F.



(a) - Infrared and digital image of station 3535+00 at 1:15 p.m. (immediately after reheating)



(b) - Infrared and digital image of station 3535+00 at 1:27 p.m. (12 min after reheating)



(c) - Infrared and digital image of station 3535+00 at 1:43 p.m. (28 min after reheating)

Figure 7 - Infrared and digital image of station 3535+00 over time

The infrared images show that the adjoining HMA pavement retains a significant amount of heat up until the new mix is placed, as shown in Figure 8. The newly placed mat is very uniform coming out of the MTV, with an average temperature of 295°F. The adjoining HMA material is still retaining heat from the infrared joint heater that passed by the location over 30 minutes previously. Overall, the images show that the heating of the joint increased the temperature of the HMA material, despite the apparent rapid loss of heat. It is noted that the infrared cameras can only measure surface temperature, and in most cases the interior temperature of the mix is elevated as the surface cools first. Field personnel observed that after heating, the HMA on the joint was malleable under boots and small forces. The ability of the material to move allows for better densification of the HMA at the joint.

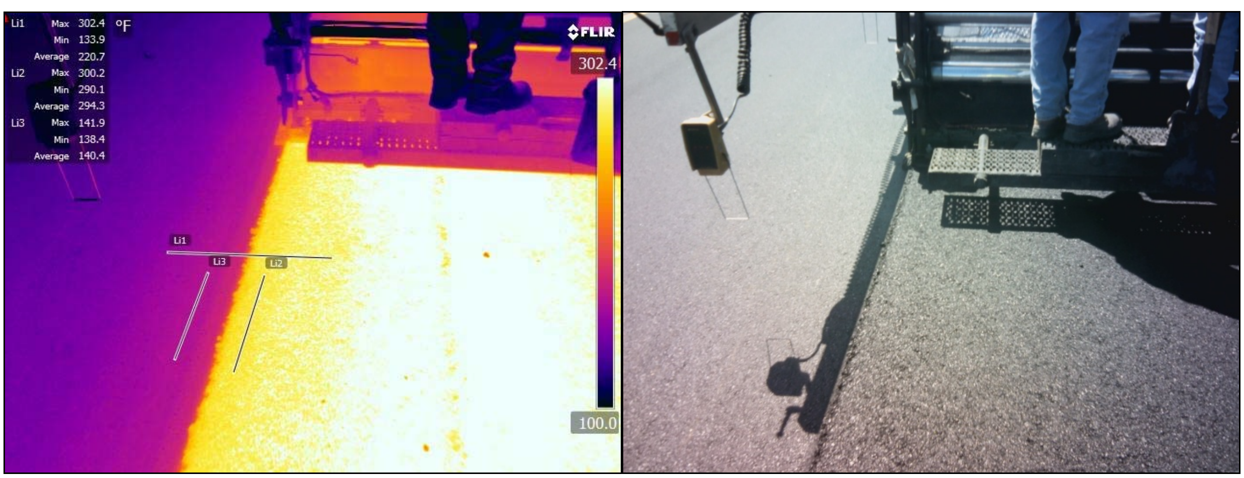


Figure 8 - Infrared and digital image of station 3535+00 at 1:46 p.m. (immediately after paving)

The infrared camera was also used on the trimmed vertical edge and notch-wedge control sections to create baselines for typical temperatures of the HMA joint material. Much like in the sections with the infrared, the existing HMA joint has surface temperature values of around 120°F during paving. Figure 9 below displays an example of a notch-wedge joint after it had been paved over. The older HMA mat has a surface temperature of 119°F, and the fresh HMA mat is over 250°F. The HMA material placed over the cold notch-wedge is cooled down to an average of 206°F. Figure 10 below displays an infrared image of the trimmed vertical edge when paved up against. The trimmed edge had an average temperature of nearly 112°F, similar to the other control sections. After the new HMA is placed against the vertical edge there is some heat transfer to the previously placed material, with the direct edge showing an average temperature of 170°F. However, the temperature of the previously placed HMA in the vertical edge and notch-wedge joint was not as high as those observed when the infrared heater was used.

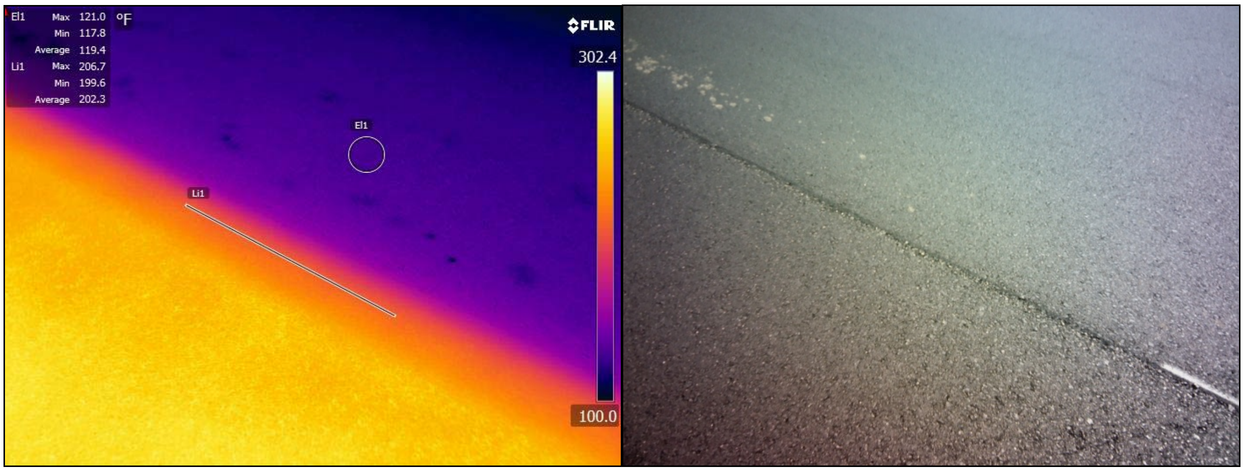


Figure 9 - Infrared and digital image of notch-wedge joint after HMA paving (fresh mat on the left)

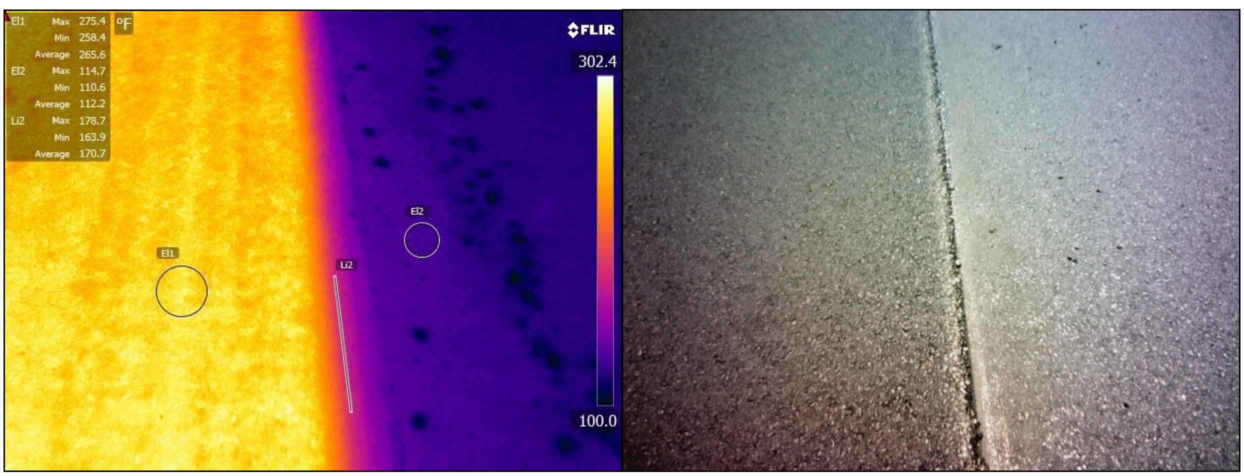


Figure 10 - Infrared and digital image of trimmed vertical edge joint after HMA paving (fresh mat on the left)

ANALYSIS & DISCUSSION

In order to determine the relative effectiveness of the three studied longitudinal joint treatments, a statistical analysis of the density data was performed. An alpha level of 0.05 (confidence level of 95%) was used for statistical tests. An analysis of variance performed on the centerline density values showed that the type of longitudinal joint treatment was not significant, $F(2,34) = 3.276$, $p = 0.502$, as shown below in Table 5. Although this analysis suggests that the longitudinal treatment type had no effect on the centerline density values, it does not take into account the compactive effort undertaken at each random location. If the mat near the centerline has lower density because of a reduced compactive effort by rollers at that location, it should be accounted for.

Table 5 - Analysis of Variance for Centerline Joint Density by Treatment Type

Summary

Groups	*Count*	*Sum*	*Average*	*Variance*
Notch-Wedge	12	11.184	93.20%	0.047%
Vertical Joint	6	5.554	92.57%	0.014%
Notch-Wedge with Infrared	19	17.58	92.53%	0.015%

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.000358	2	0.000179	0.703	0.502	3.276
Within Groups	0.008661	34	0.000255			
Total	0.009019	36				

In an effort to eliminate the potential bias of the compactive effort in each location, the centerline joint density values were normalized by the mat density value at the same location as shown in the following equation:

$$\%TMD_{normalized} = \frac{\%TMD_{joint}}{\%TMD_{mat}} \quad (1)$$

A normalized value over one would indicate a joint density that was higher than the corresponding mat core, while a normalized value of less than one indicated a centerline density less than the corresponding mat core. An analysis of variance was performed on the normalized centerline values and the results are shown below in Table 6. When normalized, the notch-wedge treatment had the highest density values and the trimmed vertical edge had the lowest. The analysis showed that the null hypothesis for the data (that the means are the same) could not be rejected. However, the relatively low p value (0.052) indicates that the data is close to showing significant differences between the treatments. In order to further investigate the differences between the treatments, a post hoc analysis using the Tukey-Kramer method was used. The Tukey-Kramer test showed that the notch-wedge normalized density values were significantly higher than those of the trimmed vertical edge; the infrared normalized densities were not significantly different from the other two groups, lying somewhere in the middle. The statistical analysis suggests that the notch-wedge treatment produced significantly higher centerline joint densities than the other two treatments, although it did have the highest variability of the three treatments.

Table 6 - Analysis of Variance for Normalized Centerline Densities by Treatment Type

Summary

Groups	*Count*	*Sum*	*Average*	*Variance*
Notch-Wedge	12	11.935	0.9946	0.00031
Vertical Joint	6	5.849	0.9749	0.00006
Notch-Wedge with Infrared	19	18.761	0.9874	0.00025

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.001550	2	0.000775	3.220	0.052	3.276
Within Groups	0.008182	34	0.000241			
Total	0.009732	36				

The statistical analysis suggests that the notch-wedge density values were significantly greater than the vertical edge densities, as was expected. Other studies have shown that the notch-wedge, if set-up correctly, can improve densities on the longitudinal joint. The statistical analysis did not find a significant difference between the density results (both centerline and normalized centerline values) for the notch-wedge and the notch-wedge with infrared heating sections. However, the temperature analysis showed that the infrared joint heater did in fact increase the temperature of the HMA joint material before being paved against. The increased temperature values should reduce the viscosity of the HMA, improving the ability of the rollers to compact the material. A number of factors are hypothesized to contribute to lack of a significant difference, the biggest being the high density values in general. The average centerline joint density measured in this study was 92.8%, which is quite high for what is typically found in other projects. An improvement in the density values with the infrared heater could be more pronounced with lower initial density material at the joint. Another factor was the distance in which the infrared heater was ahead of the paver in the operation. The heater was typically 200 to 300 feet ahead of the paver and depending on the speed of the paver; the material was allowed to cool from 10 to 30 minutes before being paved up against. The distance was elongated because of the inclusion of the MTV in the paving train and the room required for the larger live-bottom trucks to maneuver. Also, in an effort to examine the factors that affected the infrared heater control section, a regression analysis was performed on some of the data against the normalized centerline joint density values. The variables used in the analysis included the offset of the mat core, the temperature at the start of paving for the day, the temperature at the midpoint of paving for the day, and the temperature at the end of paving for the day. The only variable that was significant to the model was the temperature at the midpoint of paving, represented by T_2. The results of the regression analysis using T_2 are shown below in Table 7. The air temperature significantly predicted the normalized density values in the infrared section with an R^2 of 0.305. Increased temperatures allow the infrared heated HMA material to retain its heat longer, possibly improving compaction.

Table 7 – Regression Results for Normalized Centerline Joint Density Values

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.001356	0.001356	7.491849	0.014042
Residual	17	0.003076	0.000181		
Total	18	0.004432			

Regression Model

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	0.9049	0.0303	29.8740	<0.001
T_2	0.0011	0.0004	2.7371	0.014

Another factor in the results is the relatively high density values of the notch-wedge control section. As mentioned previously, the notch-wedge apparatus can produce high density values if it is set-up correctly. It is the Department's experience that the notch-wedge can produce very variable results based upon the installation and implementation of the apparatus on the paver. In an effort to measure this phenomenon, a similar project using a notch-wedge for the centerline longitudinal joint was investigated for joint density values. The project used a similar lift thickness with similar materials, and eleven centerline joint density cores were taken on the project. The average centerline core density was found to be 88.1% with a standard deviation of 2.075%. Obviously, the values encountered on that project are vastly different than those found in this study.

CONCLUSIONS

Based on this study's presented results and discussion of the field study of three different longitudinal joint treatments, the following conclusions are drawn:

- All three longitudinal joint treatments produced relatively high density values at the centerline joint
- Infrared imaging showed that the electric infrared joint heater was effective in increasing the material temperature of the HMA at the joint. The existing HMA was heated up to a surface temperature of 300°F and the material retained elevated temperatures up to 30 minutes after heating.
- The notch-wedge control section produced the highest centerline density values when compared to the corresponding mat cores, with the vertical edge section producing the lowest values.
- A statistical analysis showed that the longitudinal joint treatment type (against normalized density values) was not significant at a confidence level of 95%, but was significant at a confidence level of 90%.
- Post hoc analysis (suing the Tukey-Kramer method) showed a significant difference between normalized density values for the notch-wedge section and the vertical joint section. No significant improvement in normalized density was found in the infrared heater section.
- A regression analysis on the infrared heater density results showed the air temperature to be significant factor, with increasing temperature producing higher normalized density values at the centerline joint. This effect is the opposite of what was expected, as it was thought that the infrared heater would have more of a positive effect in colder temperatures. It is hypothesized that the elevated temperatures may have allowed the HMA to retain the heat from the infrared heater for longer periods of time, improving the ability of the material to be compacted.
- Logistical reasons prevented the infrared heater from operating close to the paver under production. As a result, it was often at least 10-15 minutes after the material was reheated that it was paved up against. It is hypothesized that reducing the time/distance between the infrared heater and the paver would improve the performance of the joint material and result in higher joint densities.
- Core density results from a similar project found that the notch-wedge apparatus produced vastly lower density values than those found in this project. It is hypothesized that the notch-wedge can produce highly variable results depending on the set-up and operation of the apparatus in the field.

RECOMMENDATIONS

Based upon the findings from this study, it is recommended that the Department continue to evaluate the different longitudinal joint treatments, including the use of an infrared joint heater. First, this project should be continued to be evaluated in coming years to observe actual performance of the longitudinal joint of the different control sections. An effort should be placed to find another project to use the infrared joint heater, ideally in a location where the logistics allow the heater to operate closer to the paver to maximize the positive effects of the heating on the HMA material. The relative temperature dependence of the density results with the infrared heater should be investigated further. The use of the infrared joint heater should be considered in late season paving project to see the effect of lower temperature son the effectiveness of the reheating process. The Department policy of allowing the notch-wedge as a longitudinal joint treatment should be continued, as it performed very well in this study. However, it is recommended that the Department return to utilizing a longitudinal joint density specification (with incentive/disincentive provisions) on large paving projects due to the apparent variability in results with the notch-wedge due to workmanship and installation. The inclusion of this specification in the contract would provide Contractors with incentives to ensure that longitudinal joint receive proper compaction necessary for long service life. It is evident from this study that high longitudinal joint densities can be achieved using a variety of methods if they are enacted properly.

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