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Assessment of the Impact of Unacceptable Hot-Mix Asphalt Test Parameters

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16. Abstract

According to the current standard specifications and special provisions within the Illinois Department of Transportation, four quality assurance (QA) parameters are used to assess acceptability to remain in place for hot-mix asphalt (HMA) construction projects. However, when these parameters fall outside acceptable limits, it is not clear what impact this has on the pavement service life. This report, therefore, conducted a thorough literature review of studies on QA parameters and their effects on pavement service life and studied the standard specifications of each state to determine what their current practice is in terms of percent within limits (PWL) specifications. The conclusions of this task indicated that most states use some combination of gradation, density, air voids, asphalt binder content, and volumetric asphalt film-related parameters to assess the performance of contractors. Furthermore, the research team conducted an initial review of 10 recent IDOT projects and examined pavement condition indices for three others to determine what impact, locally, unacceptable materials have on initial pavement performance. Low density showed a consistently substantial relationship to premature rutting and increased International Roughness Index. For other parameters, the findings were mixed based on data available, as some projects did show initial performance effects of unacceptable sublots while others did not show any relationship to initial performance. Finally, the research team presented recommendations for future studies considering that this research did not evaluate performance of outside acceptable limits cases over the entire life span of HMA construction projects.

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Members of the Technical Review Panel (TRP) were the following:

- Doug Dirks, TRP Chair, Illinois Department of Transportation
- Dennis Bachman, Federal Highway Administration
- Kevin Burke, Illinois Asphalt Paving Association
- Brian Hill, Illinois Department of Transportation
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EXECUTIVE SUMMARY

The Illinois Department of Transportation (IDOT) uses quality assurance (QA) test data in hot-mix asphalt (HMA) paving projects as part of their quality management programs to ensure the quality of the final product. IDOT uses four QA test parameters to evaluate if HMA is considered acceptable to remain in place. In the highest tier quality management program, Pay for Performance, IDOT can apply both incentives or disincentives based on percent within limits test results for air voids, voids in mineral aggregate (VMA), and in-place density. Additionally, there are monetary deductions for unconfined edge density and dust to asphalt binder ratio. The goals of this study were twofold: to conduct a review of existing research and specifications that capture the acceptable limits used to determine pay across various state agencies in the United States and to initially assess the impact of unacceptable materials in Illinois on a limited number of projects.

The literature review indicated that there is currently a gap in terms of existing research on the effectiveness of the acceptable limits applied in the United States, with few studies assessing field performance of unacceptable materials and no identified laboratory studies of unacceptable materials. The studies that do exist confirmed the validity and helped develop more accurate pay factors. The specification review indicated that most states have some combination of air voids, gradation, and asphalt binder content in one form or another, while many but relatively fewer consider VMA. Most limits are similar to those used in Illinois.

The review of IDOT pavement performance data considered rutting data, International Roughness Index (IRI), and IDOT’s Condition Rating Survey (CRS). Granular data to the nearest 0.1 mile were observed for rutting and IRI, while CRS was examined at the project level. Project-level data could not capture any initial issues derived from unacceptable materials, while some sections showed there were initial effects in terms of rut depth and IRI. The findings in this stage had some inconsistencies, but a general trend was observed that low density led to worse initial performance, based on this small initial dataset. Furthermore, the projects evaluated were completed within the past five years and pavement performance data to date does not capture the HMA life span. The research team concluded with recommending future steps IDOT can take to monitor field performance of unacceptable materials which remain in place. Regarding a framework for IDOT to conduct future field monitoring of HMA sublots, it is recommended that IDOT develop a database for this purpose that includes unacceptable, acceptable, and incentive-earning sublots. Future research can be conducted to establish the framework for this database to allow IDOT to collect this data seamlessly.

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CHAPTER 1: INTRODUCTION

The Illinois Department of Transportation (IDOT) uses three quality management programs to assess the quality of hot-mix asphalt (HMA) construction projects. In each quality management program, quality assurance (QA) test results are evaluated with respect to acceptable limits. In some cases, HMA does not meet acceptable limits, but is allowed to remain in place.

Currently, IDOT has acceptable limits for four parameters: air voids, field voids in mineral aggregate (VMA), density, and dust/asphalt ratio (although the latter is not required for stone-matrix asphalt mixes). The current limits are shown in Table 1, adopted from IDOT's *Standard Specifications for Road and Bridge Construction* (IDOT, 2022).

Table 1. IDOT Acceptable Limits

Test Parameter	Acceptable Limits
Air Voids	2.0%–6.0%
Field Voids in Mineral Aggregate (VMA)	−1.0%–3.0% based on minimum required field VMA by mix type
Density	90.0%–98.0% (dense graded) 92.0%–98.0% (stone-matrix asphalt)
Dust/Asphalt Binder Ratio	0.4%–1.6%

The objectives of this study are as follows:

- Complete a literature review on HMA acceptable limit parameters and ranges.
- Determine the significance of incentivized, compliant (100% pay) and noncompliant (disincentivized) mixes on field performance and relate these to the corresponding incentives and disincentives.
- Recommend a framework for IDOT to monitor field performance of HMA sublots.

CHAPTER 2: LITERATURE REVIEW

BACKGROUND ON PERCENT WITHIN LIMITS SPECIFICATIONS

NCHRP Report 409 (Cominsky et al., 1998) investigated the Superpave QC/QA plan and the tolerance for critical volumetric parameters and field production. In addition to developing a contractor QC guide for mix design, production, placement, and compaction, the report also recommended requirements for state agency assessment and acceptance to verify the projects. As the control of in-place parameters is the focus of the present report, only this part is summarized herein. For in-place compaction control, in-place air voids were recommended to be measured in at least five randomly selected sampled sublots per 12 ft wide, 5,000 ft long sublot. For QC, contractors should develop a control chart for density based on measurements either using nondestructive techniques or cores from the sublots.

For QA, sampling and testing are conducted less frequently. Cominsky et al. (1998) provided a general procedure for determining the percent within limits (PWL). The procedure is described briefly below as follows for a two-sided PWL:

1. Locate *n* random sampling positions.
2. Make a measurement at each position (using nondestructive techniques) or extract a core to make a measurement at each position.
3. Average the lot measurements (Equation 1).
4. Compute the standard deviation of the lot measurements (Equation 2).
5. Determine the upper quality index (Equation 3), where *U* is the upper limit.
6. Determine the lower quality index (Equation 4), where *L* is the lower limit.
7. Estimate the percentage of material that falls within both the upper and lower limits using Figure 1.
8. Compute the PWL (Equation 5).

$$\bar{x} = \sum_{i=1}^{n} \frac{x_i}{n} \tag{1}$$

$$s = \sqrt{\sum_{i=1}^{n} \frac{(x_i - \bar{x})^2}{n-1}} \tag{2}$$

$$Q_U = \frac{U - \bar{x}}{s} \tag{3}$$

$$Q_L = \frac{L - \bar{x}}{s} \tag{4}$$

$$PWL = (P_U + P_L) - 100 \tag{5}$$

Where:

$\bar{x}$ is the average of all measurements for a given lot

x_i is a single measurement

n is the number of sublots in a lot

s is the standard deviation of lot measurements

Q_U is the upper quality index

Q_L is the lower quality index

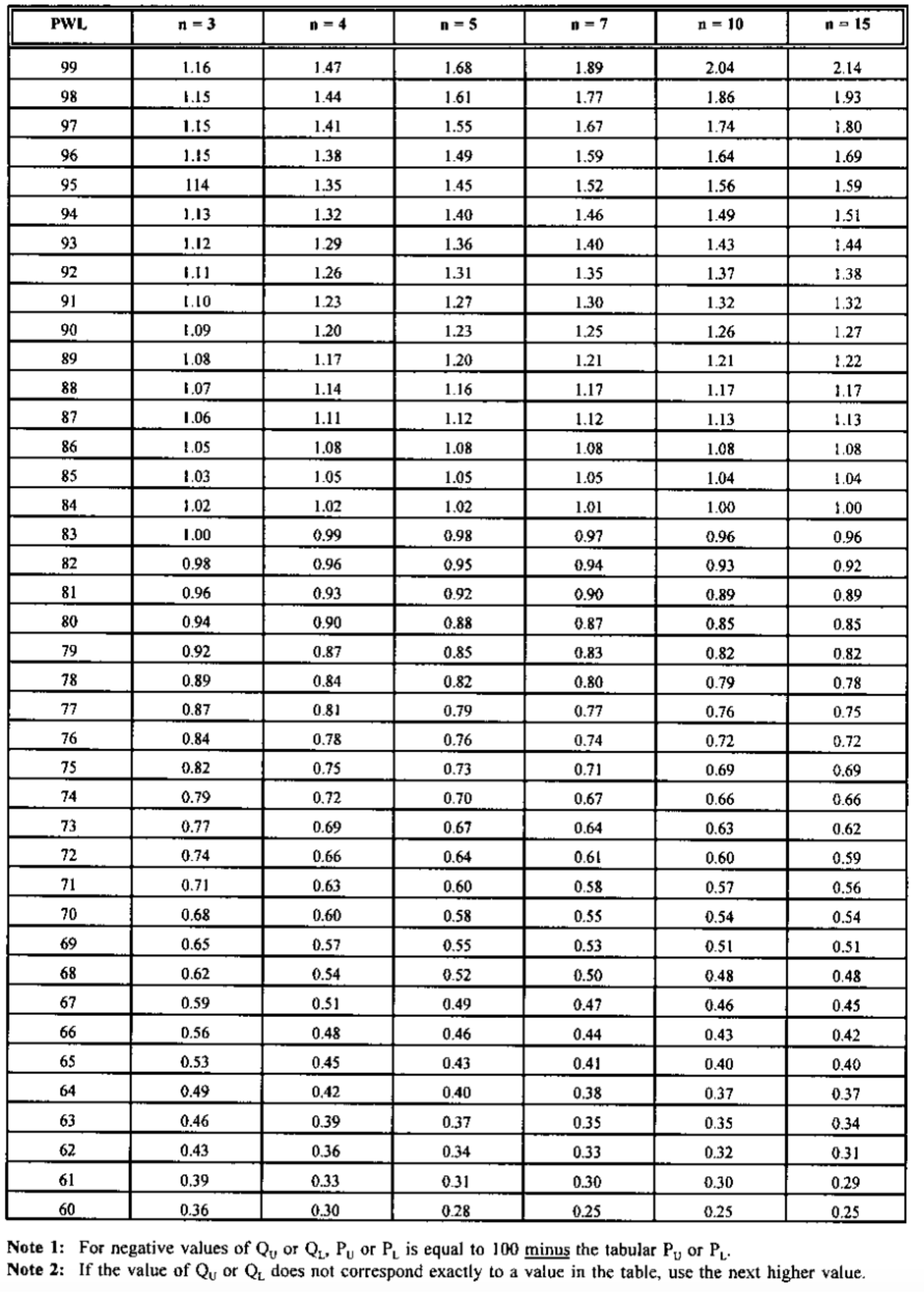
U is the upper specification limit

L is the lower specification limit

P_U is the percent of measurements within the upper limit

P_L is the percent of measurements within the lower limit

PWL is the total percent within limits



PWL	n = 3	n = 4	n = 5	n = 7	n = 10	n = 15
99	1.16	1.47	1.68	1.89	2.04	2.14
98	1.15	1.44	1.61	1.77	1.86	1.93
97	1.15	1.41	1.55	1.67	1.74	1.80
96	1.15	1.38	1.49	1.59	1.64	1.69
95	114	1.35	1.45	1.52	1.56	1.59
94	1.13	1.32	1.40	1.46	1.49	1.51
93	1.12	1.29	1.36	1.40	1.43	1.44
92	1.11	1.26	1.31	1.35	1.37	1.38
91	1.10	1.23	1.27	1.30	1.32	1.32
90	1.09	1.20	1.23	1.25	1.26	1.27
89	1.08	1.17	1.20	1.21	1.21	1.22
88	1.07	1.14	1.16	1.17	1.17	1.17
87	1.06	1.11	1.12	1.12	1.13	1.13
86	1.05	1.08	1.08	1.08	1.08	1.08
85	1.03	1.05	1.05	1.05	1.04	1.04
84	1.02	1.02	1.02	1.01	1.00	1.00
83	1.00	0.99	0.98	0.97	0.96	0.96
82	0.98	0.96	0.95	0.94	0.93	0.92
81	0.96	0.93	0.92	0.90	0.89	0.89
80	0.94	0.90	0.88	0.87	0.85	0.85
79	0.92	0.87	0.85	0.83	0.82	0.82
78	0.89	0.84	0.82	0.80	0.79	0.78
77	0.87	0.81	0.79	0.77	0.76	0.75
76	0.84	0.78	0.76	0.74	0.72	0.72
75	0.82	0.75	0.73	0.71	0.69	0.69
74	0.79	0.72	0.70	0.67	0.66	0.66
73	0.77	0.69	0.67	0.64	0.63	0.62
72	0.74	0.66	0.64	0.61	0.60	0.59
71	0.71	0.63	0.60	0.58	0.57	0.56
70	0.68	0.60	0.58	0.55	0.54	0.54
69	0.65	0.57	0.55	0.53	0.51	0.51
68	0.62	0.54	0.52	0.50	0.48	0.48
67	0.59	0.51	0.49	0.47	0.46	0.45
66	0.56	0.48	0.46	0.44	0.43	0.42
65	0.53	0.45	0.43	0.41	0.40	0.40
64	0.49	0.42	0.40	0.38	0.37	0.37
63	0.46	0.39	0.37	0.35	0.35	0.34
62	0.43	0.36	0.34	0.33	0.32	0.31
61	0.39	0.33	0.31	0.30	0.30	0.29
60	0.36	0.30	0.28	0.25	0.25	0.25

Note 1: For negative values of Q_U or Q_L, P_U or P_L is equal to 100 minus the tabular P_U or P_L.

Note 2: If the value of Q_U or Q_L does not correspond exactly to a value in the table, use the next higher value.

Figure 1. Table. Table showing all quality index values.
Quality index values for estimating percent within limits.

Source: Cominsky et al. (1998)

PREVIOUS RESEARCH ON PAY FACTORS IN HMA CONSTRUCTION SPECIFICATIONS

Quality management programs in HMA construction have increasingly moved toward using a PWL framework for determining contractor bonuses and disincentives on large projects. Illinois is among these, now generally using PWL for Pay for Performance (PFP) projects with quantities above 8,000 tons of HMA, while generally using quality control for performance (QCP) for projects with quantities between 1,200 and 8,000 tons and QC/QA for other projects with quantities less than 1,200 tons. QC/QA was the first non-method specification used in Illinois, beginning in 1992 (Patel et al., 1997). In 2010, IDOT implemented QCP and PFP as new specifications for larger quantities to improve their HMA quality and comply with regulations from the Federal Highway Administration (Al-Qadi et al., 2020).

Since then, researchers have conducted various studies to better understand the effectiveness of the program and identify improvements. Rivera-Perez et al. (2022a, 2022b) identified that 44%–55% of produced HMA during 2015 and 2016 were subjected to disincentives at an average of $20,000 per project. IDOT and contractor test results were statistically comparable over 80% of the time in terms of air voids, VMA, and density. Disincentives were primarily caused by production and construction issues (Al-Qadi et al., 2021). Sayeh and Al-Qadi (2023) then ran an economic analysis on the same set of data and determined that the major drivers of disincentives were core density followed by air voids, and that reducing the standard deviation of core density from 1.67 to 1.0 would result in average increases in pay per project of $38,000. Outside of Illinois, research in Alaska also indicated the variability between lab- and plant-produced mixes, and it found much higher differences in volumetric and mechanical properties as compared to composition properties (Liu et al., 2017).

Illinois is not the only state to utilize this type of quality management program. Over the last 70 years, agencies have worked to develop better programs for quality management. In California, Deacon et al. (1997) developed a framework based on modeling both the effect of quality on pavement performance and a costing model to quantify this effect in terms of dollars. They then developed a combined pay factor based on each pay quantity, which depended on asphalt binder content, air void content, mineral filler, fine aggregate, and pavement thickness. Later, Popescu and Monismith (2006) followed up that study with another revision to the performance-based approach that included a new performance-based pay factor calculator to replace the existing PWL scheme. They also proposed determining pay factors for existing QC/QA projects and evaluating the effectiveness of the proposed PWL program on those sections. Recently, Le et al. (2022) conducted a case study of Seoul, South Korea, using the model developed by Popescu and Monismith (2006), considering the average relative performance as an alternative to PWL. However, they noted that this method needs field performance data validation.

Indiana Department of Transportation recently conducted a study (Park et al., 2016) in which they attempted to develop a decision tree for unacceptable materials. However, the results of their study indicated that there was not reliable information provided from their Quality Related Specification Software (QRSS) to develop such a process.

RELATIONSHIP BETWEEN IN-PLACE VOLUMETRICS AND FIELD PERFORMANCE

Early studies of pay factors based on Superpave design indicated mixed findings on the effect of the in-place properties used to derive these factors and pavement performance. For example, Hand et al. (2004) studied sections of I-80 near Reno, Nevada, and found little relationship between pay factors and performance. Mensching et al. (2013) also observed that the models used in their study did not correspond much to changes in job mix formula (JMF) parameters. This lack of sensitivity was associated with challenges in predicting performance life based on pay factors and inherent shortcomings in the model used to make these predictions.

However, a more recently conducted study in Wisconsin (Faheem et al., 2018; Hosseini et al., 2020) collected rutting, alligator cracking, longitudinal cracking, and transverse cracking data to correlate with the construction parameters. The geo-referenced quality database from highway construction projects by the Wisconsin Department of Transportation was utilized for distress collection. The paper established statistical correlations between QC measures during asphalt mix production and surface construction, and the resulting pavement performance in service. These distresses and their impact were quantified using a developed Deterioration Index. VMA, air voids, and density all showed a relationship with both rutting and alligator cracking. Later, the same group used as-produced and as-constructed data to develop deterioration models that consider in-place properties, including air void content, VMA, density, asphalt content, and layer thickness (Hosseini et al., 2022).

Wang et al. (2023) recently highlighted some changes that have been made by agencies as part of volumetric design, including increasing VMA, removing the upper voids filled with asphalt (VFA) limit, and either increasing or decreasing design air void content. However, they noted that these changes should be done with caution, as they may affect other mix design variables such as gradation, especially in the face of applying the volumetric design procedure to new technologies and mixes with recycled materials.

Studies on Effect of In-Place Air Voids and Density

Over the last several years, an interest at the national level has resulted in Federal Highway Administration research, which indicated the importance of achieving in-place density and encouraging contractors to improve performance based on awarding bonuses for excellent field density (Aschenbrener et al., 2019). In addition, improving specifications can directly improve performance in terms of achieving in-place density; however, addressing density alone cannot overcome other construction issues such as segregation or other volumetric parameters outside acceptable limits (Aschenbrener & Tran, 2020; Mohamed & Tran, 2022). Currently, there are a few studies that have correlated the effects of in-place volumetrics when the mix is placed and performance of HMA. Many early studies indicated that rut depth was directly related to a low in-place air void content (Brown & Cross, 1989; Ford, 1988). However, it is important to note that these studies did not measure the air voids at construction. Rather, they were forensic studies of pavements after rutting had occurred or did not occur, meaning it is very possible that rutting occurred due to other factors, but the additional densification caused the air void content to reduce due to shear flow (Brown & Cross, 1989; Zhang et al., 2017). Therefore, these findings are more applicable to mix design than to construction. The findings of such studies are also mixed. Other studies have found a lack of any relationship between in-place air voids and rutting in the field (Khattak & Peddapati, 2013). Meanwhile, Xu and Huang (2012) observed that in-place density had a relationship with rut depth, but did not have data about density at compaction. It is worth noting that, often, the opposite result is observed in the lab when producing specimens (Seo et al., 2007), which further drives the point that in-place volumetrics in the middle of the project cannot represent volumetrics at the start of pavement life.

Tran et al. (2016) conducted a literature review on the effect of in-place air voids on pavement service life. This review included extensive review of the WesTrack experiments, which directly evaluated the effect of in-place air void content between extreme values of 4%, 8%, and 12%. Based on the WesTrack test sections, both lab tests on extracted materials and field testing revealed substantial increase in fatigue life of the sections when air voids were reduced by 1% (Epps et al., 2002; Seeds et al., 2002). The WesTrack results also showed improved resistance to rutting in the field when air voids were reduced by 1%. Based on these results and other studies, Tran et al. (2016) also conducted a simplified life cycle cost analysis (LCCA), which indicated 8.8% agency savings based on increasing required density by 1%. This is reasonably consistent with the findings of Linden et al. (1989), who observed around 10% decrease in pavement service life when air voids were increased by 1% above the allowable 7%, based on Washington state Pavement Management System data. Based on these findings, Salini and Lenngren (2022) developed a generic pay penalty scheme for asphalt concrete falling above 7% air voids.

New Jersey Department of Transportation (NJDOT) conducted a comprehensive study of the effect of in-place air void QA data on pavement performance (Wang et al., 2015). Their study demonstrated a relationship between air voids outside of acceptable limits according to NJDOT specifications and decreasing pavement service life. They also used concepts of LCCA to suggest the development of pay adjustment factors sensitive to material and construction variabilities as well as the agency's practices for maintenance, which ultimately dictate costs incurred by unacceptable performances and savings due to better than acceptable performance, which result in contractor bonuses. Note that this study occurred on a network level, rather than examining specific projects, which is the intent of later parts of the present report.

Although few experimental studies have been conducted in this direction, one of the most recent studies was for Brazilian construction projects. The study observed significantly decreased stiffness and therefore decreased fatigue life based on the FHWA FlexPAVE framework when air voids exceeded 7% in place, based on field cores that should be compacted to 5.5% according to Brazilian specifications (Schuster et al., 2023). However, note that the FlexPAVE software is not currently used in Illinois to quantify fatigue resistance of asphalt pavements.

Studies on Effect of VMA

VMA has also been a challenging parameter to relate to field performance. Previous research has suggested that difficulties in meeting VMA requirements should result in a minimum requirement being replaced with a film thickness requirement, since they serve a similar function when combined with an air void requirement of ensuring sufficient asphalt binder is present to prevent cracking (Hinrichsen & Heggen, 1996; Kandhal et al., 1998; Li et al., 2009). The need for sufficient asphalt binder content has been well-demonstrated in recent lab studies for lab-produced mixtures using cracking potential tests (Al-Shamsi et al., 2017; Hill, 2019; Hu et al., 2011). In addition, VMA has served as in input in recently developed models for field cracking as part of the Wisconsin DOT studies referenced earlier in this report (Faheem et al., 2018; Hosseini et al., 2020). However, the impact on long-term pavement performance is less clear. Zhang et al. (2019) conducted a statistical evaluation of sections tested during NCHRP 09-49A and determined that effective binder content and field VMA had impacts on rutting, but that the impact of VMA was not exactly clear, noting the need for more research. Schram and Abdelrahman (2011), through a long-term field study, observed that asphalt film thickness had a good relationship with both surface raveling and rutting, while VMA had no such relationship in their study.

Studies on Effect of Other Quality Parameters

In South Carolina, one study of rideability was conducted that examined the impact of nighttime versus daytime paving. It determined that nighttime projects typically received more rideability bonuses (Ogunrinde et al., 2020). Wang et al. (2020) conducted a study of initial International Roughness Index (IRI) and its impact on pavement service life. In general, they observed a moderate relationship with R^2 of about 0.6. This led to the development of a pay factor framework using a probabilistic LCCA approach. Praticò (2013) presented an LCCA-based performance pay adjustment model that included drainability, storage capability, and noise as potential “premium” performance metrics, and later presented a framework for determining costs of premature failure (Praticò, 2015).

Some previous work under the National Cooperative Highway Research Program and other projects suggested that using predicted pavement life based on measured HMA properties and *Mechanistic-Empirical Pavement Design Guide* distress predictions could operate as a new pay framework (De Jarnette et al., 2013; Oshone et al., 2019). However, this approach has not yet been widely investigated. Chehab and Hamdar (2020) developed a similar framework for QA based on volumetrics, performance testing, and mechanistic-empirical performance prediction for airfield pavements.

Recently, Hajj et al. (2021) conducted a case study of Maine DOT as part of balanced mix design implementation. Their study indicated a need for greater attention to be paid to material passing the #200 sieve in terms of dust to asphalt binder ratio. They also emphasized the importance of ensuring bulk specific gravity of aggregate (G_{sb}) is accurately measured.

INNOVATIVE APPROACHES IN QUALITY MANAGEMENT

One interesting approach was examined in a study that explored the best value concept as part of the selection process (Elyamany & Abdelrahman, 2010). The best value approach involves selecting a contractor not only on lowest bid, but also considering past performance on similar projects. In this study, field data indicated that the top five quality characteristics, based on a dataset from the Nebraska Department of Roads, were density, asphalt content, gradation, air voids, and VMA, in order of importance. Using a probabilistic approach, the best value framework could predict the potential performance of contractors based on their past performance. While this selection methodology is unlikely to be implemented for pavement construction projects, it does provide insights into the most important parameters with respect to developing such a framework.

STATE DOT ACCEPTABLE LIMITS

Since the 1960s, QC and QA requirements have been developed by state DOTs as directed by the Federal Highway Administration. Under these QC/QA programs, the contractor is responsible for the quality control process, while the state DOT assumes responsibility for quality assurance. HMA materials are typically divided into lots, and each lot is further divided into sublots. Samples are typically collected randomly from these sublots for testing purposes. In Illinois, one sublot is generally either every 1,000 tons of HMA produced for larger tonnage projects or 3,000 tons of HMA produced for smaller tonnage projects. To study the QA approaches of different states in the United States and to better compare with the current QA program in Illinois, this section of the report reviewed most states' quality management programs and provides a brief review of QA parameters in each state. The following information is obtained from DOT Quality Management System manuals, special provisions, and standard specifications.

Note that this information comes from the research team's best interpretation of publicly available information on state DOT websites. However, there can easily be information missed as each DOT has a unique way of writing construction specifications and includes different information in different places, and information should be validated by users or other researchers before using any information in this report for practice or research. Note also that information here generally focuses on typical HMA projects and sometimes SMA and other HMA mixes where available. However, small quantities were not a focus of this review, and are generally not covered for each state.

Table 2 demonstrates which states use which tests or parameters for quality assurance as it relates to pay factors as they were found in the sources discussed in the rest of this chapter. However, it is critical to note that this table does not indicate that the measurements are the same. For example, states have different equipment, test methods, and differences between methods. Furthermore, some states use contractors to take measurements, some use DOT labs to perform these measurements, and some use third-party testing. Therefore, this table simply provides a summary of parameters but not an exhaustive review of practice and cannot be used to directly draw similarities between state specifications. Also, in this table, only dense-graded HMA is considered, as requirements for other mix types can get complex.

Table 2. Summary of Specification Tests (Dense-Graded HMA Only)

State	Density	Air voids	VMA	Dust/AC ratio	Asphalt content	Gradation	Other
Illinois	X	X	X	X			
Alabama	X	X			X		
Alaska	X				X	X	
Arkansas	X	X	X		X		
California	X	X			X	X	
Colorado	X				X	X	
Connecticut	X	X	X		X		
Florida	X	X			X	X	
Georgia	X				X	X	
Idaho	X	X	X	X			
Indiana	X	X			X		
Iowa	X	X					Film Thickness
Kansas	X	X					
Kentucky	X	X	X		X		
Maine	X	X	X		X	X	Depends on project type
Maryland	X				X	X	
Massachusetts	X	X			X		
Michigan	X	X	X		X		
Minnesota	X	X			X	X	Film thickness
Mississippi	X	X	X		X	X	
Missouri	X	X	X		X		TSR
Montana	X	X	X	X			VFA
Nevada	X				X	X	
New Hampshire	X				X	X	
New Mexico	X	X	X		X		
New York	X	X				X	
North Dakota	X				X	X	Binder Testing
Ohio	X				X	X	
Oklahoma	X	X			X		
Oregon	X				X	X	
Pennsylvania	X				X	X	
Rhode Island	X	X			X		

State	Density	Air voids	VMA	Dust/AC ratio	Asphalt content	Gradation	Other
South Carolina	X		X		X	X	
South Dakota	X	X					
Tennessee	X				X	X	
Utah	X				X	X	
Vermont	X	X					
Virginia	X				X	X	
Washington	X	X	X		X	X	
West Virginia	X				X	X	
Wisconsin	X	X	X		X	X	
Wyoming	X				X	X	Binder Testing

Alabama

Alabama DOT applies both incentives and disincentives for good and poor performance, respectively (ALDOT, 2022). Alabama applies pay factors for in-place density, asphalt content, and voids in total mix (VTM) (with density and VTM being used for Superpave mixes and stone matrix asphalt [SMA] only). For bituminous base course, porous bituminous base, SMA, and open graded friction course (OGFC), asphalt content has specific more stringent requirements than those for Superpave mixes. For SMA, the requirements for VTM are also more stringent than those for dense-graded mixes. All acceptable limits depend on the number of tests per lot. The density requirement for Superpave and SMA mixes is based on a target of 94% for most mixes, with a few exceptions, which are detailed in the standard specifications. It should also be noted that there are specific requirements for OGFC related to the 3/8” standard sieve and No. 8 standard sieve.

Alaska

Alaska DOT uses two pay factors and bases the HMA pay adjustment on the lower of the two. The first is a composite factor based on gradation and asphalt content, and the second is based on density. The lower density limit is 92%, while the upper limit is 100%. Asphalt content should be within 0.4% of the JMF in either direction, higher or lower. Alaska also applies incentives for longitudinal joint density greater than 92% and disincentives for longitudinal joint density less than 91%.

Arkansas

Arkansas DOT has acceptable limits for four parameters: asphalt content, air voids, VMA, and density (ArDOT, 2014). For air void content, the compliance limits are 3%–5%, while pay reduction is done for mixes as low as 2.5% or as high as 5%, after which the lot is rejected if the average measurement is outside this value. For the asphalt content, values plus or minus 0.3% from the JMF are allowed, while pay reduction occurs for values 0.3%–0.6% higher or lower than the JMF, and average values higher or lower than that result in lot rejection. Acceptable density is 92%–96%, while pay reduction is performed when density is as low as 91% or as high as 97%, and values outside that range result in lot reduction. VMA has different requirements depending on the mix type, similar to Illinois.

California

California uses the statistical pay factor PWL specification referenced by the previous studies described above (Caltrans, 2024). This specification requires determination of a composite factor, which is a weighted average of five pay factor characteristics. These characteristics are asphalt content, gradation (both percent passing #8 and #200 sieves), air void content, and core density (Caltrans, 2024).

Colorado

Colorado DOT has six elements of interest in its PWL specification. These elements are percent passing the #8 and larger sieves, percent passing the #30 sieve, percent passing the #200 sieve, asphalt content, in-place density, and joint density. These and the sampling and testing procedures are detailed in the Colorado DOT *Field Materials Manual* (CDOT, 2023).

Connecticut

Connecticut DOT considers mat and joint density, air voids, VMA, and asphalt content. The pay factors for density follow an adjustment described in Table 3.

Table 3. Connecticut Density Pay Adjustment Factors

Average % Density	% Pay Adjustment
100–97.1	−2.5
97.0–94.0	+2.5
93.9–92.0	0.0
91.9–91.0	−2.5
90.9–89.1	−5.0
89.0–87.0	−30
86.9 or less	−50 or rejection

Florida

Florida DOT bases pay factors on gradation, asphalt content, air voids, and density (FDOT, 2024). Florida's specification limits are shown in Table 4.

Table 4. Florida Specification Limits

Quality Characteristic	Specification Limit
% Passing #8 sieve	Target +/− 3.1
% Passing #200 sieve	Target +/− 1.0
Asphalt content (%)	Target +/− 0.4
Air void content (%)	4 +/− 1.2
Density, vibratory mode (%)	93 +2, −1.2
Density, static mode (%)	93 +3, −1.5

Georgia

Georgia DOT (GDOT, 2021) uses a pay factor of 1.00 when the range between highest and lowest in-place density is no more than 5%. Otherwise, a pay factor of 0.95 is used. However, this disincentive does not apply if all density results in a given lot are 93% or higher, for small quantities, or in other very specific cases such as trench widening and certain high nominal maximum aggregate size (NMAS) mixes. Georgia DOT also applies disincentives for coarse aggregate (#8 sieve size and greater) gradation based on the control sieves and asphalt content, with different limits depending on where in the structure the mix is placed (surface vs. subsurface).

Idaho

For some Superpave mixes, the Idaho Transportation Department (ITD, 2023) requires two pay factors, with one pay composite factor based on air voids, VMA, and dust proportion. The other pay factor is based on density. For other Superpave mixes, there is just one composite pay factor based on asphalt content, gradation, and density. Density limits are 92%–100%, and asphalt content should be no more than 0.3 difference from the JMF. Air void limits depend on the mix type and gradation limits depend on the band.

Indiana

Indiana DOT (INDOT, 2024) uses Superpave 5 for dense-graded HMA, requiring air voids to be 5% at N_{design}. In terms of acceptable limits, Indiana DOT has the specification limits shown in Table 5 for density, air voids, and effective binder content. For open-graded mixtures, pay factors are based on binder content and air voids at N_{design}. Binder content should be within 0.5% of the design for full pay and air voids should be within 4% of the design for full pay. For SMA, INDOT applies pay adjustments for gradation, binder content, and density.

Table 5. Indiana DOT Acceptable Limits

Parameter	Limits
Air Void Content	3.6%–6.4%
V_{be}	Specified – Specified + 2.5%
Density	Minimum 93%

Iowa

Iowa DOT (2023) has limits for film thickness, density, and air voids. The PWL limit for air voids is 1% in either direction and the PWL limit for density is between 91.5 and 100%. The film thickness requirement is between 8.0 and 15.0 for most mixes, and only has a minimum of 8.0 for interlayer and thin lift HMA.

Kansas

Kansas DOT (2023) has pay adjustments for both air voids and density. For air voids, the acceptable limits are 2.5%–5.5%, while density pay factors depend on the layer thickness.

Kentucky

For the Kentucky Transportation Cabinet (KTC, 2019) to achieve 100% pay, asphalt content should be within 0.4% of JMF for surface mixes and within 0.5% of JMF for binder mixes. VMA should be greater than or equal to the minimum VMA for the mix. Lane density should be 92%–97% for all mixes, and density of 94%–96% earns a bonus. For surface mixes, joint density is also measured, and joint density should be 90%–96.5% for full pay and 92%–96% for a bonus. Air voids should be 3.0%–4.5%, with air void content of 3.0%–4.0% earning a bonus. The KTC also has a range of specialty mixtures that have disincentives for binder content, gradation, and fineness modulus.

Louisiana

The Louisiana Department of Transportation and Development has pay factors for density and requires SMA to be at minimum 93.5% of maximum, mainline asphalt pavements to be 92.0% of maximum, and low volume pavements to be 90.0% of maximum. There is also a 50% pay reduction for using the wrong binder grade.

Maine

Maine DOT (2020) has four methods for determining pay factors. Method A within this PWL scheme uses Equation 8 for determining the pay adjustment due to density, where *PF* represents the pay factor, *Q* represents the quantity in tons, and *P* represents the price per ton. Besides density, this method uses Equation 9 to determine the composite pay factor due to air voids, asphalt content (AC), and VMA. The acceptable limits are 4.0% +/− 1.5% for air voids, 95% +/− 2.5% for density, and the target +/− 0.4% for AC. For VMA, the limit depends on the maximum aggregate size.

$$\text{PA} = (\text{density PF- } 1.0)(\text{Q})(\text{P}) \times 0.50 \tag{8}$$

$$\begin{gathered}\text{PA} = (\text{voids @ N}_{\text{design}}\text{ PF- } 1.0)(\text{Q})(\text{P})\times 0.20 \\ + (\text{VMA @ N}_{\text{design}}\text{ PF- } 1.0)(\text{Q})(\text{P})\times 0.20 + \\ (\text{AC PF}1.0)(\text{Q})(\text{P})\times 0.10\end{gathered} \tag{9}$$

Method B uses the same pay factor equations but has slightly different limits for air voids (4.0% +/− 2.0%) and AC (target +/− 0.5%). Method C uses the same Equation 8 for the density pay adjustment. However, Method C does not consider air voids or VMA, and instead uses Equation 10, which relies on gradation and AC to determine the pay adjustment. The AC acceptable limit is target +/− 0.5%, and each gradation sieve has a different acceptable range, which is +/− the allowable difference from the target.

$$\begin{gathered}\text{PA} = (\text{\% Passing Nominal Max aggregate} \\ \text{size PF-}1.0)(\text{Q})(\text{P})\text{X}0.05+(\text{\% passing } 2.36 \\ \text{mm PF}1.0)(\text{Q})(\text{P})\text{X}0.05+(\text{\%passing } 0.30 \\ \text{mm PF-}1.0)(\text{Q})(\text{P})\text{X}0.05+(\text{\%passing } 0.075 \\ \text{mm PF}1.0)(\text{Q})(\text{P})\text{X}0.10+(\text{AC PF-} \\ 1.0)(\text{Q})(\text{P})\text{X}0.25\end{gathered} \tag{10}$$

Method D utilizes price adjustments for AC, density, and % passing the 2.36 mm, 0.30 mm, and 0.075 mm sieves. The acceptable limits and corresponding price adjustments for unacceptable materials using this method are shown in Table 6. Note that there are no bonuses mentioned.

Table 6. Maine DOT Method D Acceptable Limits

Property	Specification Limits	Price Adjustment
AC	Target +/− 0.5%	−5%
% passing 2.36 mm sieve	Target +/− 5%	−2%
% passing 0.30 mm sieve	Target +/− 3%	−1%
% passing 0.075 mm sieve	Target +/− 3%	−2%
Density	95 +/− 2.5%	−10%

Maryland

Maryland DOT (MDOT, 2023) provides full pay for average lot density greater than 92% with no individual lot below 91% and applies disincentives for average lot density of less than 92%. Below 88%, the engineer may reject the material. Overall, Maryland uses a density pay factor and a composite pay factor with 62% of the weight on the asphalt content, 7% on the combined aggregate passing the #4 standard sieve, 7% on the combined aggregate passing the #8 standard sieve, and 24% on the combined aggregate passing the #200 standard sieve.

Massachusetts

Massachusetts DOT (MassDOT, 2023) uses PWL and has three parameters for HMA: air voids, density, and asphalt content. For open-graded friction course, only asphalt content affects pay adjustments, and for asphalt rubber gap-graded mixes, both asphalt content and density are used. Asphalt content should be within 0.4% for HMA and OGFC and within 0.6% for asphalt rubber gap-graded mixes. Density should always be between 91.5% and 98.5% for asphalt rubber gap-graded mixes and HMA, while air voids for HMA should be 2%–6%.

Michigan

Michigan DOT (MDOT, n.d.) uses PWL and examines air voids, asphalt content, VMA, and density. The acceptable limits vary greatly depending on which type of mix is used, of which Michigan has many and makes available in an Excel sheet. In this sheet, effective specific gravity (G_{se}) is also tracked but does not appear to affect the pay factors.

Minnesota

Minnesota DOT (MnDOT, 2020) has both incentives and disincentives for density. Minnesota DOT also applies pay deductions for unacceptable materials in terms of asphalt content, production air voids, gradation, aggregate crushing (for individual failures only), and asphalt film thickness, as described in the previous MnDOT studies. The density requirement to achieve full pay, bonuses, and disincentives depends on the design air voids and the position (longitudinal vs. mat density) as well as the traffic level.

Mississippi

Mississippi DOT (MDOT, 2017) applies disincentives for materials produced in the warning bands and outside acceptable limits, as shown in Table 7. Required density is either 92% or 93% depending on the lift within the pavement, whether the project is a single lift overlay, and if the mix is an untreated shoulder mix, and disincentives are applied for lower density, with densities less than 90% and 91%, respectively, requiring removal and replacement.

Table 7. Mississippi DOT Pay Factors

Item	Produced in Warning Bands	Produced Outside Acceptable Limits and Remaining in Place
Gradation	0.90	0.75
Asphalt Content	0.85	0.75
Air Voids	0.70	0.50
VMA	0.90	0.75

Missouri

Missouri DOT (MoDOT, 2024) uses a composite pay factor derived from density, asphalt content, VMA, and air voids. When coring is not required, the composite pay factor is derived from asphalt content, VMA, and air voids. All of these factors are weighted equally in either pay factor determination method. Missouri also has a price adjustment for tensile strength ratio (TSR) wherein a bonus is paid for TSR greater than 90% and full pay is achieved for TSR between 75 and 89%.

Montana

Montana DOT (MDT, 2024) measures the density, air voids, VMA, VFA, and dust/asphalt binder ratio as part of its acceptance testing. Pay factors are applied accordingly.

Nevada

Nevada DOT (Hale, 2017) as of 2017 uses a pay factor based on overall PWL. $PWL_{overall}$ is dictated by gradation (25%), asphalt content (33%), and density (42%). If the PWL of a specific lot is less than 60 for any measured property, the overall pay factor cannot be greater than 100%, and if the PF is less than 90%, the contractor must remove and replace the material.

New Hampshire

New Hampshire DOT (NHDOT, 2016) has a lower specification limit of −2% and upper specification limit of +2% for in-place air voids. The overall composite pay factor consists of material properties and other properties, depending on the pavement type. For HMA, gradation, asphalt content, and density are considered. Gradation and asphalt content limits depend on the NMAS, and density should be within 2% in either direction of the design for full pay. The composite pay factors for “Tier 1” pavements include the adjustments for thickness, cross slope, and ride smoothness, while “Tier 2” pavements only utilize pay factors derived from HMA properties described above.

New Jersey

New Jersey DOT conducted a study on HMA pay factors in the mid-2010s (Wang et al., 2015; Wang et al., 2016), which led to the current specification. The current specification includes pay adjustment for density for HMA and stone-matrix asphalt (NJDOT, 2019).

New Mexico

New Mexico DOT (NMDOT, 2019) requires any HMA or warm-mix asphalt (WMA) lots constructed with density below 90% and above 98% to be rejected. One hundred percent pay is given for density between 92.5% and 95.99%, while other values are assessed penalties. Air voids should be within 1.3% of the mix design to receive full pay and are rejected if the difference is more than 2%. Asphalt content must be within 0.29% of the design to receive full pay, and the material is rejected if the asphalt content deviation is more than 0.56%. VMA is also used and depends on the mix type.

New York

New York State DOT awards full pay for air voids between 2.5% and 4.5%, and bonuses for material between 2.67% and 4.33%. Disincentives are assessed for air voids outside of these criteria. It also awards bonuses and assesses penalties for gradation based on percent passing various sieves (NYSDOT, 2022). Density requirements change based on the type of compaction, but minimum density required for full pay is 93% (NYSDOT, 2024).

North Carolina

For density, North Carolina DOT (NCDOT, 2018) uses Equation 12 to determine the reduced pay factor when a penalty is applied. Pay adjustments due to other mix factors are mentioned, but no specific quantities are provided in the standard specifications.

$$PF = 100 + \frac{(Actual\ Density - Specified\ Density)}{2} * 30 \qquad (12)$$

North Dakota

North Dakota DOT (NDDOT, 2023) has a comprehensive pay factor scheme that considers mix, binder, and aggregate properties. If two consecutive gradation tests in a single day fall outside acceptable limits, the adjustment factor is applied as (100−U)/100, where *U* is the largest deviation from the acceptable limits. For asphalt content within 0.24% of the specified asphalt content in the mix design, full pay is given, while disincentives are applied when it deviates 0.24%–0.39%, and disincentives are determined by the engineer if the deviation is more than 0.4%. For density, North Dakota DOT pays bonuses when density above 93% is achieved and charges disincentives for density between 90% and 92%. Density below 90% necessitates removal and replacement. North Dakota also has pay disincentives for binder test results including the Superpave performance grading criteria and the multiple stress creep recovery test, if the binders fail any of these tests. If more than one of these binder tests are failed, the one resulting in the largest disincentive will be applied. For longitudinal joint density, fixed price adjustments are applied.

Ohio

Ohio DOT (ODOT, 2023) awards bonuses for mat density between 94.0% and 95.9% and full pay for density between 93.0% and 96.9%. For density between 90.0%–92.9% and 97.0%–97.9%, disincentives are applied and for density between 89.0% and 89.9%, the district can choose to apply a pay factor of 0.7 or require removal and replacement. For cold longitudinal joints, Ohio uses the equations in Table 8 to determine pay factors based on the percent within tolerance concept. If a lot has greater than 92.0% density on each core, a 2% maximum incentive is applied regardless of the above-mentioned method. Ohio also has disincentives for unacceptable mixes in terms of asphalt binder content and percent aggregate passing the 12.5 mm, #4, and #8 sieve sizes. The binder content should be within 0.3% of the JMF and the tolerance for gradation depends on the sieve size.

Table 8. Ohio DOT Pay Factors

Lot Percent within Tolerance	Surface Course Pay Factor
>= 90	$\frac{PWT-90}{10}*0.02+1$
61–89	1.00
50–60	$1-\frac{60-PWT}{10}*0.05$
<= 49	0.95

Oklahoma

Oklahoma DOT (ODOT, 2019) uses a composite pay factor that considers air void content as 30%, density as 40%, and asphalt content as determined by an ignition oven as 30%. Density ranging from 92% to 97% is awarded full pay, while disincentives are charged if density is between 88.1% and 91.9%, and the material is considered unacceptable if the density is above 97% or below 91.9%. Air void content should be within 1.5% of the target for full pay, and air voids differing from the target between 1.5% and 2.5% are charged disincentives. Asphalt content should be within 0.4% for full pay and ranges of 0.41% to 0.8% difference from the target are charged disincentives. Air void contents with differences more than 2.5% and asphalt contents with differences more than 0.8% from the respective targets are considered unacceptable.

Oregon

The Oregon Standard Specifications (ODOT, 2021) detail Oregon DOT's HMA composite pay factors, which are derived from asphalt content (28%), gradation (28%), and density (56%). Gradation limits are specified for all coarse aggregate bands, the No. 30 band, and the No. 200 band. Asphalt content must be within 0.5% of the mix design, and in-place density should be at least 92% as measured by a nuclear gauge. A recent report by Newcomb et al. (2016) mentioned mix moisture content based on AASHTO T329 as a factor in the composite pay factor, and although there is a limit of +/− 0.8% mentioned in the standard specifications, it was not mentioned as part of the composite pay factor.

Pennsylvania

Pennsylvania DOT (PennDOT, 2020) uses a PWL framework that considers asphalt content (30%), the percent passing the #200 standard sieve (10%), the percent passing the primary control sieve (10%), and in-place density (50%). The acceptable limits depend on the mixture NMAS, the mix type, and the lift.

Rhode Island

Rhode Island DOT (RIDOT, 2024) pays incentives for asphalt content within 0.2% of the design asphalt content and charges disincentives if the binder content deviates by 0.4% or more. If the difference is more than 0.7%, removal and replacement are required. Incentives are also paid if air voids are within 0.5% of the designed air void content, while disincentives are applied if the air voids deviate from design by more than 1%, and removal and replacement is required if the deviation is more than 3%. For mat density greater than 94%, incentives are provided, and disincentives are applied for mat density below 93%, while removal and replacement are required if mat density is less than 89%.

South Carolina

South Carolina DOT's (SCDOT, 2007) acceptable limits are listed in Table 9. Pay factors are determined based on asphalt content, gradation, and density, with the density requirements varying depending on the type of mix.

Table 9. South Carolina DOT Acceptable Limits

Parameter	Surface Course Tolerance (%)	Intermediate Course Tolerance (%)
Asphalt Content (%)	0.36	0.43
Air Void Content (%)	1.15	1.15
VMA (%)	1.15	1.15
Gradation	Depends on gradation band	Depends on gradation band

South Dakota

South Dakota DOT (SDDOT, 2015) has two pay factor attributes for "Class Q" HMA: air voids and in-place density. Air voids should range from 3%–5% while density should range from 92%–96%. Each is weighted at 50% of the total pay factor in the PWL scheme.

Tennessee

Tennessee DOT (TDOT, 2021) applies disincentive pay factors for asphalt content and gradation that are outside acceptable limits. For asphalt content, all mixes should be within 0.3% of the design to receive full pay if 1 test is run and 0.25 if two or more tests are run; mixes that fall outside of these limits are assessed disincentives. Gradation requirements depend on the sieve size. There is also a density requirement that depends on the annual average daily traffic (AADT).

Texas

The target lab-molded density in Texas is 96.5%. For dense-graded HMA, Texas DOT pays incentives for materials within 1% of this target and charges disincentives if the materials deviate from this target between 1.0% and 1.8%. Above 1.8% deviation, removal and replacement are required. For in-place air voids, incentives are provided when values are between 3.8% and 8.4%. Above 8.5% and below 3.7%, disincentives are applied. For Superpave mixes, the upper limit for density for full pay is 7.5% and for SMA it is 7.0% (TxDOT, 2014).

Utah

Utah DOT (UDOT, 2024) requires HMA density to be between 90.5 and 96.5%. Longitudinal joint density should be between 89.5% and 97.5%. For SMA, density should be between 92% and 97.5%. There are also requirements for asphalt content and gradation. For HMA, SMA, and open graded surface course, asphalt content should be within 0.35% of the target value, and gradation requirements depend on the sieve size.

Vermont

For density, the Vermont Agency of Transportation (VTrans, 2024) provides full pay when density ranges from 92.5% to 96.5%, with a bonus applied for density ranging from 93.4% to 95.4%. Vermont also applies pay adjustments for air voids. The equations to determine the overall pay factors depend on the type of project.

Virginia

Virginia (VDOT, 2020) uses asphalt content and gradation in conjunction with a “points” system to determine pay. Each gradation band or AC content that is out of the acceptable limits (within 0.27% of mix design for AC) is assessed a disincentive in terms of adjustment points, and if the total adjustment points are greater than 25 for a single lot, the material is deemed unacceptable and must be removed and replaced. For density, when control strips are not constructed, minimum density for full pay is 92.5% and 92.2% for surface and intermediate/base courses, respectively. When control strips are constructed, the density should be 98%–102% of control strip density for full pay.

Washington

Washington state DOT (WSDOT, 2024) has pay factors for VMA, air void content, gradation, asphalt content, and density. For density, the acceptable range is 92%–100%. For the other parameters, a composite pay factor is used. VMA should be no more than 0.5% lower than the minimum specified for a type of mix. Air void content should be between 2.5% and 5.5%, and asphalt content should be no more than 0.5% more or 0.4% less than the mix design. The materials-related contributions to the composite pay factors for HMA are shown in Table 10.

Table 10. HMA Pay Factor Components for Washington State

Constituent	Pay Factor
Aggregate passing #4 size and above	2
Aggregate passing #8 sieve	15
Aggregate passing #200 sieve	20
Asphalt binder content	40
VMA	10
Air Voids	20

West Virginia

West Virginia DOT (WVDOT, 2023) has a PWL scheme that considers density, asphalt content, and filler content (material passing the #200 standard sieve). For mat density between 93% and 97%, full pay is awarded. Density above 97% is left to the engineer's discretion, while density below 93% is assessed as a disincentive. For joint density, 90%–97% results in full pay while above 97% is at the engineer's discretion. For asphalt and filler contents, full pay is awarded if the PWL is 90% or greater, and disincentives are applied if they are below 90%.

Wisconsin

Wisconsin DOT (WisDOT, 2024) applies incentives for high density compared to the specification, with a bonus of $0.80 per ton for densities 1.8% higher than the requirement and $0.40 per ton when density is 1.1%–1.8% higher than required. Full pay is achieved when density is between 0.4% lower and 1.0% higher than the requirement, and disincentives are charged if the density is more than 0.4% lower than the requirement.

Wisconsin has warning bands and JMF limits for gradation, asphalt content, air void content, and VMA, although no disincentives are assessed for asphalt content; it is only used to determine if corrective action is required. Table 11 shows the associated disincentives and the acceptable limits.

Table 11. Wisconsin DOT Acceptable Limits and Pay Factors

Parameter	Disincentive Applied When Within Warning Band	Disincentive Applied When Outside JMF Limits	Acceptable Limits (compared to JMF)
Asphalt Content (%)	None	None	−0.3%
Air Void Content (%)	70%	50%	+1.3/−1.0
VMA (%)	90%	75%	−0.5%
Gradation	90%	75%	Depends on gradation band

Wyoming

Wyoming DOT (WYDOT, 2021) applies pay factors to asphalt binder based on binder properties similarly to North Dakota DOT. However, these requirements are not as restrictive as North Dakota DOT's, as they allow some variation from the Superpave requirements with full pay still awarded. For example, the dynamic shear rheometer (DSR) unaged result can be as low as 0.84 kPa and still receive full pay, compared to the Superpave criterion, which is 1.0 kPa. For asphalt content, 100% pay is provided if the value is within 0.25% of the mix design, and disincentives are applied if it is between 0.25% and 0.50% away from the design. If it deviates by more than 0.50%, the lot is rejected. For gradation, each band has specific requirements. For density, a quality index is used as defined in Equation 14, where $\bar{x}$ represents the average density in percent for the lot and s represents the sample standard deviation of the percent density. If the quality index is less than 0.00, the lot is rejected, while disincentives are applied if the quality index is between 0.01 and 1.55. Full pay is awarded for a quality index between 1.56 and 3.57, and incentives are applied for quality factors above 3.57.

$$Q_I = \frac{\bar{x} - 92.00}{s} \tag{13}$$

Other Specifications

Delaware's (DelDOT, 2024) standard specifications and special provisions do not explicitly mention a PWL scheme but do address that acceptance and pay adjustment will be judged by laboratory compaction, bulk specific gravity, theoretical maximum specific gravity, asphalt content, and gradation. Hawaii DOT (HDOT, 2005) similarly does not mention pay factors in their standard specification but does mention that density should be between 92% and 97% and has tolerances for asphalt content and gradations. Nebraska DOT (NDOT, 2017) also mentions using department software to calculate a composite pay factor based on weighted pay factors for each type of asphalt concrete and each pay factor, including density and smoothness.

Summary

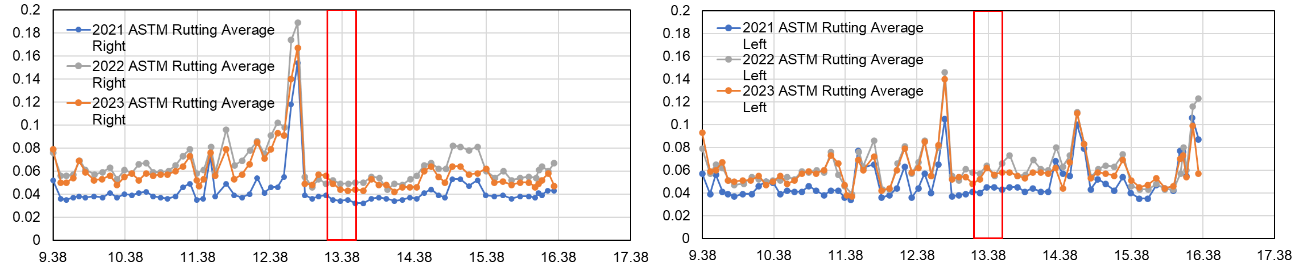
Overall, the vast majority of state DOTs have moved toward PWL schemes and many use parameters similar to IDOT. However, some have varying schemes and have implemented other criteria in pursuit of better overall material quality. Although many specifications do outline their logic, many are not based on individual DOT research and instead focus on conventionally known values such as 7% density at compaction. Therefore, further study is warranted to determine the effect of these quality parameters on actual pavement performance. The following chapter uses a few known sections to perform this type of analysis.

CHAPTER 3: IDOT CONSTRUCTION DATA ANALYSIS

With the help of the Technical Review Panel, the research team identified 13 projects of interest in terms of the performance of materials that were deemed unacceptable at placement. Each project is discussed in detail below, and then initial thoughts related to these projects are presented. The goal of this task was to identify any possible relationships between parameters that cause disincentives to be assessed and the initial performance of pavements. Note that only surface lifts were considered for the purpose of this task, due to the inability to core and test underlying materials. In addition, only International Roughness Index (IRI) and rut depth were considered at the present time, since these projects were all recent and cracking was very unlikely to be observed. IRI is a common measure of pavement smoothness, in which a lower value represents a smoother pavement surface and better ride quality. Note that 1 of the 13 projects was a shoulder mix, so it is not included in the analysis, because IRI and rut depth data were not available for the shoulder. The results are still shown for completeness. Condition Rating Survey (CRS) data were also investigated, but only in terms of project level, as CRS data for more granular spots were not available.

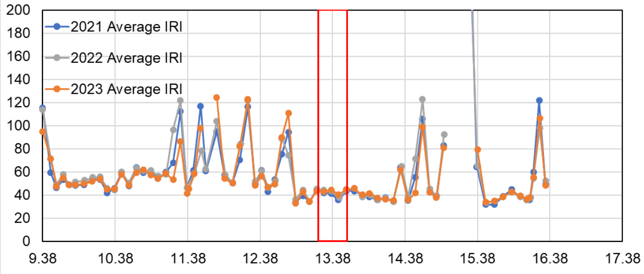
RUT DEPTH AND IRI DATA

Project 1 had a sublot with unacceptable density, at which density was too high (98.4%; higher than the upper limit of 98%). Figure 2-a and Figure 2-b show the rutting average for the right and left wheel path, respectively, and Figure 2-c shows the average IRI for the project over three years. The spot with high density and the preceding and following 0.2 miles are highlighted by a red box. For this project, there is not any visible influence of the unacceptable material on either parameter. Note that this project used stone-matrix asphalt and had the highest average daily traffic (Table 12) of any project in this study.



(a) Rutting average (right wheel path)

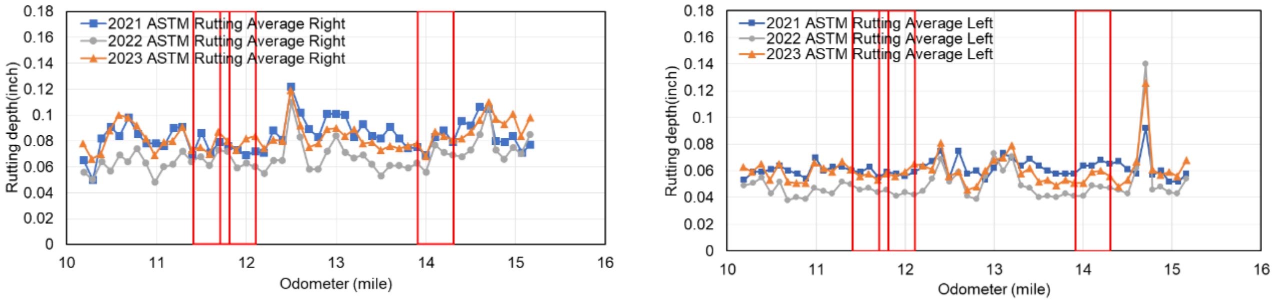
(b) Rutting average (left wheel path)



(c) Average IRI

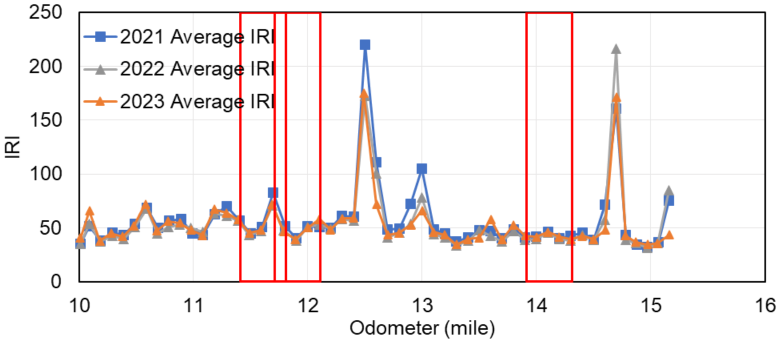
Figure 2. Plot. Project 1 rut depth and IRI.

Project 2 had five sublots with unacceptable density, at which density was too low. This was an SMA project, so it was expected to have density above 92%, but these five sublots measured between 89.3 and 91.5%. Figure 3-a and Figure 3-b show the rutting average for the right and left wheel path, respectively, and Figure 3-c shows the IRI for the project over three years. The spots with low density and the preceding and following 0.2 miles are highlighted by red boxes. Again, low density spots in this project did not appear to have short-term impacts on pavement performance.



(a) Rutting average (right wheel path)

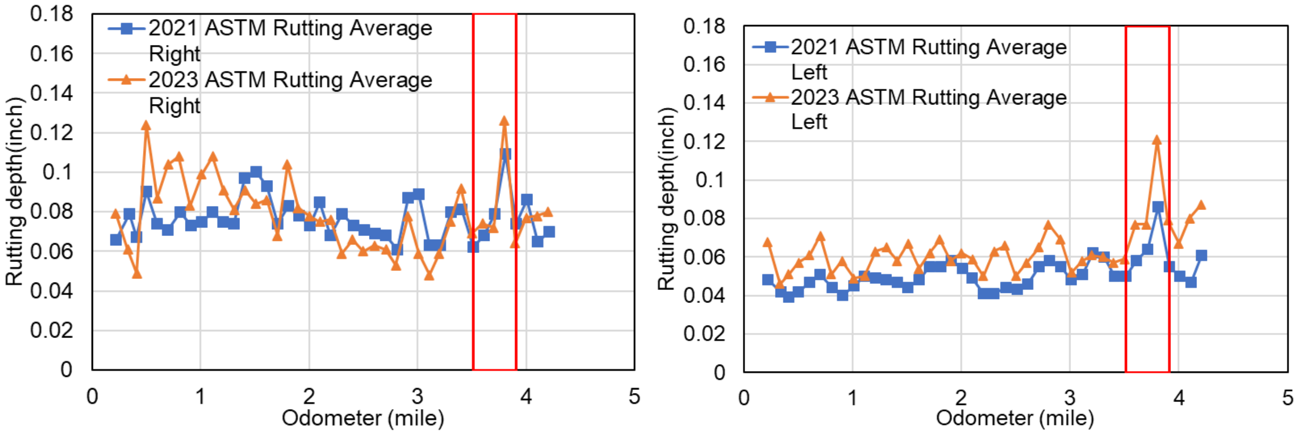
(b) Rutting average (left wheel path)



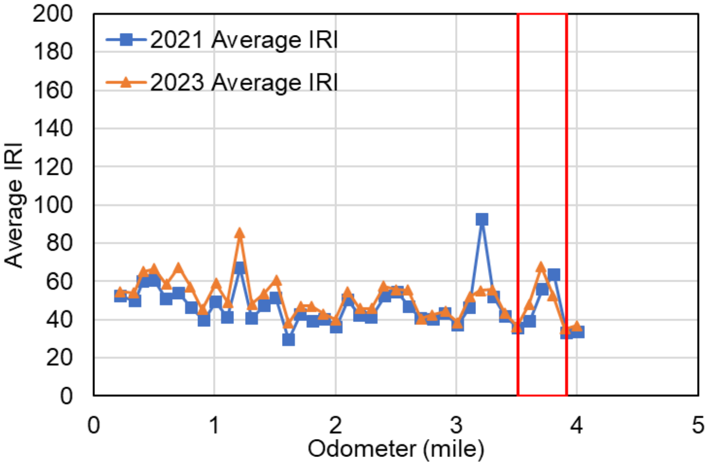
(c) Average IRI

Figure 3. Plot. Project 2 rut depth and IRI.

Project 3 had a sublot with unacceptable density, at which density was too low (89.5% compared to the allowable 90% for dense-graded HMA). Figure 4-a and Figure 4-b show the rutting average for the left and right wheel path, respectively, and Figure 4-c shows the IRI for the project over two years. The spot with low density and the preceding and following 0.2 miles are highlighted by a red box. Local peaks in rut depth and IRI were observed close to the point at which the unacceptable material was placed. However, IRI did not appear to be substantially affected despite a small local peak and was good overall.



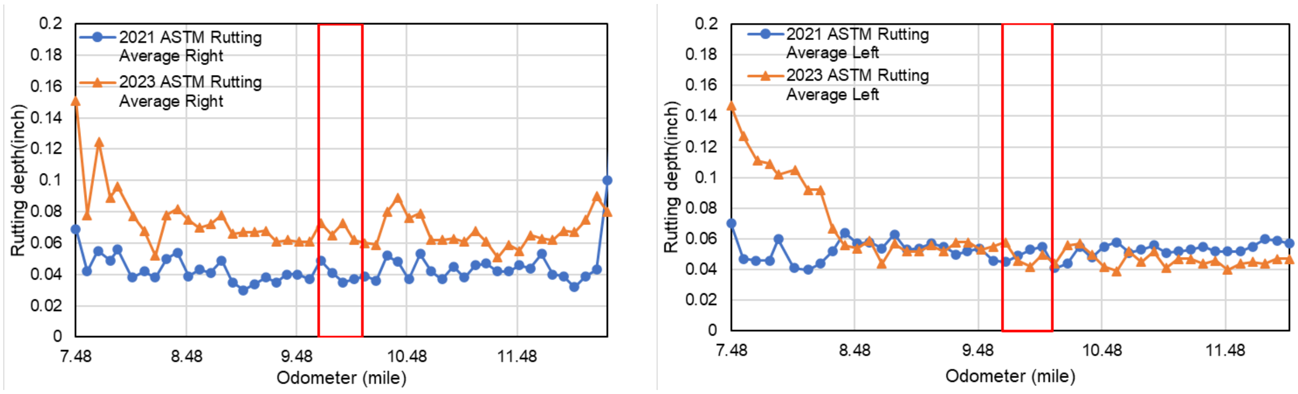
(a) Rutting average (right wheel path) (b) Rutting average (left wheel path)



(c) Average IRI

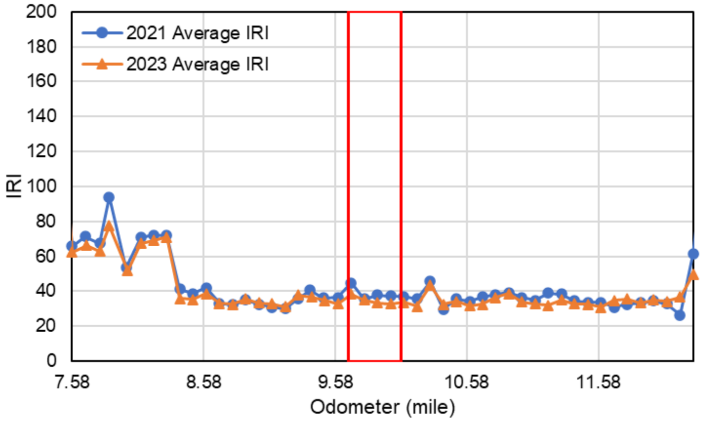
Figure 4. Plot. Project 3 rut depth and IRI.

Project 4 had a sublot with unacceptable air voids, at which air void content was too high (6.4%, which is higher than IDOT's maximum of 6%). Figure 5-a and Figure 5-b show the rutting average for the left and right wheel path, respectively, and Figure 5-c shows the IRI for the project over two years. The spot with high air voids and the preceding and following 0.2 miles are highlighted by a red box. No substantial differences in rut depth or IRI were observed in these parts of the project.



(a) Rutting average (right wheel path)

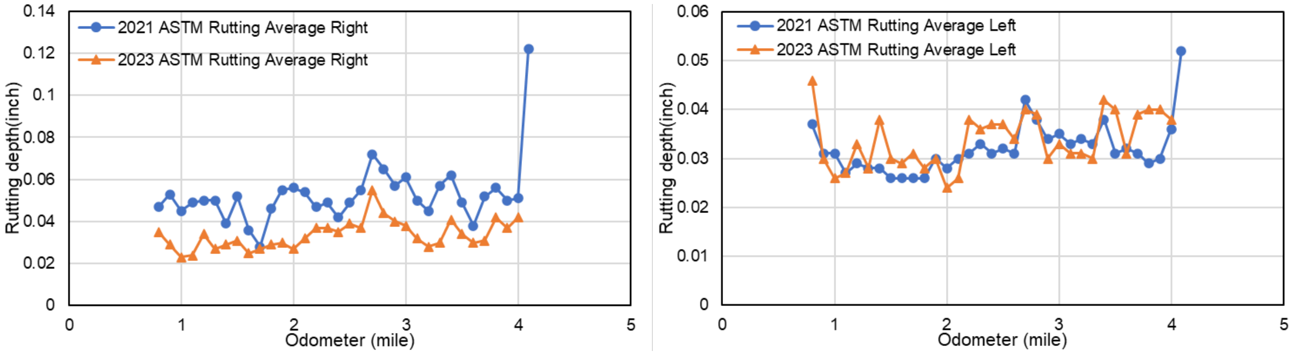
(b) Rutting average (left wheel path)



(c) Average IRI

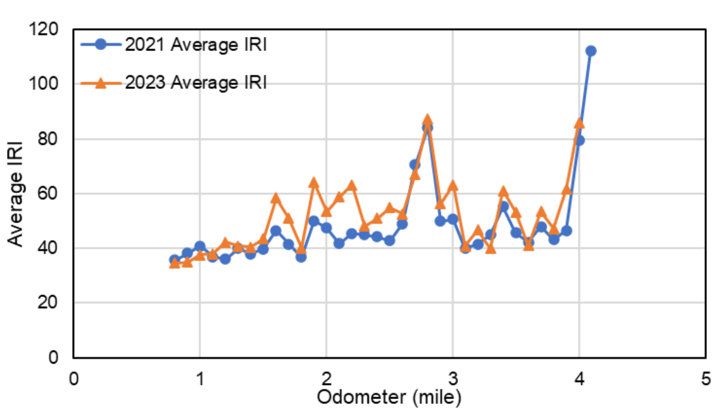
Figure 5. Plot. Project 4 rut depth and IRI.

Project 5 had a sublot with high density (98.5% compared to IDOT’s maximum of 98%) right at the end of the project. Figure 6-a and Figure 6-b show the rutting average for the left and right wheel path, respectively, and Figure 6-c shows the IRI over two years. At the final point of the project, a substantial increase in IRI was observed. However, note that these types of peaks were observed in IRI testing in many sections, even those with no unacceptable materials, and may be a result of the test method which sometimes yields outlier values at end points of the measurements. The 2021 rut depth data also have a substantial increase at the same point, but this was not observed in the 2023 data, which were mostly lower than 2021, so it is also possibly erroneous.



(a) Rutting average (right wheel path)

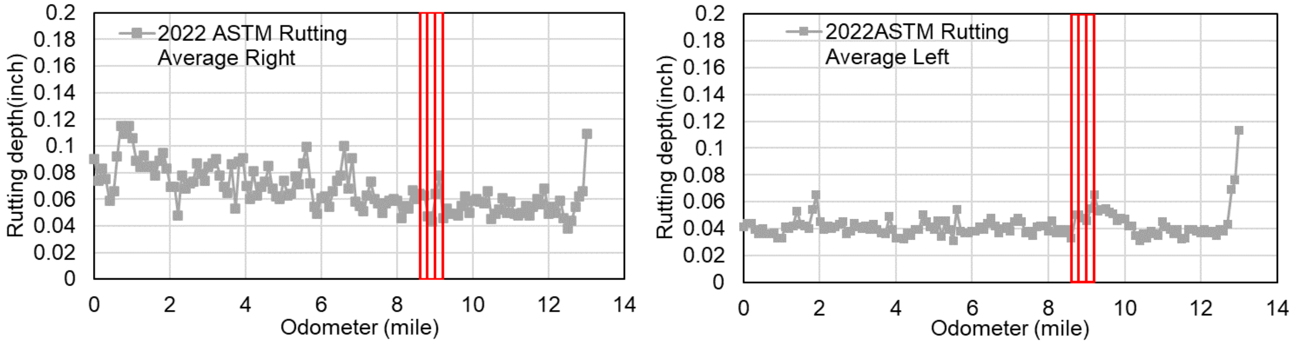
(b) Rutting average (left wheel path)



(c) Average IRI

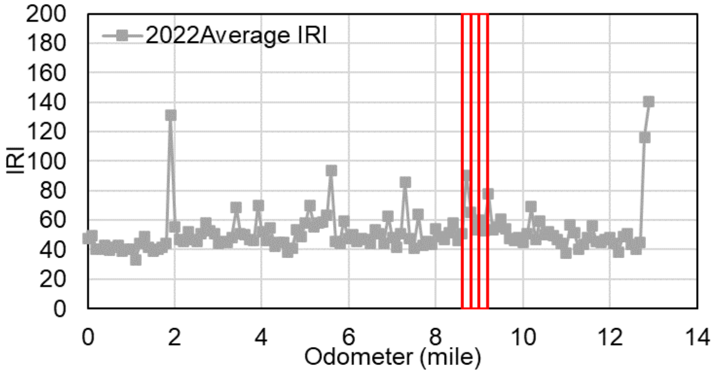
Figure 6. Plot. Project 5 rut depth and IRI.

Project 6, a dense-graded mix, had two sublots with unacceptable density, at which density was too low (89.4% and 89.0% compared to IDOT’s minimum of 90%). Figure 7-a and Figure 7-b show the rutting average for the left and right wheel path, respectively, and Figure 7-c shows the IRI for the year 2022, which was the only one available. The spots with low density and the preceding and following 0.2 miles are highlighted by a red box. While there are some spikes locally at these points, the overall data are difficult to discern and are broken down further below.



(a) Rutting average (right wheel path)

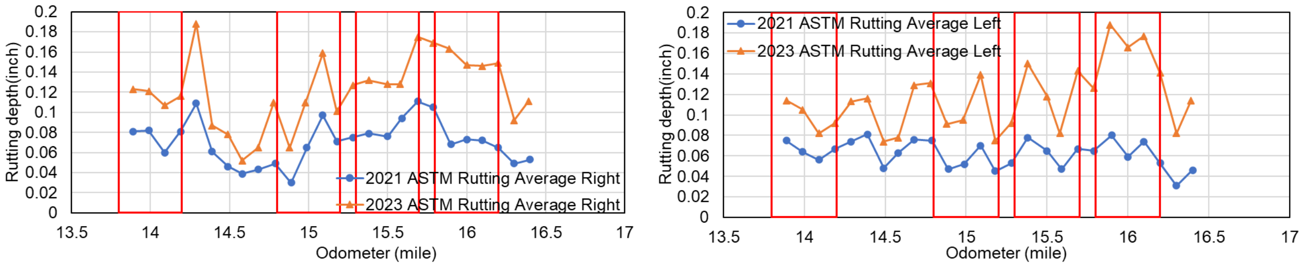
(b) Rutting average (left wheel path)



(c) Average IRI

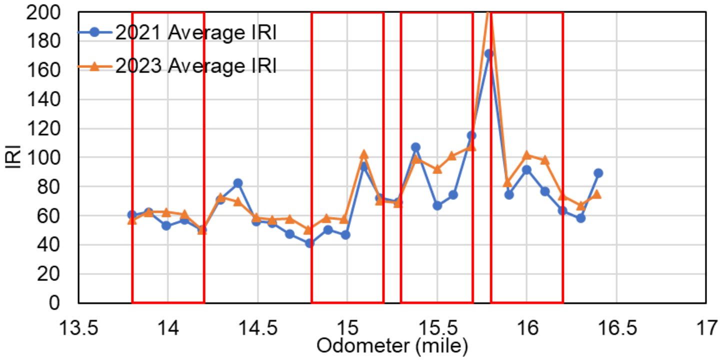
Figure 7. Plot. Project 6 rut depth and IRI.

Project 7, a dense-graded mix, had five sublots with unacceptable density, at which density was too low. Density in these sublots ranges from 89.2% to 89.7% while IDOT's minimum is 90%. Figure 8-a and Figure 8-b show the rutting average for the right and left wheel path, respectively, and Figure 8-c shows the IRI for two years, 2021 and 2023. The spots with low density and the preceding and following 0.2 miles are highlighted by a red box. While there are some spikes locally at these points, the overall data indicate that IRI and rut depth are overall very high. Further individual project-level analysis is presented below.



(a) Rutting average (right wheel path)

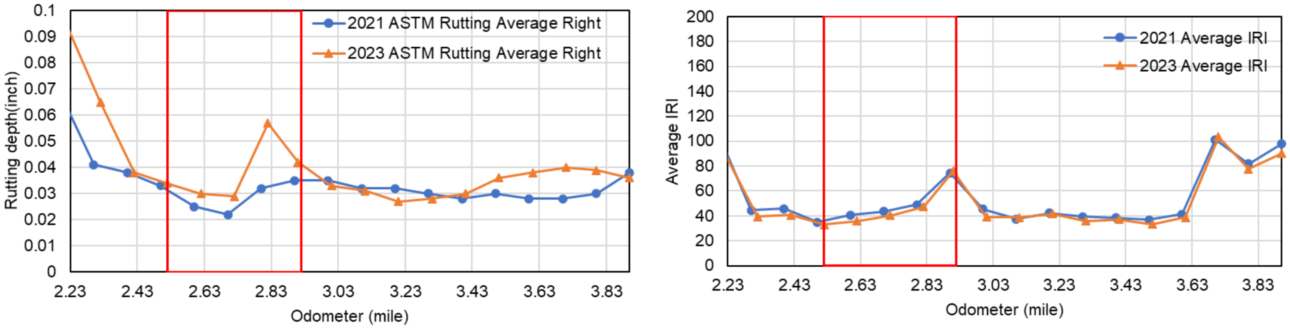
(b) Rutting average (left wheel path)



(c) Average IRI

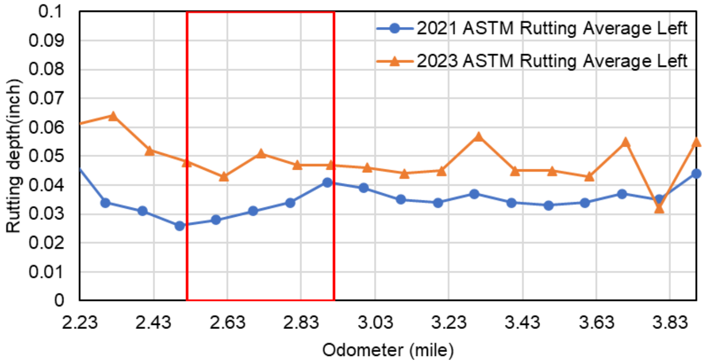
Figure 8. Plot. Project 7 rut depth and IRI.

Project 8 had one unacceptable sublot that had low VMA of 13.9%. Figure 9-a and Figure 9-b show the rutting average for the left and right wheel path, respectively, and Figure 9-c shows the IRI for two years, 2021 and 2023. The spots with low VMA and the preceding and following 0.2 miles are highlighted by a red box. Overall, not much substantial change in rut depth was observed, which is expected because low VMA is typically related more to cracking resistance. However, there was an IRI spike near the unacceptable material. This could be related to the unacceptable material due to cracking or raveling. Therefore, it is recommended to further monitor this section and conduct experiments on extracted material from this location.



(a) Rutting average (right wheel path)

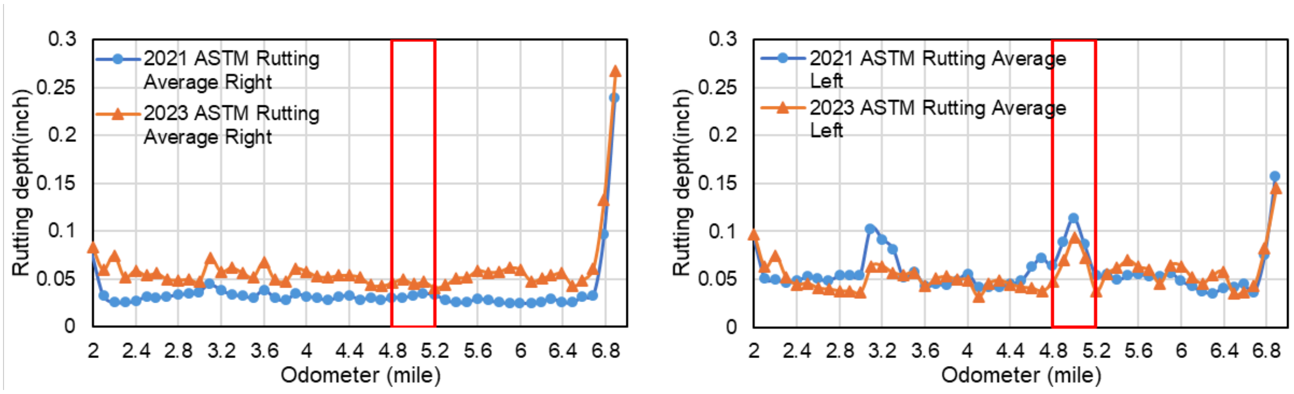
(b) Rutting average (left wheel path)



(c) Average IRI

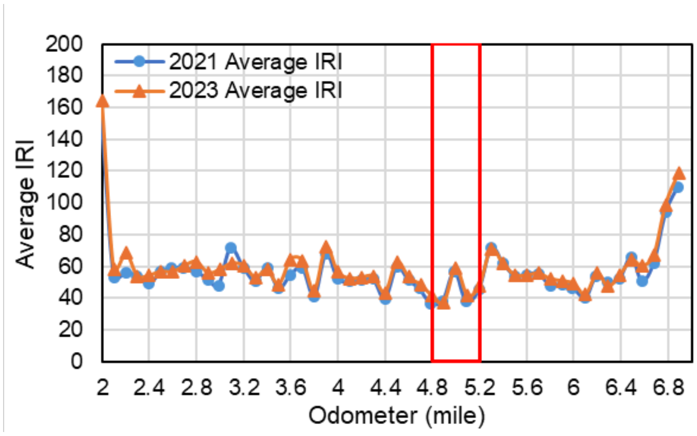
Figure 9. Plot. Project 8 rut depth and IRI.

Project 9 had one unacceptable sublot that had high air void content of 6.4% compared to IDOT's maximum of 6%. Figure 10-a and Figure 10-b show the rutting average for the left and right wheel path, respectively, and Figure 10-c shows the IRI for two years, 2021 and 2023. The spots with low air voids and the preceding and following 0.2 miles are highlighted by a red box. Overall, there was not much of a substantial difference observed at this location.



(a) Rutting average (right wheel path)

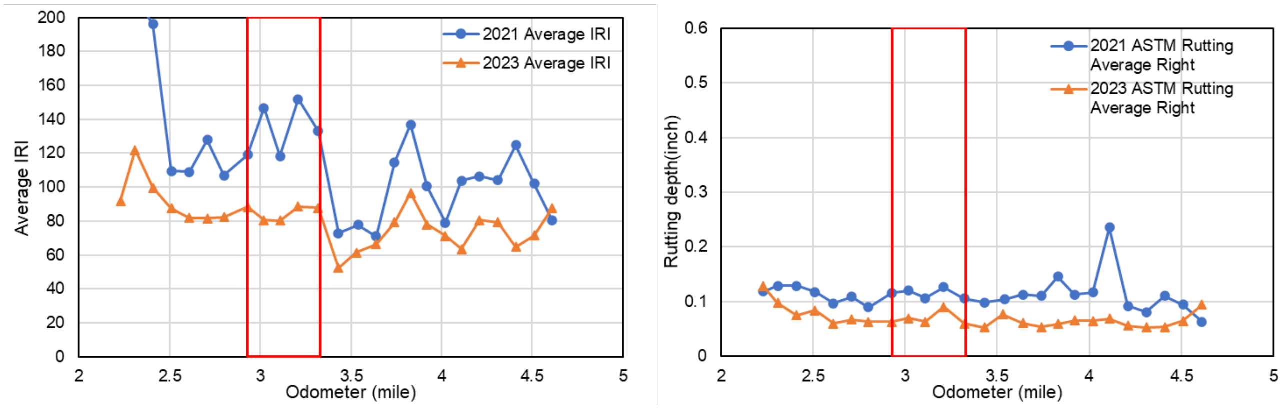
(b) Rutting average (left wheel path)



(c) Average IRI

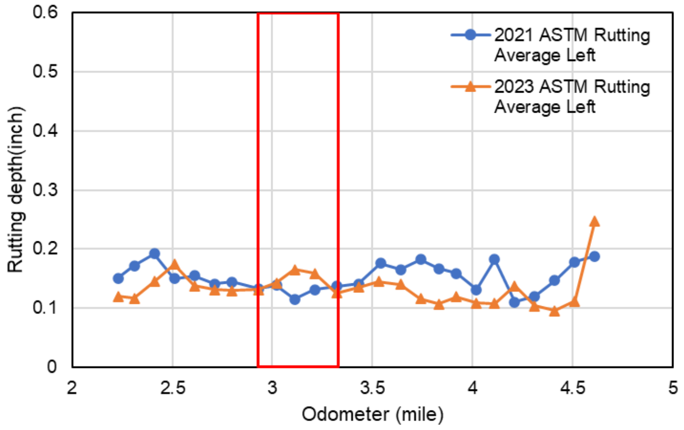
Figure 10. Plot. Project 9 rut dept and IRI.

Project 10 was a surface maintenance at the right time (SMART) overlay, where the unacceptable material was in a shoulder mix. This material had low VMA at 13.6%. It was not possible to tell via rut depth and IRI data if the influence of the unacceptable material was significant because these materials were on the shoulder where measurements are not taken. However, the data and the coordinates at which this material occurred are shown in Figure 11. Note that both rut depth and IRI were very high for these sections overall.



(a) Rutting average (right wheel path)

(b) Rutting average (left wheel path)



(c) Average IRI

Figure 11. Plot. Project 10 rut depth and IRI.

CONDITION RATING SURVEY DATA

For each project, the CRS was determined to better understand if the presence of unacceptable sublots had any adverse impact compared to projects without unacceptable material. IDOT CRS is rated on a scale of 0–9 and serves as an overall indicator of pavement surface condition. Table 12 shows the CRS of each project, along with the project number and the average annual daily traffic of each project. Note that some values in Table 12 have more than one value because the project includes multiple groups of data. Also, note that Table 12 contains two projects for which granular data could not be obtained because of a mismatch in terms of GPS coordinates. However, overall CRS was considered since it was known there were unacceptable materials. Project 12 is performing well, but note that for Project 11, CRS was low quite early in the service life, especially given the low traffic levels and truck traffic on this route. Overall, the results indicated that there is not often an impact of this point of unacceptable materials in terms of CRS very early in the service life, given that all but two projects had excellent CRS values.

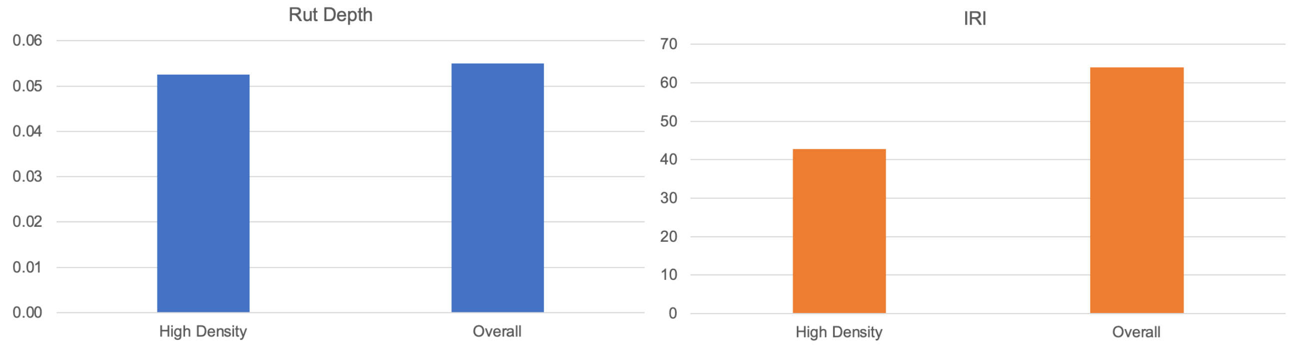
However, it is worth noting that these projects are all recently paved. Therefore, there is not sufficient time to evaluate the impacts that these parameters have, and unacceptable materials are thought to reduce overall pavement life. Therefore, a careful tracking protocol is proposed in Chapter 4 to determine how best to evaluate these sections and others with failing materials both at present and in the future.

Table 12. CRS of Each Project Studied

Project	Year Placed	Condition Rating Survey	Average Annual Daily Traffic	Percent Truck Traffic
1	2020	8.0	43,400	15.0%
2	2020	7.4	25,200	33.9%
3	2020	8.9	1,450	20%
4	2020	8.9	1,850	24.6%
5	2019	8.4	2,750	8.4%
6	2021	8.4	2,000–2,250	14%
7	2020	8.8	5,550–13,200	13.8%
8	2020	8.9	4,350	9.8%
9	2020	8.6	8,050	7.5%
10	2021	6.4	49,200	16.0%
11	2020	6.5	4,300	6.8%
12	2019	8.4	21,400	5.6%

DATA SUMMARY AND ANALYSIS

In order to properly compare project-level data with specific spots of interest, the research team checked, for each type of unacceptable material, what the local rut depth and IRI were compared to project-level data. Relevant projects are shown below. Figure 12 shows this comparison for Project 1, which had high density. Note that the values shown in this chart are the three-year averages for rut depth and IRI for the local sublot data and the two-year averages for the overall project data. These sublots actually performed slightly better than the rest of the project. Two other high-density sections were included in this project; however, one was the end point for which data may be skewed, and the other had an incorrect location marker.

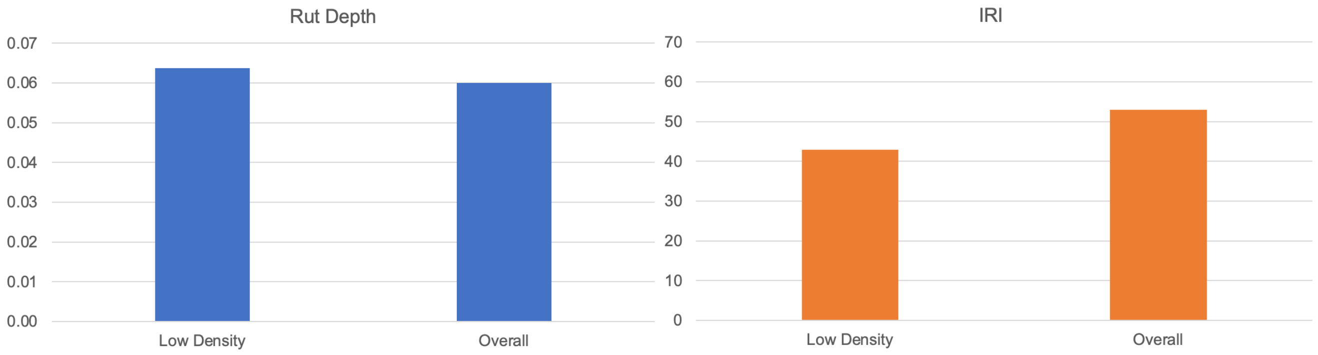


(a) Rut depth

(b) IRI

Figure 12. Graph. Comparison of high-density sublot to entire project for Project 1.

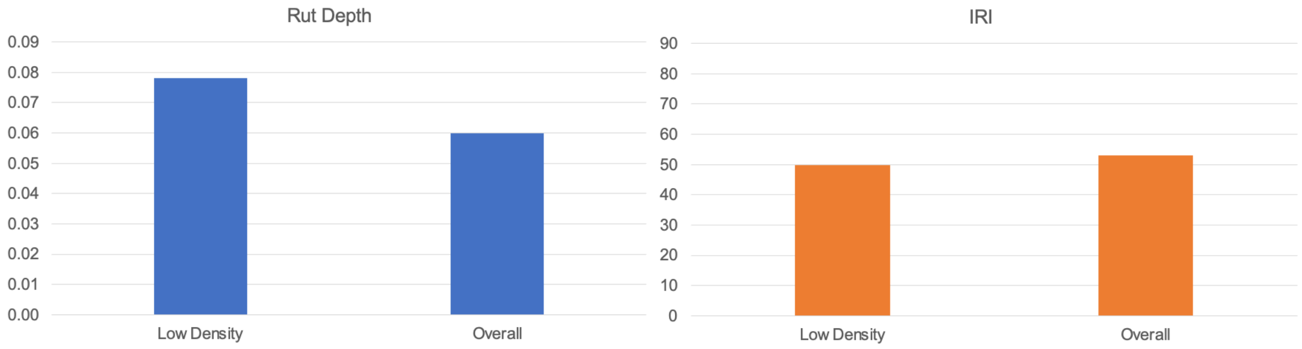
Figures 13–16 show the average rut depth and IRI across the years measured for Projects 2, 4, 6, and 7, respectively, which had sublots with low density. In all four cases, low density appeared to impact rut depth adversely, causing an increase in rutting. This was especially true for two projects that showed substantial differences. In terms of IRI, the difference was less clear, with two sections showing higher values and two showing lower than the project overall when density was low.



(a) Rut depth

(b) IRI

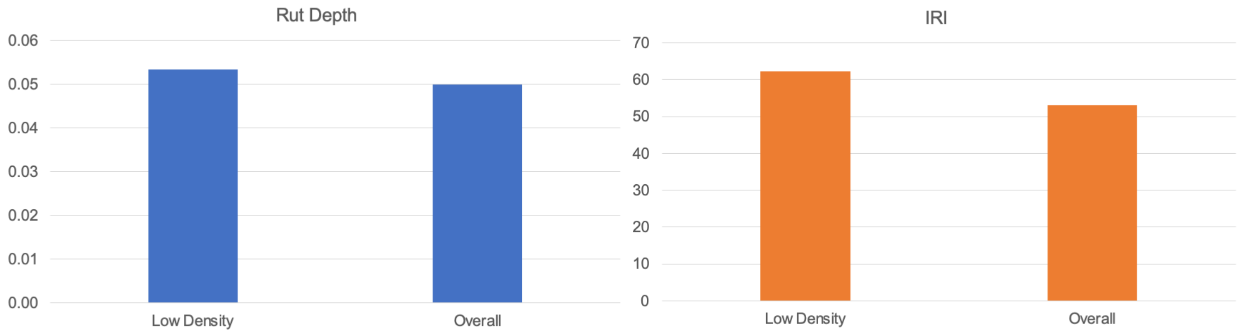
Figure 13. Graph. Comparison of low-density sublots to entire project for Project 2.



(a) Rut depth

(b) IRI

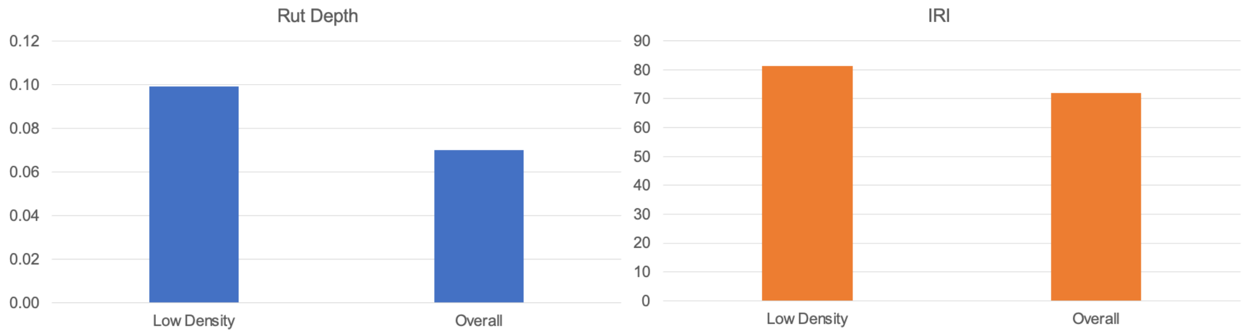
Figure 14. Graph. Comparison of low-density sublots to entire project for Project 4.



(a) Rut depth

(b) IRI

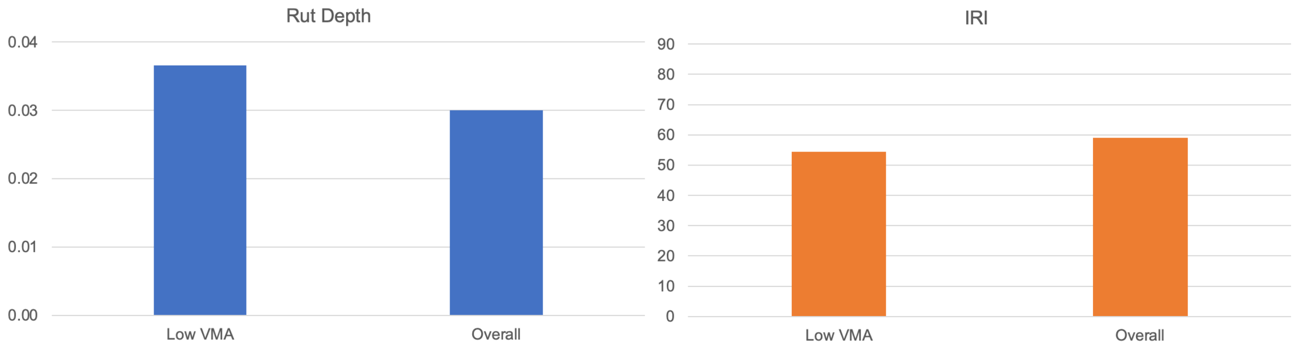
Figure 15. Graph. Comparison of low-density sublots to entire project for Project 6.



(a) Rut depth (b) IRI

Figure 16. Graph. Comparison of low-density sublots to entire project for Project 7.

Figure 17-a and Figure 17-b show the average rut depth and IRI, respectively, across the years measured for Project 8, which had one sublot with low VMA. The rut depth was higher for the low VMA sublot, and IRI was about the same, with the overall IRI being slightly higher than the low VMA sublot. However, the rut depth result is not necessarily expected, as low VMA is not known to be an indicator of poor rutting resistance.



(a) Rut depth (b) IRI

Figure 17. Graph. Comparison of low VMA sublots to entire project for Project 8.

CHAPTER 4: SUMMARY AND CONCLUSIONS

This project conducted a thorough review of existing literature and specifications that govern acceptable quality assurance parameters for various agencies. In addition, the research team identified 12 projects of interest and analyzed 10 of these projects from IDOT in which unacceptable hot-mix asphalt was placed and allowed to remain in place. The main findings of this study are as follows:

- A review of all 50 states’ standard specifications and special provisions indicated that most states use some combination of asphalt content, air voids, gradation, and in-place density to determine appropriate pay factors for HMA. Fewer states include VMA, but it is still a fairly standard parameter, which can also be substituted for film thickness in some cases. A few states include other parameters such as binder properties and moisture content, but these are rarities. In general, limits are similar in terms of value between different states, although some states offer incentives, and some do not for various parameters.

- Despite most states having relatively similar specifications, few studies have been conducted to ensure these limits are representative of the effect of QA parameters on pavement performance. The few studies that have been conducted, however, have shown good relationships between meeting these parameters and pavement service life. It is also important to emphasize that, to the research team’s knowledge, no experimental studies have been conducted to determine the effects of acceptable limits since the inception of the Superpave mix design.

- Low density appeared to relate to premature rutting and higher IRI values overall. The overall effect of the materials falling outside of other acceptable limits depended largely on the project in terms of rut depth and IRI. It stands to reason that these parameters can have substantial effect on the life of a pavement; however, it is worth noting that the parameters assessed in this study were not always significant. It is also important to note that the data were very preliminary since all projects in this study were recently paved. Future work is needed to determine the actual effects of these unacceptable materials on performance.

- CRS data did not show any substantial impact from unacceptable parameters. It is postulated that much longer time scales are needed to see project-level effects of unacceptable materials.

It is the opinion of the research team that further research be conducted to determine the appropriateness of existing acceptable limits, incentives, full pay, and disincentives for HMA materials. Note that incentivized and compliant materials have not yet been studied, as this study focused on non-compliant materials. Therefore, the research team proposes a comprehensive field study based on the forthcoming IDOT pavement management and evaluation manual. All data from all projects (those having incentives, full pay, disincentives, and outside acceptable limits) on all roadways throughout the state using the methods discussed in the manual would need to be compiled. As this is a forthcoming manual, data would need to be collected over the course of at least one, if not two, HMA overlay life spans per roadway to have a comprehensive dataset for a review to begin. Finally, the research team conducted a field inspection with IDOT personnel as part of this study, which can be continued at the locations of specific locations of interest, as well as monitoring annual IRI, rutting, and CRS data to assess the deterioration of materials that were unacceptable. These results would allow for more comprehensive understanding of the performance of unacceptable materials and over a shorter time frame.

Regarding a framework for IDOT to conduct future field monitoring of HMA sublots for better understanding, it is recommended that IDOT develop a database for this purpose that includes unacceptable, acceptable, and incentive-earning sublots. The research team recommends future research to determine which data should be collected and how it should be collected outside of field cores, to ensure the data is ready for analysis and will lead to beneficial outcomes for IDOT.

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