DEPARTMENT OF TRANSPORTATION

Understanding and Improving Pavement Milling Operations

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16. Abstract (Limit: 250 words)

Asphalt milling is an essential construction activity. It requires concentrated high-intensity applications of force to the existing pavement to remove the asphalt material. The impact that the induced stresses have on the pavement below the mill line is unknown. Consequently, selected milling parameters rarely consider the impact the milling may have on the remaining layers. This study evaluates milling parameters to provide an enhanced understanding of their impacts on the layer directly below the mill line. Five parameters were evaluated and include the time between milling and post-mill overlay construction, existing pavement structure, temperature while milling, depth of milling relative to layer interface, and rotor speed. Pre- and post-milling cores were collected adjacent to each other and evaluated for physical and mechanical properties. The measured properties of the pre- and post-milling cores were statistically compared to determine the impact of milling operations on the integrity of the asphalt concrete immediately below the mill line. Based on the results from this study, it was determined that leaving milled pavement exposed for longer periods of time or milling at cooler temperatures can cause a decrease in the strength of the layer below the mill line and a decrease in the expected pavement life of the new pavement structure. The depth of milling or changing the rotor speed while milling did not have significant impacts on the layer directly below the mill line. In consideration of the results of this study, research with a wider variety of pavements and milling conditions is warranted.

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Asphalt Pavement Milling Best Practices through Enhanced Understanding of Milling Process

Final Report

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TABLE OF CONTENTS

List of Figures

List of Tables

Executive Summary

Milling of asphalt pavements is a commonly used technique in many cases of maintaining and rehabilitating roadways. It is implemented frequently in circumstances where a pavement is experiencing functional distresses, but not substantial structural distresses. This is because it involves partial to full removal of the HMA layer, leaving the remaining layers in place. Generally, an overlay is then placed on top of the milled structure. This way, the functional distresses in the pavement are addressed, and in a more economical and sustainable manner than repaving and replacing the entire structure.

The possible disadvantage of implementing milling operations is the potential it has to cause harm to the layers below the mill line due to it being a relatively high-stress activity. Presently, this potential is rarely taken into consideration when selecting milling parameters. Instead, milling parameters are often selected based on cost, past routine, and the existing pavement's state. In this study, the impact of implementing different milling parameters on the pavement layer directly below the mill line was evaluated. Five milling parameters were assessed in this study, each with multiple variations: the pavement temperature at the time of milling, the amount of time between milling and post-mill overlay construction, the depth of milling relative to the layer interface, the structure of the existing pavement, and milling operational parameters such as rotor speed. To compare the impact of the different milling parameters on the layer directly below the mill line, pre- and post-milling cores were collected under each milling parameter variation. The pre- and post-milling cores were then trimmed to represent the equivalent layer directly below the mill line. These cores were then evaluated in the laboratory to measure specific gravity, permeability, resilient modulus, and indirect tensile strength. A statistical analysis was then performed to compare the equivalent pre- and post-milling cores to determine if the milling operations inflicted a significant impact on the physical or mechanical properties of the pavement layer directly below the mill line.

The results from this analysis determined that performing milling operations and then leaving the milled pavement exposed to traffic and weather for extended periods, can cause the strength of the layer directly below the mill line to decrease significantly. In comparison, the results from the conditions evaluated in this study showed that there are not consistent significant differences between pre- and post-milled pavement layers' structural and volumetric properties due to the differences in the pavement structures (which also considers different pavement ages and conditions) evaluated, the depths of milling relative to the layer interface evaluated, or the rotor speeds evaluated. Based on the limited amount of testing conducted in this study, milling at cooler pavement temperatures can cause a significant decrease in the indirect tensile strength of the HMA that remains below the mill line. There is a likely interaction effect of the pavement temperature while milling and the strength of the remaining layers, therefore causing a resultant effect on the post-milled pavement. Further research efforts that include evaluation of milling under various pavement temperatures are needed to confirm these preliminary outcomes and determine if there is a need to develop guidelines for minimum allowable milling temperature.

Chapter 1: Introduction

Asphalt milling is an unavoidable, commonly used alternative used for pavement maintenance and rehabilitation to extend a pavement's life. Asphalt milling is an appropriate process for pavements with surface damages such as cracking, raveling, or uneven slope. In most of the cases, the base is still strong, and a full-depth reclamation and repaving is not required. As an alternative, the top-most layers that have distresses can be removed using a cold planning or milling machine and be substituted and/or overlaid with a new hot mix asphalt (HMA) layer. The operation involves removal of part of a layer from the pavement up to the removal of a full HMA layer for functional or structural repair purposes.

Milling is a high-energy activity that may induce high-stress damage below the milling line. This can lead to cracking and loss of material that makes the new pavement more vulnerable to reflective cracking after placing the overlay and to moisture damage, thereby causing premature failure. Current asphalt milling operations follow typical or experience-based practices based on existing distress conditions and budgets; they have minimal consideration for existing pavement properties (e.g., mix type, type of interface with the underlaying layer) or operational parameters (e.g., speed of milling) with respect to the milling depth. The chosen milling depth may not be appropriate for the actual conditions and the process has the potential to leave crushed, cracked, or missing aggregates on the milled pavement (scabbing is one of these aspects). The ratio of the milled thickness to the remaining thickness significantly affects the life of the pavement. Scabbing or delamination, which is a common issue in milling, occurs when the milling depth is less than the depth to the layer interface. Currently, there is little to no consideration of the impact that milling parameters may or may not have on the HMA layer that remains below the mill line, as depicted in Figure 1-1 below. Therefore, there is a need to understand milling operations and understand their effects on pavements and overlay performance by studying several parameters that are involved in causing stresses below the mill line. These parameters can be divided into two categories:

1. Milling operation variables: milling depth, milling speed (ft/minute), drum rotational speed, drum diameter, teeth geometry and configuration, and teeth condition.
2. Pavement variables: mixture type, gradation, mixture stiffness (related to gradation, temperature, age of pavement, and binder grade), layer thickness, and interface bond type.

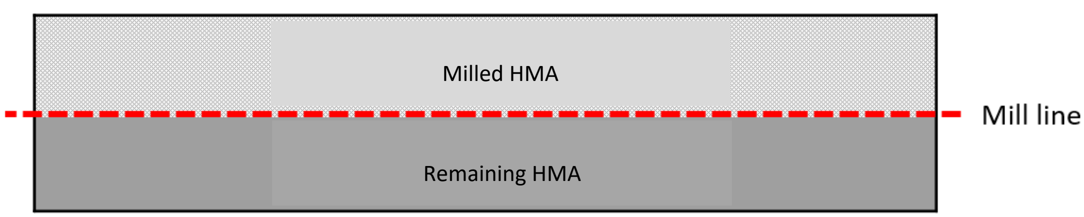


Figure 1-1 Mill Line Description

The objective of this project was to study the impact of specific milling parameters on the pavement layer directly below the mill line. To do this, pre-milling and post-milling cores were collected adjacent to each other. These cores were then evaluated in the laboratory for bulk specific gravity, permeability, resilient modulus, and indirect tensile strength to determine if there were differences to the HMA, pre- and post-mill. The laboratory testing results were then compared.

This Final Report serves as the deliverable for Task-7 of the National Road Research Alliance study titled *Understanding and Improving Pavement Milling Operations*. This report is a compilation of all previous tasks performed for this project and discusses the literature review, state of the practice, review of milling specifications, MnROAD pavement study sections used to obtain field samples, and laboratory testing methods and results, along with data analysis results and conclusions.

Chapter 2: Literature Review

Pavement milling has become a routine activity in the US and most parts of the world for asphalt pavement maintenance, rehabilitation, and construction. This activity, which generally constitutes about 20% of the pavement construction budget, is critical for ensuring sustainable pavements. It ensures the removal of the existing pavement in a safe and accurate manner and the procurement of the old materials for recycling. The purpose of this section is to present a state-of-the-art review of milling in asphalt pavements. This section presents the necessity of milling, procedures and equipment, different types of milling, and currently available research on milling.

Milling is defined as a process that removes materials from an existing asphalt pavement (that is slated to be maintained, rehabilitated, or reconstructed) to provide a suitable platform on which to build the new overlay pavement structure (Dunn and Cross, 2001) or to reconstruct the roadway. The method of pavement milling was developed in the 1960s by Wirtgen in Germany (Volk, 2016), first through concrete breaking machines (1960s), then through heated mix removal/recycling (1970s), and finally through cold milling (1980s). Since then, milling of asphalt pavement layers has become a commonplace activity in pavement preservation projects all over the world because of its many advantages, namely the ability to maintain the geometry of roads and utility structures, improve clearances for bridge structures on highways, and the recovery of Reclaimed Asphalt Pavement (RAP) (Kandhal and Mallick, 1997).

Milling is the most widely used method for the recovery of RAP from old pavements, prior to the placement of a new overlay (West, 2015). RAP is one of the most recycled materials (82.2 million tons, 46.8% increase in 2018 compared to the total estimated tons of RAP used in 2009) in infrastructure construction (Williams et al., 2019). Recycling of RAP in such amounts leads to significant savings in the use of virgin mineral aggregates (a natural resource) and asphalt binder (a petroleum product whose price fluctuates with that of crude oil), and hence to a significant amount of conservation of our natural resources.

The upper layers of most pavements, either on roadways or airfields, are made up of asphalt mixes or Portland Cement Concrete (PCC). Most of the pavements in the world are surfaced with asphalt mixes, or what is commonly known as hot mix asphalt (HMA). The primary components of these mixes are asphalt binder (bitumen) and mineral aggregates. After construction, as a result of the combined action of traffic and the environment, a pavement deteriorates, and ultimately reaches a point where it needs maintenance or rehabilitation (M/R). When designed and constructed properly, this expected progressive degeneration is due to the generations of stresses and strains at different depths, resultant formation of fatigue cracks and/or permanent deformation (rutting), or deterioration of surface properties such as texture, which are related to roughness/smoothness, and friction.

Application of a new layer (overlay) of HMA on the existing degenerated pavement increases the overall thickness of the pavement, which necessitates the relocation of drainage and other structures (such as guardrails) and can also reduce the overhead clearance under bridges. Furthermore, the existence of cracks and ruts underneath the new overlay causes reflection cracks or premature failure of the pavement. Therefore, one good option is to remove the existing deteriorated layer and place a new layer in its place. Before the advent of the milling machine, the only option to remove existing pavement layers was the use of scarifies, dozers, or earthmoving equipment fitted with ripper teeth (Figure 2-1).

Figure 2-1 Dozer with Tipper-Tooth (Kandhal and Mallick, 1997)

This process resulted in the formation of slabs of asphalt mix, which needed to be further crushed and then transported by haul trucks for disposal, along with a significant amount of dust and noise. Furthermore, the removed material was not suitable for recycling without significant additional processing. The ripper equipment used for breaking and removing the existing pavement causes a very uneven surface (on which the overlay needs to be placed). Also, because the material is obtained in unusable form, it is generally more economic to discard it in landfills – which has a significantly negative consequence on the environment. Landfill spaces are dwindling, and deposits of asphalt materials are undesirable as, over the long term, they may lead to environmental concerns. Hence, a new method was necessitated to remove deteriorated pavement layers in an accurate and uniform way and to procure the recycled materials in a usable way.

The process of pavement milling helps in avoiding the above problems. The basic idea of milling is to remove the deteriorated pavement layer to a desired depth using a controllable force, such that the existing damaged layer is removed completely, and the resulting surface is even. One advantage of milling, as opposed to the ripping and crushing operation, is that the removal and crushing of the material takes place simultaneously, resulting in materials in a granular form (RAP material). Generally, the resulting material can be utilized for recycling as is or with minimal processing and there is minimal need to reduce the size of the materials in this case. Milling is mostly carried out for asphalt pavements, although it is used for concrete pavements as well, generally for texturing or improvement of the surface, or for the removal of an asphalt overlay. The improvement of surface texture is also a growing area for asphalt pavements. When adequate funds are not available for maintenance activities, and/or, when the surface has poor ride quality (for example, inadequate friction or excessive roughness), milling to a shallow depth is carried out for asphalt pavements.

For many years, the concept of traditional milling has been adopted by most agencies in asphalt rehabilitation (ARRA, n.d.). However, traditional milling leaves the pavement surface with a rough surface which might cause some limitations in some roadway rehabilitation treatments. Micro-milling, on the other hand, is an alternative to traditional milling where it utilizes the same equipment but with additional teeth placed on the cutting drum. Its application results in a smoother pavement surface due to the reduced distance between the ridges and the valleys of the milled surface as shown in Figure 2-2. Micro-milling is used in some limited applications where a smoother milled pattern is desired such as thin surface treatments/overlays (i.e., chip seal, slurry seal, cape seal, micro surfacing, thin lift overlays, etc.), pavement marking removal, and some surface corrections like surface profiling, grade correction, friction restoration, and bump removal. It is important to mention the difference in the end product (RAP) between the traditional milling and micro-milling. The latter generates finer materials close to the required project gradation which diminish the need for crushing before reclaiming the RAP into HMA.

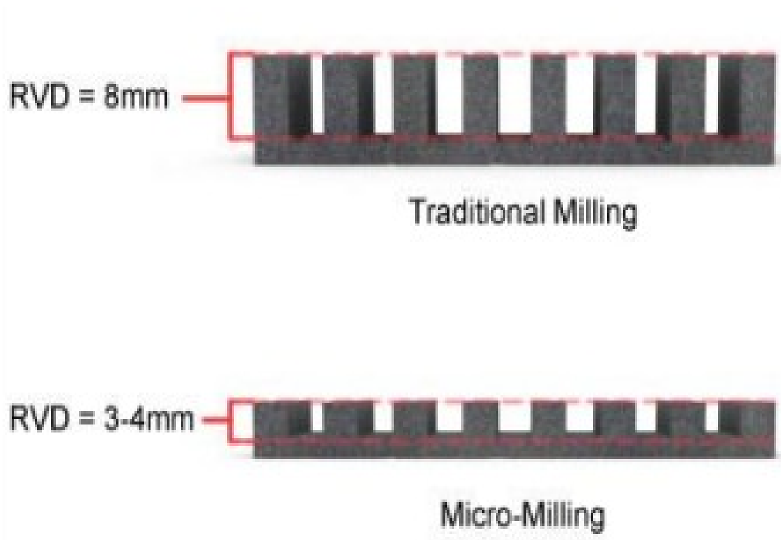


Figure 2-2 Comparison of Ridge to Valley Depth (RVD) (ARRA, n.d.)

Micro-milling is mostly used in applications where the required cutting depth is two inches or fewer (ARRA, n.d.). However, a combination of traditional milling and micro-milling can be utilized when the necessary cutting depth exceeds two inches. In this case, conventional milling will be employed to remove existing pavement material, afterward the surface is finished by micro-milling a couple of inches.

There are several advantages of milling, which are as follows:

1. Enables users to avoid changes in horizontal and vertical alignments and reconstruction of shoulders during maintenance and rehabilitation work.
2. Allows removal of all different surface distresses such as rutting and different types of cracking
3. Improves ride quality.
4. Profile crown and cross-slope of existing pavements can be improved.
5. Offers much higher productivity than ripping and crushing operations.
6. Conserves natural aggregates and asphalt binder and enables recycling.
7. Provides materials for pavement widening or shoulder construction.
8. Minimizes air quality problems (dust) compared to ripping and crushing operations.

2.1 Milling Equipment, Procedure, and Developments

Cold milling or planing, or more commonly termed milling, is conducted without the application of heat on the pavement. This is the method of automatically controlled removal of pavement using self-propelled equipment with adequate power for traction and stability (ARRA, 1992). A picture of a modern milling machine is shown in Figure 2-3. Cold milling or cold planing is defined by ARRA (2016) as follows: “Cold Planing (CP) consists of milling a portion of the existing asphalt or concrete pavement to the length, depth, and width shown on the plans to remove wheel ruts and other surface irregularities, restore proper grade and/or transverse slope of pavement as indicated in the plans and specifications. The milled surface shall provide a texture suitable for use as a temporary riding surface or an immediate overlay.”

The decision regarding the depth of milling is generally based on available budget and time (Hall et al., 2001), and the milling operation is conducted considering accuracy (slope, depth, and grade), environmental factors (noise and dust) and safety (exposure to milling drum and teeth).

Figure 2-3 Modern Milling Machine in Action

Milling can be carried out to remove: (1) existing surface deformations and irregularities; (2) materials to a uniform depth and uniform cross slope; (3) an entire asphalt mix layer; and (4) materials to variable depth along the project length (ARRA, 1992). Milling is also often intended to treat pavement distresses including raveling, bleeding, shoulder drop off, rutting, corrugations, shoving, removal of aged asphalt, poor ride quality caused by bumps and sags, possible bonding problems between present pavement and new overlay, and diminished curb reveal heights (ARRA, 2001).

Milling should remove the pavement accurately to a specified depth, grade, and slope, and the resulting surface should be free from ruts, bumps, or other imperfections. Specifications require the milling equipment to have an automatic system for controlling grade elevation and cross slope, and the ability to maintain a uniform profile and cross slope. It should be able to establish profile grades within ± 3 mm (within ± 1/8 in) accurately and automatically along each edge of the machine. Another key requirement is the ability to control milling generated dust generation effectively.

2.1.1 Equipment Description

Cold planing requires a series of equipment essentially: a modern cold planer, haul trucks, water truck, and sweeper or power broom (ARRA, 2001). A milling machine shown in Figure 2-7 is a self-propelled and self-powered equipment that contains a drum with rows of milling teeth, and a conveyor system that routes the milled material to a receiver truck. Milling machines come in different sizes, depending on the milling width, and with different power. The milling process involves forced removal (through fracture and fragmentation) of the pavement material with very high strength “teeth” that are fixed on a drum, illustrated in Figure 2-8. This drum is made out of high-quality steel which rotates continuously underneath high horsepower equipment and travels in the direction of milling. Each drum has several rows of teeth, made up of a combination of high-strength and wear-resistant materials that are staggered in such a way to facilitate optimum milling efficiency and the continuous directing of the milled material in the RAP conveyor system, illustrated in Figure 2-9. The teeth come in different sizes and spacing – both of which are dictated by the type, depth, and material of milling. The tips of the teeth are generally made out of tungsten carbide. When worn out due to repeated use, the teeth can be removed from the holders (which are welded to the drum) with pneumatic powered tools. Hammon (2015) defined the tooth wear mechanism into four stages as illustrated in Figure 2-4, where the tooth top gage height decreases and flattens. A tool lose around 9.3 mm (0.365 inch) of gage height at stage 3 and its surface area increases by 287% going from 97 mm^2 (0.15 in^2) in the initial stage to 277 mm^2 (0.43 in^2) in stage 4.

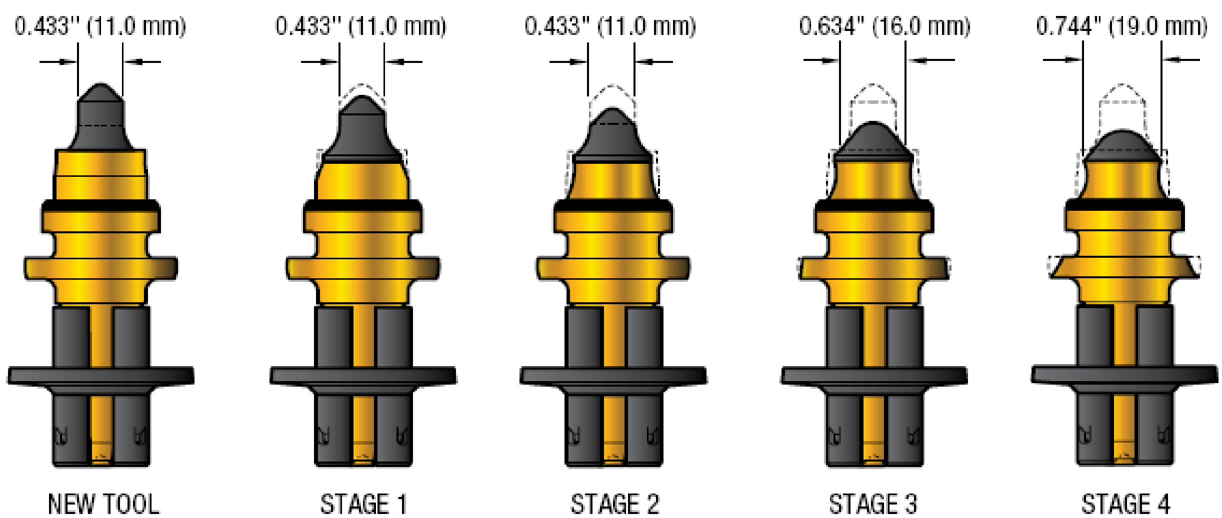


Figure 2-4 Tooth Wear Stages (Hammon, 2015)

Worn tools would affect the milled surface pattern and texture because of the misalignment of the tooling on the tooth holder due to face wear as shown in Figure 2-5. Another aspect that is influenced by the worn tools is the production efficiency of the machine in a certain project. Figure 2-6 shows that a stage 4 teeth wear would necessitate the decrease of the milling machine advance rate by a significant amount in order to reach the same milling depth compared to new teeth and thus decreasing the production rate of milling (Hammon, 2015).

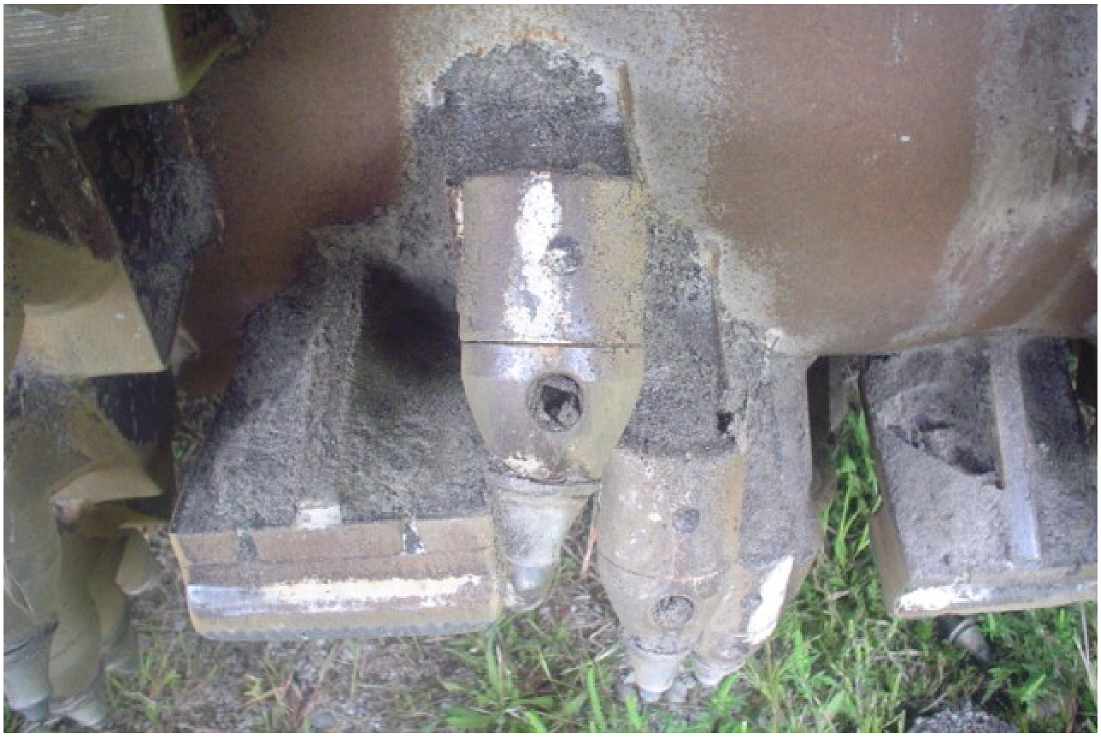


Figure 2-5 Misaligned Tool on Tooth Holder (Hammon, 2015)

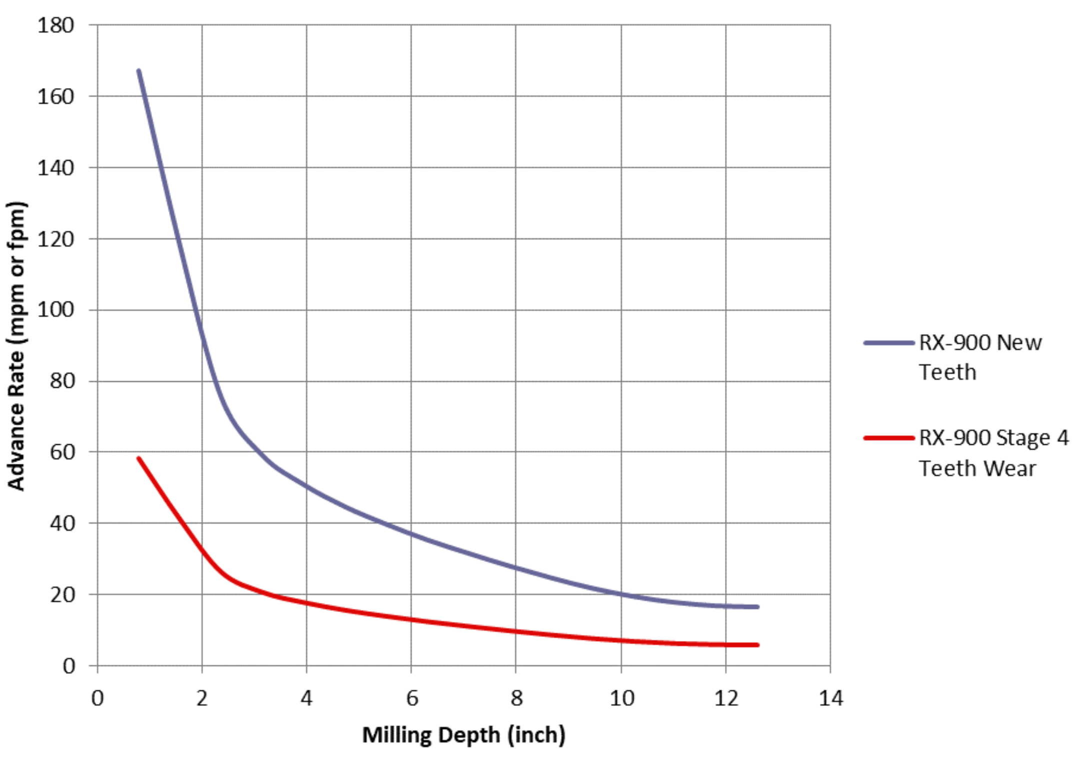


Figure 2-6 Milling Machine Teeth Production Tradeoff (Hammon, 2015)

The entire assembly is protected by an enclosure during operation, and generally includes a conveyor belt system (consisting of a primary and a secondary conveyor) that captures the milled material and directs it upward to a point where it can be deposited in a truck. The conveyor system can be folded into the machine to reduce its size during transportation. The milling assembly may also contain a controllable screed which ensures a uniform and desirable size of the milled material and prevents “slabbing” and the deposit of chunks of milled material into the RAP conveyor system.

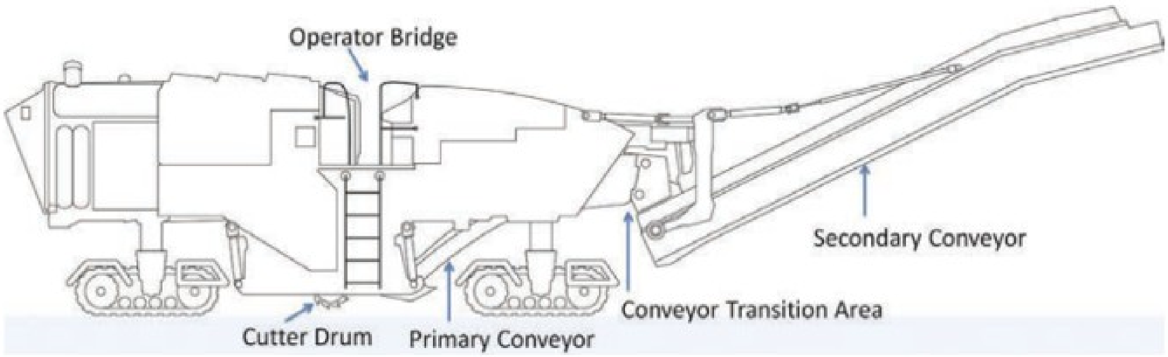


Figure 2-7 Schematic of a Typical Milling Machine (NIOSH, 2015)

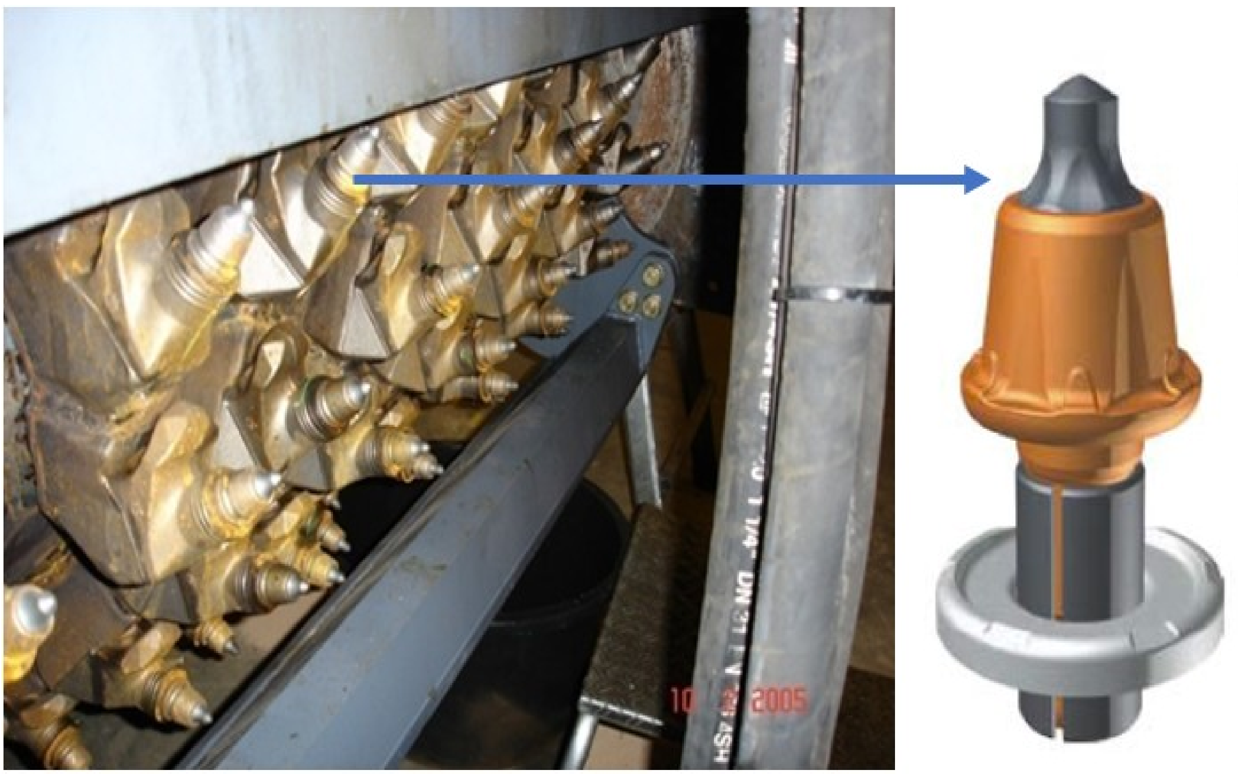


Figure 2-8 Milling Teeth or Picks (Wirtgen, 2018)

Figure 2-9 Staggered Teeth on the Milling Machine (Wirtgen, 2018)

2.1.2 Procedure Description

The milling machine, which can be on wheels or tracks, lowers the rotating drum first at the starting point while stationary, and when the milling depth is reached, it starts moving forward. The drum can be rotated in the upcutting or downcutting modes. Generally, for milling the upcutting mode is preferred. Note that similar milling machines are also modified and used as cold recycling machines, which may sometimes work in the downcutting mode. During milling, water is sprayed through a system of nozzles to keep the milling teeth from heating up excessively and minimize the generation of dust. The entire milling assembly is protected with barriers on both side of the milling machine that come down before the start of milling.

A desirable milled surface is one with uniform, discontinuous longitudinal striations, or another uniform pattern, and it should not appear to be gauged or torn (Figure 2-10). Generally, the milling depth is recommended to be above or below a layer interface to avoid delamination, depressions, and the generation of large RAP pieces.

(a) (b)

Figure 2-10 Different Milling Patterns: (a) Uniform milling pattern (Kandhal and Mallick, 1997), (b) Delamination while milling (Ensell, 2012)

Different types of milling equipment, with different teeth spacing and drum widths, are available to allow milling to a wide range of depths as well as widths of 1 to 3.9 m (3.3 to 12.8 ft). Figure 2-11 and Figure 2-12 present the different types of drums and milling patterns, respectively. Some examples of different sizes and capacities of milling machines are displayed in Figure 2-13.

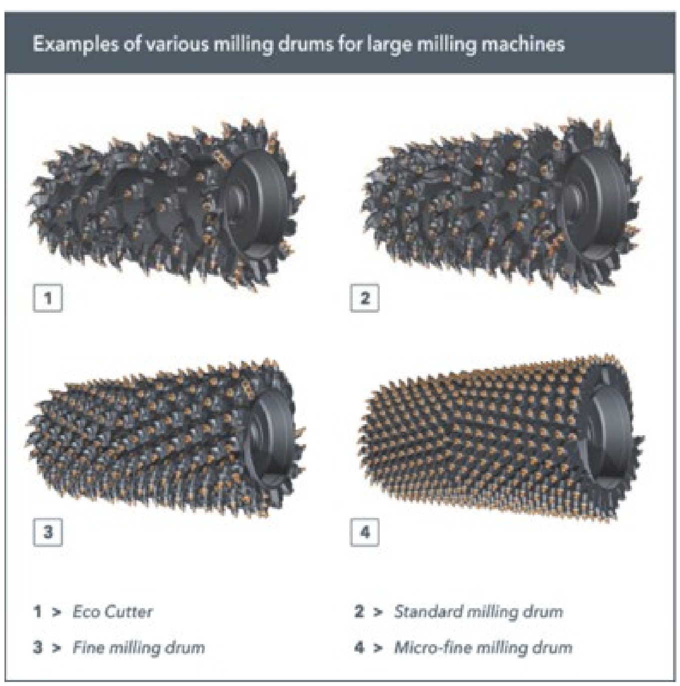
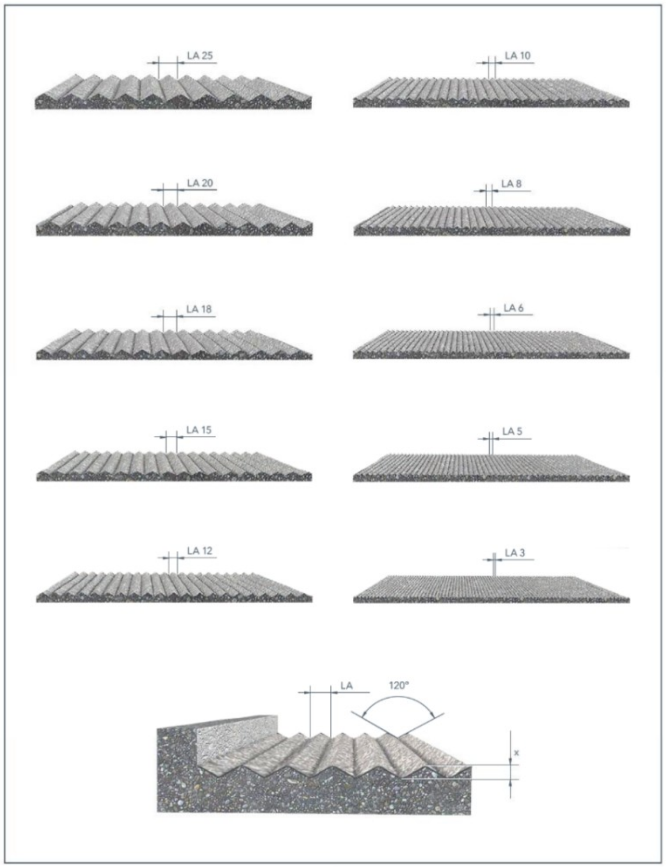


Figure 2-11 Different Types of Drums (Wirtgen, 2018).



Type of milling drum	LA = Line spacing	x = Theoretical base height	Max. milling depth	Usage options
Eco Cutter Rough milling drums	20 mm	5.77 mm	up to 35 cm	**For greater demands on volume milling performance** > Concrete milling > Complete removal of road surfaces
	25 mm	7.21 mm		
Standard milling drums	12 mm	3.46 mm	up to 35 cm	**Universal milling drum for versatile use** > Removing surface and binder courses > Complete removal of road surfaces > Concrete milling
	15 mm	4.33 mm		
	18 mm	5.19 mm		
Fine milling drums	8 mm	2.31 mm	up to 8 cm	**For high demands on macro- and micro-profile** > Removal of surface layers, incl. construction of a more even surface > Corrective milling work on roadway profiles
	10 mm	2.88 mm		
Micro-fine milling drums	3 mm	0.87 mm	up to 3 cm	**For the highest demands on macro- and micro-profile** > Increase in surface grip by roughening roadway surfaces using the micro-fine milling process > Increasing the evenness of concrete roadways > Preparation milling for surface treatment, cold paving of thin layers and other thin-layer paving > Removal of coatings from road surfaces or hall floors > Removal of markings on the road surface > Milling into markings on the road surface
	5 mm	1.44 mm		
	6 mm	1.73 mm		

Theoretical base height of typical milling drum line spacings

Figure 2-12 Different Milling Patterns (Wirtgen, 2018)

Figure 2-13 Examples of Milling Machines of Different Sizes and Capacities (ASTEC, 2021, Wirtgen, 2021)

To control the amount of dust generated during cold planing and to extend the cutting tools service life, a moderate amount of water is sprayed. Water is continuously supplied into the milling machine onboard storage tank by means of water trucks. The loading conveyors equipped with the milling machine can be adjusted for speed and height to fully load the RAP generated during the milling operation onto haul trucks. However, some fines and loose RAP remain in the rough texture of the milled surface and therefore the need of power brooms, vacuum sweepers, and/or power sweepers to clean the roadway before it is open to traffic. The milled surface can be left intact and traffic control lines can be drawn on the surface or overlayed by a HMA overlay depending on the adequacy of the underlying pavement structure (ARRA, 2001).

2.1.3 Development of Milling Machine

Since the 1970s, there have been significant developments in size, horsepower, and capacity of milling machines which have resulted in the reduction of the cost of milling (Brock and Richmond, 2007). These developments include the following: (1) provision of adjustable screed near the milling drum to control the size of the milled particles; (2) advanced sensor-based grade and slope control systems; (3) better ergonomics and control for the machine operator; (4) adjustable conveyor systems for truck loading both along and sideways; (5) better and longer-lasting milling teeth and holders; (6) rapid changing systems for worn-out milling teeth; (7) better maneuverability; (8) wheel and track-mounted machines; (9) front and rear-loading designs; (10) height and speed adjustable conveying system for efficient truck loading; and, (11) better dust control systems.

2.2 Productivity of Milling Machines

The productivity of milling machines has increased significantly over the years. However, the output is dependent on a number of factors such as machine, materials, site, traffic, transport, and operator (Figure 2-14). Factors that can reduce productivity include the following: (1) RAP transporting truck delays; (2) separated/isolated milling areas that need repeated transfer of milling machine; (3) traffic obstructing or delaying milling; (4) utilities or other obstacles on the road; (5) winding or uphill/downhill roads; and, (6) inclement weather.

Generally, the output (for asphalt pavements) increases with an increase in pavement temperature. The industry has developed guidelines for estimating the output of specific machines under specific conditions. An example flowchart, with the use of an output diagram for a specific machine, is shown in Figure 2-15. Modern milling machines can be equipped with integrated telematics systems, consisting of laser scanners, sensors, and Global Positioning Systems (GPS) that can automatically keep track of actual milled area and volume.

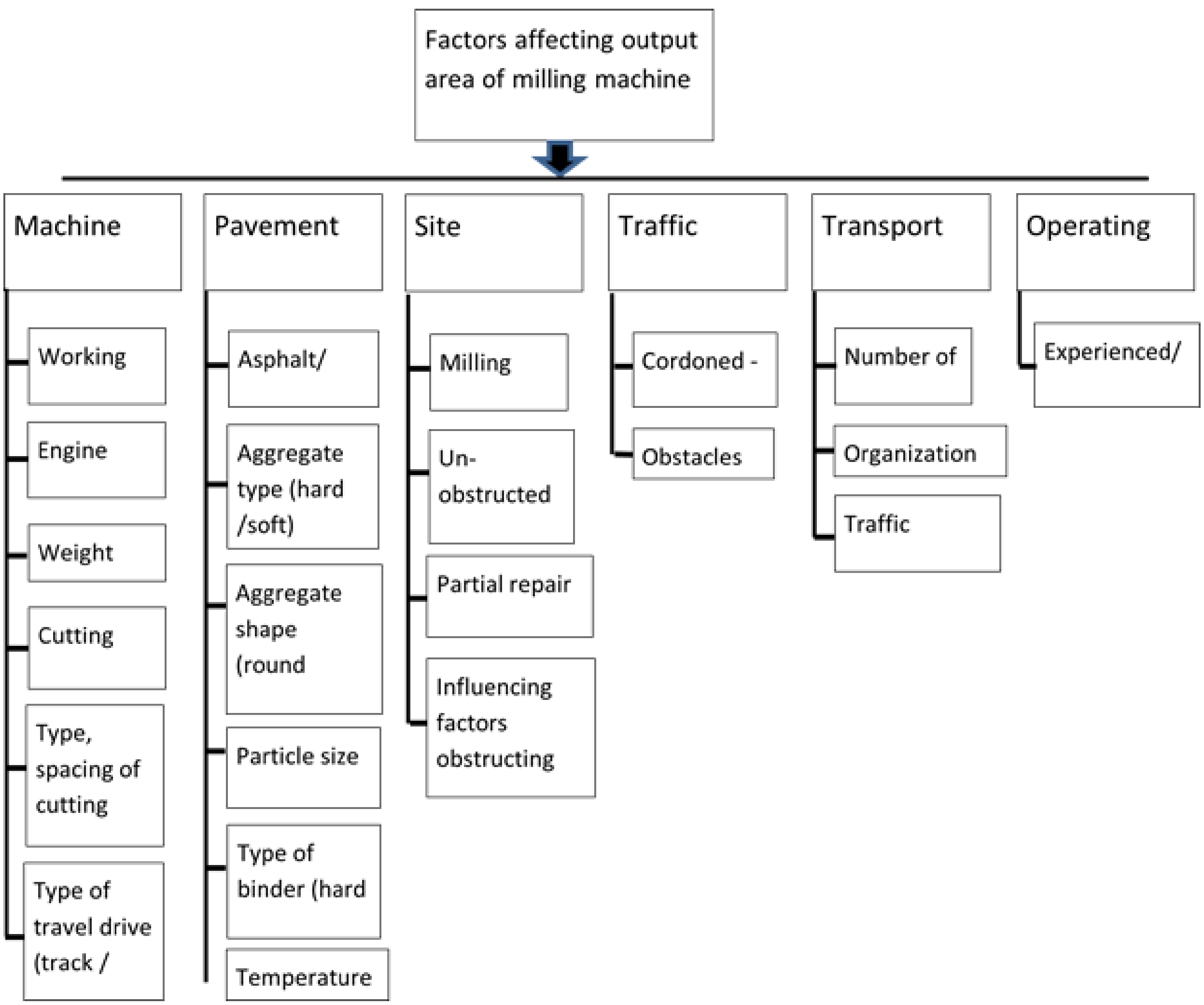


Figure 2-14 Factors Affecting Milling Area Output (Adapted from Wirtgen, n.d.)

Step 1: Select machine on the basis of width and depth of cut

Step 2: Estimate theoretical output area of milling for the specific machine and pavement conditions

Step 3: Determine the allowance factor for site specific conditions

Step 4: Estimate practical output area of milling

<u>Formula for calculations</u>

Practical output area, m^2/h, $F_P = A * F_T$

A = allowance factor; F_T = Theoretical output area, m^2/h, from chart.

A = 0.3 – 0.5, for built-up areas; 0.5 – 0.7, for open areas

Practical reclaimed volume, m^3/h, $Q_v = F_p * T * 0.013$

T = milling depth, cm

Practical reclaimed quantity, tonnes (t)/h, $Q_T = F_p * T * 0.024$

Total reclaimed volume, m^3/h, $Q_{GV} = F_F * T * 0.013$

Total reclaimed quantity, t, $Q_{GT} = F_F * T * 0.024$

F_F = Milling area, m^2

Working time required for job, hour, $Z = F_F/F_P$

<u>Effect of pavement temperature:</u>

Area output at 0°C = 0.6 * Area output at 15°C

Area output at 30°C = 1.3 * Area output at 15°C

<u>Example output area calculation for Wirtgen Milling machine, Model W 2200</u>

Engine output: 671 kW/900 HP; Milling width: 2.2 m; Milling depth: 0-35 cm

Calculation 1: Complete removal of asphalt mix layer: Milling depth, T, cm = 30; width, W, m = 4; Length, m = 5,000; Total milled area, F_f, m^2 = 20,000; Type of asphalt mix: moderately hard

From chart, F_T = 560 m^2/h; selected A = 0.6, for the following conditions: 1. Site traffic does not much interference; 2. Availability of sufficient trucks.

$F_P = A * F_T = 0.6 * 560 = 336$ m^2/h; $Q_v = F_p * T * 0.013 = 336 * 30 * 0.013 = 131$ m^3/h; $Q_T = F_p * T * 0.024 = 336 * 30 * 0.024 = 241.9$ t/h;

$Q_{GV} = F_F * T * 0.013 = 20,000 * 30 * 0.013 = 7,800$ m^3; $Q_{GT} = F_F * T * 0.024 = 20,000 * 30 * 0.024 = 14,200$ t

$Z = F_F/F_P = 20,000/336 = 59.5 \approx 60$ working hours

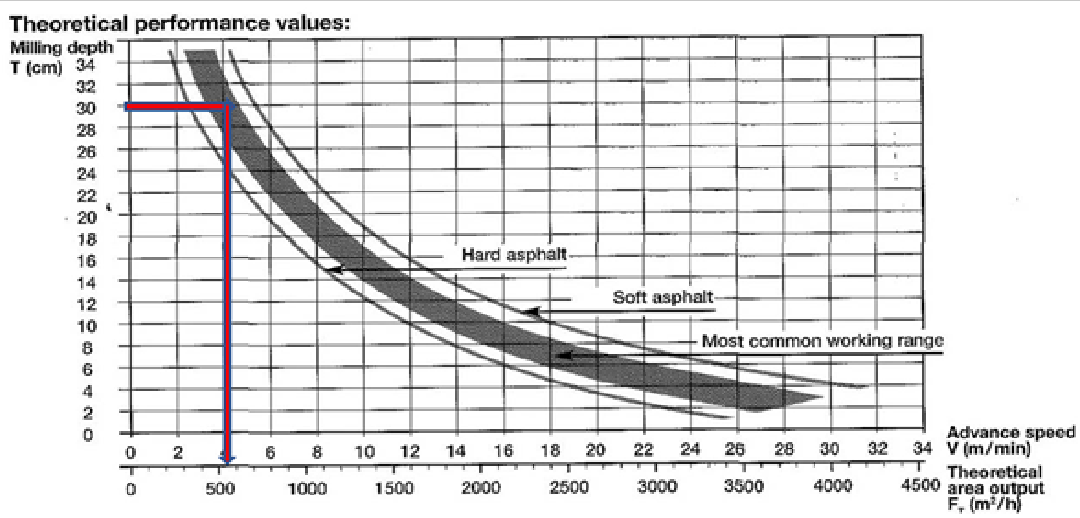


Figure 2-15 Formula and Example Calculation of Milling Output Area (Adapted from Wirtgen, n.d.)

2.3 Published Research on Milling

Published research conducted on milling can be broadly classified into four main areas: (1) effect of pavement conditions on milling and overlays (e.g., level of distress); (2) milling operations concerns; (3) environmental and health concerns of milling; and (4) modeling and simulation of milling operations. Reviews of the available literature are presented below collected from published journals such as Transportation Research Record (TRR), research gate, agency guidelines, federal publications, industry guidelines and brochures literature, and articles in relevant magazines. The literature review focused on studies pertaining to asphalt overlays on asphalt pavements and information relevant to the project. Table 2-2,Table 2-4,Table 2-5, and Table 2-6 present the key findings for each study included in the following four subsections respectively.

2.3.1 Effect of Pavement Conditions on Milling and Overlays

Tarr et al. (2000) conducted a study on the mechanistic design of white topping on new and existing asphalt pavements. The study involved data acquisition from three instrumented test sections in Colorado and their analysis. One of the objectives of the study was to evaluate the interface bonding strength between the cement slab and the asphalt pavement surface under milled and unmilled conditions. Load (89.3 kN, 20 kip single axle load) induced strain were obtained from gages installed at the center and the longitudinal edge of the slabs. Field samples were obtained to determine direct interface shear strength. The following observations (see Table 2-1) were made for joint spacing of 1.52 and 1.8 m (5 and 6 ft): (1) the interface shear strength increased between 28 days and 1 year; (2) for newly placed asphalt pavements, the increases were an average of 80 % and 590 % for unmilled and milled conditions, respectively, although the authors caution that the results could be misleading because of very low initial strengths; and, (3) shear strength increased by an average of 54 % for existing milled asphalt pavements. No data were available for unmilled existing pavements. The strain gages from the different sections (Figure 2-16) showed a higher strain (by 50 %) for milled compared to unmilled conditions for new pavements, but lower strain (25 %) for the milled conditions, for the existing pavements. The authors recommended further testing for various joint spacing before the inclusion of interface conditions in the white topping design procedure.

Note that this study indicates that the impact of milling may be affected by a number of factors, including the condition and type of the existing surface.

Table 2-1 Test Slab Preparation and Shear Strength (Tarr et al., 2000)

Site	Test Slab	AC Surface Condition	28 Day Interface Shear Strength, psi	1 Year Interface Shear Strength, psi
Santa Fe	1	New	45	80
	2	New	30	60
	3	Milled	10	80
Longmont	1	Existing	100	-
	2	New	60	105
	3	New	70	105
	4	Existing Milled	65	100
	5	Existing Milled	-	155
Lamar	B	Existing Milled	80	-
	E	Existing Milled	90	-
	F	Existing Milled	110	-

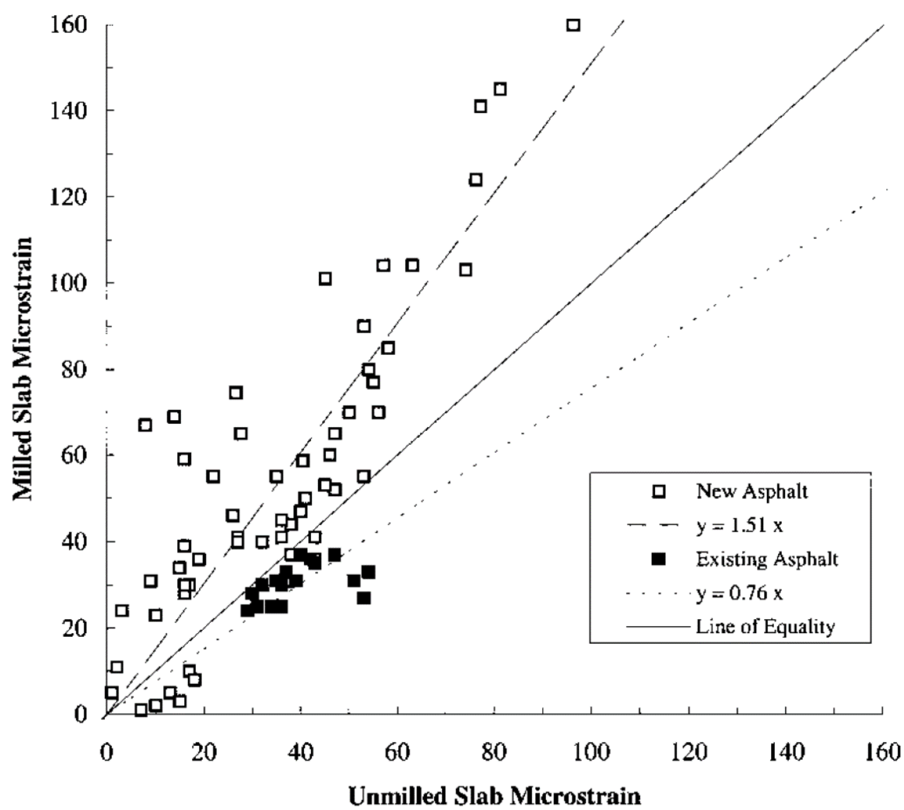


Figure 2-16 Effect of Interface Milling on Load Induced Strain (Tarr et al., 2000)

Hossain and Wu (2002) conducted an evaluation of the structural life of asphalt pavements before and after mill-and-fill work, for the Kansas DOT. They conducted Falling Weight Deflectometer (FWD) tests on pre-milled, milled and overlaid (filled) pavements in ten different test sections consisting of both interstate and state highways. The authors utilized ten 305 m (1000 ft) long asphalt pavement sections, which have been previously milled and filled. The PSI of the sections (according to the Federal Highway Administration (FHWA) Highway Performance Monitoring System (HMPS) equation) prior to milling ranged from 2.89 to 3.72, with longitudinal (fatigue) cracking, transverse cracking, and rutting as the most common distresses. The HMA overlay thickness ranged from 25 to 64 mm (1 to 2.5 inch), with an additional section having a thickness of 150 mm (6 inch). For this study, full-depth beam samples were extracted from each section. For the analysis of the FWD test results, the pavements were modeled as four-layered structures before the overlay and five-layer structures after the overlay. Layer moduli and critical strains (bottom of HMA and top of the subgrade) were estimated. The mean modulus of elasticity at 20^{o}C (68^{o}F) of the existing HMA layer ranged from 1,468 to 8,075 MPa (213 to 1171 ksi), whereas that of the HMA overlay ranged from 1,550 to 6,270 MPa (225 to 909 ksi). The beam samples were tested in the laboratory for the estimation of fatigue lives under constant stress mode at 20^{o}C (68^{o}F), which were then correlated to critical strain and layer modulus. Samples cored out from the outer third of the tested beams were utilized for the determination of voids.

With reference to the mill-and-fill thickness versus predicted fatigue and rutting pavement lives, the authors made several conclusions, which included the following: (1) if fatigue cracking is not present in the existing pavement, milling would decrease the fatigue life. In such a situation, the fatigue life would increase only if the milling is conducted to a greater depth; (2) the critical pavement responses remained unaffected by mill-and-fill work. The authors inferred that there is no damage to underlying layers from this type of rehabilitation work; (3) fatigue lives of pavements with very high HMA and HMA base moduli are insensitive to mill-and-fill thickness; (4) rutting lives of pavements are insensitive to mill-and-fill thickness if there is no mixture or constructed related problems; and, (5) to achieve a significant gain in fatigue life, the mill-and-fill thickness should be ≥ 1.25 times the thickness of the remaining HMA layer thickness.

The authors also made several recommendations, which include the following: (1) for pavements with no signs of fatigue cracking, mill-and-fill should be minimized, and the highest depth of milling should equal the highest rut depth; and, (2) for the Kansas Turnpike that was studied, the optimum mill-and-fill thickness ranged from 50.8 to 76.2 mm (2 to 3 inch), and that a minimum thickness of 76.2 mm (3 inch) should be selected.

Some observations can be made regarding this study: (1) in most cases, the overlay thickness is not great enough to justify the consideration of a fifth layer during backcalculation of FWD data, as conducted in the study; (2) while the authors did consider the critical strains for fatigue and rutting failures, they did not consider the potential of reflective cracking, which may occur because of damage in the underlying layer during mill and fill work; (3) the conclusions and recommendations regarding the decrease in fatigue life of pavements with no fatigue problem by mill-and-fill work, and the need for a minimum mill-and-fill thickness to achieve a gain in fatigue life by mill-and-fill work indicate that the work actually does result in a lowering of the structural capacity of the pavement, which can be counteracted only by providing adequately thick new HMA layer; and, (4) the life of the mill-and-fill pavement depends significantly on the ratio of the milled thickness to the remaining thickness of the existing pavement, which in most cases the milling depth is selected on the basis of rule of thumb or experience with specific distress, such as rutting, and not on the basis of any engineering analysis.

West et al. (2011) conducted a study of pavement condition data, with respect to overlay thickness (50 and 125 mm), milled/unmilled condition, and with 30% RAP and without RAP from eighteen Long Term Pavement Program (LTPP) SPS5 test sections. The overlay ages ranged from 14 to 22 years, and the evaluated parameters included the International Roughness Index (IRI), rutting, fatigue cracking, transverse cracking, longitudinal cracking and block cracking, and raveling. From a statistical analysis of the data, the authors concluded that milled sections had less fatigue and transverse cracking, and lower IRI, but higher rutting (however, the difference was very small, 1 mm or 0.04 inch), compared to the unmilled sections. They also reported a slight tendency of unmilled sections to perform better than milled sections in terms of raveling (not significant). Therefore, overall, West et al. (2011) concludes that the effect of milling prior to rehabilitation is beneficial, as it helped in lowering several typical distresses and did not appear to be a significant factor for the other distresses.

The details of milling conditions, such as depth of milling and speed of milling machine (or drum rotation speed or tooth tip speed) are not available. All milling was considered to be equal. The differences in milling conditions need to be considered to evaluate the effect of milling on pavement performance, since it has been demonstrated by others that milling conditions significantly affect the condition of the milled surface.

Wen et al. (2005) conducted a study on surface preparation of asphalt and concrete pavements prior to mill-and-fill projects in Wisconsin. They reviewed the construction records and performance of 22 10-year-old asphalt overlay over asphalt pavement projects, and three recent projects in more detail, through distress survey and FWD testing. The existing pavements showed a variety of distress including transverse cracking and rutting. The authors made the following conclusions and recommendations: (1) pavements with an overlay thickness of > 50 mm (2 inch) were unaffected by the existence of block cracking in the existing surface; (2) reflection cracking, from alligator and transverse cracking were observed in mill and fill projects; and, (3) longitudinal cracking in mill-and-fill projects could be avoided by maintaining a ratio of overlay thickness to milling depth of ≥ 3.

While the authors conclude that mill-and-fill was ineffective in preventing reflective cracking, no mention is made regarding the selection method of milling depth. It appears that in most cases, the depths were determined on the basis of rut depths or local distresses (such as patches). In one case the transverse cracks were more prominent after milling than before, and the overlay was placed on top of them. It appears to be that the milling depth did not penetrate below the distressed layers in such cases. No information is available regarding conclusions from FWD testing of the mill and overlay projects.

Table 2-2 Summary of Literature Review on Available Studies for Evaluation of Pavement Condition for Milling Operations

Reference	Summary of key findings from reference
Tarr et al., 2000	Existing asphalt pavement should be milled and cleaned before concrete placement for an overall reduction of 25 percent in the critical load-induced stresses. Pavement should not be milled before patching to avoid a 50 percent increase in critical load-induced stresses.
Hossain and Wu, 2002	For high traffic pavements, an optimal mill-and-fill depth can be found for fatigue. Mill-and-fill strategy may reduce fatigue life of pavements with low traffic volumes. This strategy is more cost-effective with higher traffic. It is neither susceptible to rutting, nor cause damage to the existing pavement layers.
West et al., 2011	Thicker overlays improved pavement performance except for rutting, and milling prior to rehabilitation decreased IRI, fatigue cracking, and transverse cracking but increased potential for rutting. did not have a significant impact on longitudinal cracking, block cracking, or raveling.
Wen at al., 2005	Block cracking in existing asphalt pavement does not adversely affect the overlay when milling is used. Existing asphalt pavement with extensive alligator cracking should be pulverized to prevent the reflection of underlying alligator cracking. Milling the existing asphalt pavement cannot eliminate the reflection of transverse cracking in existing asphalt pavement. The ratio of overlay thickness to milling depth should be kept a minimum of three to prevent longitudinal cracking from reoccurring in overlay.

2.3.2 Milling Operations Concerns

Pavement texturing is an alternative technique for mill-and-fill (Gao et al., 2015). Due to lack of funding or weather restriction, its common to perform pavement texturing before placing an overlay where around 9.5mm (3/8 inch) is milled off the pavement surface and left without a new wearing course. The milled surface can be opened to traffic while having the required texture and skid resistance. Pavement texturing reduce rutting with milling 13 mm (0.5 inch) from the pavement surface but is noisier than unmilled roads. Nonetheless, the milling speed and cutting depth are milling factors that affect the duration of skid enhancement. Therefore, the purpose of this study was to texture 31 different asphalt pavements (seal coat and HMA sections) by varying milling aspects from milling drums, forward speeds to cutting depths. The data collected include macrotexture and skid resistance and were measured before and 3, 6, 12, 18 months after the milling. It was concluded that higher milling speeds result in higher friction and texture. Another observation is that milling using finer drums generates better skid resistance and macrotexture after 18 months compared to milling using conventional drums. In addition, pavement texturing on seal coats can serve around 12 months, while milling HMA surfaces can provide service life up to 18 months.

The authors recommend the following guidelines concerning pavement texturing: (1) for sections with high initial skid resistance, the use of finer milling drums is recommended over the standard milling drums; (2) an onward speed of 21-24 m/min (70-80 ft/min); and (3) for both seal coat and HMA sections, a milling depth of 6 to 13 mm (0.25 to 0.5 inch) is adopted.

Gallivan and Gundersen (2005) presented a newly developed specification of measurable surface macrotexture measurements for milled asphalt pavement surfaces. The INDOT study was driven by a concern about recurring acceptance failure of paving jobs that included milling. The specific concerns that were noted include: (1) significant number of exposed, loose aggregates and inconsistent ridges on the milled surface; (2) lack of proper cross slope; (3) problem of collecting representative samples behind the paver because of rough milled surface; (4) nonuniform surface causing nonuniform paving depth, and problem of achieving adequate density; and, (5) bridging of the high points by steel roller drums, leading to nonuniform compaction.

The authors note that the original INDOT specifications mandated milling requirements of “conglomerate particles that would pass 2-inch sieve” and “meet a 3 m (10 ft) straightedge requirement of not exceeding 6 mm (1/4 inch)”. In 2000 the specifications were modified to include automatic control devices to establish profile grades and not to vary longitudinally more than 6 mm (1/4 inch) using a 4.9 m (16 ft) straightedge. In 2003, INDOT included the surface macrotexture requirements. INDOT defines five different milling procedures as follows:

1. Asphalt scarification/profile milling to provide a roughened surface texture of an existing surface, remove cracks sealants, and correct minor cross slope deficiencies ($\leq$ 5 mm, ¼ inch).
2. Asphalt milling to remove material from an existing pavement to a specific average depth to uniform profile. Note that in this case the milling depths are specified as either one of 25 mm (1 inch), 38 mm (1.5 inch), 50 mm (2 inch), 75 mm (3 inch) or 100 mm (4 inch).
3. Asphalt removal milling to remove an entire asphalt overlay from an existing concrete or bridge base.
4. Portland cement concrete milling to remove materials from an existing PCC pavement to a specified average depth to a uniform profile to correct cross slope or crown conditions or maintain vertical clearances or curb heights.
5. Transition milling to provide a connection or smooth transition between an HMA overlay and an adjoining pavement with a slope and depth that is specified in standard drawing.

The newly developed macrotexture measurement test was based on the existing sand patch test (ASTM E965-96), Measuring Pavement Macrotexture Depth Using a Volumetric Techniques. Improvements were needed as the test was not considered to be suitable for use on grooved surfaces on pavements with large surface voids ($\geq$ 25 mm, 1.0 inch). Specifically, appropriate changes to the quantity of glass beads and the size of the spreading tool were investigated. Based on experiments and considerations of practicality, the researchers recommended the following modifications: (1) 200 ml of filler materials (glass beads), as it was found to be sufficient to cover a representative area of the milled surface; (2) use of small glass beads (ASTM M247, Glass beads used in traffic paints); and, (3) a 200 mm (8 inch) diameter disk as a spreader, as it was found to be able to bridge between the groove high points. The authors note that the test results showed good relationships between the test patch, milled surface, and speed of the milling machine. The refined macrotexture measurement method has proved to be a better method for INDOT compared to the existing ASTM E965-96 method. From the results, initially, a Macrotexture Ratio (MTR) parameter equation was utilized as follows in Eq. (2-1).

$$MTR = \frac{\pi \times \left(\frac{D}{2}\right)^2}{VGB \times 100} \quad (2\text{-}1)$$

Where D = diameter of the circular area, mm, and VGB = volume of the glass beads, ml

In the next step, MTR measurements were made in several jobs with different milling speeds, and the results were correlated to density and ride quality. Based on these measurements, requirements for two minimum MTRs were developed: ≥ 2.2 for single coarse overlay and ≥ 1.8 for multiple coarse overlays. Based on these values, criteria for the diameter (D) of the filled area was specified in Eq. (2-2) with the following equation.

$$D = \sqrt{MTR \times VGB \times 100 \times \frac{4}{\pi}} \quad (2\text{-}2)$$

Table 2-3 presents the different values and the INDOT requirements. Figure 2-17 shows the testing and measurement procedures. The authors note that the difference in test results is expected for differences in milling operations which include speed of the milling machine, number and type of the milling teeth, and type and depth of the HMA surface layer. Instead of specifying these parameters individually, INDOT decided to use the MTR/D parameters as end result specifications to obtain good quality milled surface. This INDOT procedure is actually referred to as a standard method for evaluation of macrotexture of milled pavements by ARRA (2016), for jobs in which the milling depth is ≤ 100 mm (4 inch).

Although this approach provides a specification for the smoothness of a milled surface, it does not provide one for the structural or material integrity of the layer that remains after milling.

Table 2-3 Macrotexture Ratio Based on 200 ml of Glass Beads (Gallivan and Gundersen, 2005)

Average Diameter, mm	Macro Texture Ratio	Average Diameter, mm	Macro Texture Ratio	Average Diameter, mm	Macro Texture Ratio
190	1.42	225	1.99	260	2.65
195	1.49	230	2.08	265	2.76
200	1.57	235	2.17	270	2.86
205	1.65	237	2.20**	275	2.97
210	1.73	240	2.26	280	3.08
214	1.80 *	245	2.36	285	3.19
215	1.81	250	2.45	290	3.30
220	1.90	255	2.55	295	3.42

Figure 2-17 INDOT Macrotexture Measurement Procedure; Left to Right: Pouring Glass Beads (200 ml, from 2-4 inch height) After Cleaning the Area with Power Broom, Hard and Soft Brush, Spreading the Beads (200 mm plexiglass disk in circular motion), Measuring Diameter of the Area Covered (average of four measurements at 90°, with a standard 12 inch ruler) (Gallivan and Gundersen, 2005, Gallivan, 2005)

Ensell (2012) presented some key observations regarding the importance of various milling-related factors that are critical for obtaining adequate pavement smoothness. To ensure milling pattern, the author cautions against worn-out tooth holders (and misaligned teeth) and recommends slow speed during slope correction operations, and selection of an appropriate milling depth to avoid scabbing also known as delamination (Figure 2-18). Scabbing is a common issue while milling, it occurs when the milling depth is close to the depth of an existing lift interface and as a result the existing pavement layer is not fully removed; therefore, the need to select an appropriate milling depth. Ensell (2012) also recommends milling of ruts to prevent recurrent rutting failures due to differential compaction (Figure 2-19) and slowing down for micro-milling. He mentioned that most milling is performed in the upcutting mode, and although downcutting would result in a finer RAP (pulverization as done mostly in Full Depth Reclamation (FDR)), and a smoother texture, a better approach is increasing the drum speed (especially the tip speed) which would result in less chunking of the material and better productivity (foot per minute) without affecting the milling pattern. (Note that the tip speed (velocity, ft/sec) is directly related to drum speed (RPM); $V=\omega r$: V(velocity, ft/sec), ω(angular velocity, radians/sec), r(radius, ft)).

Figure 2-18 Example of Scabbing (Ensell, 2012)

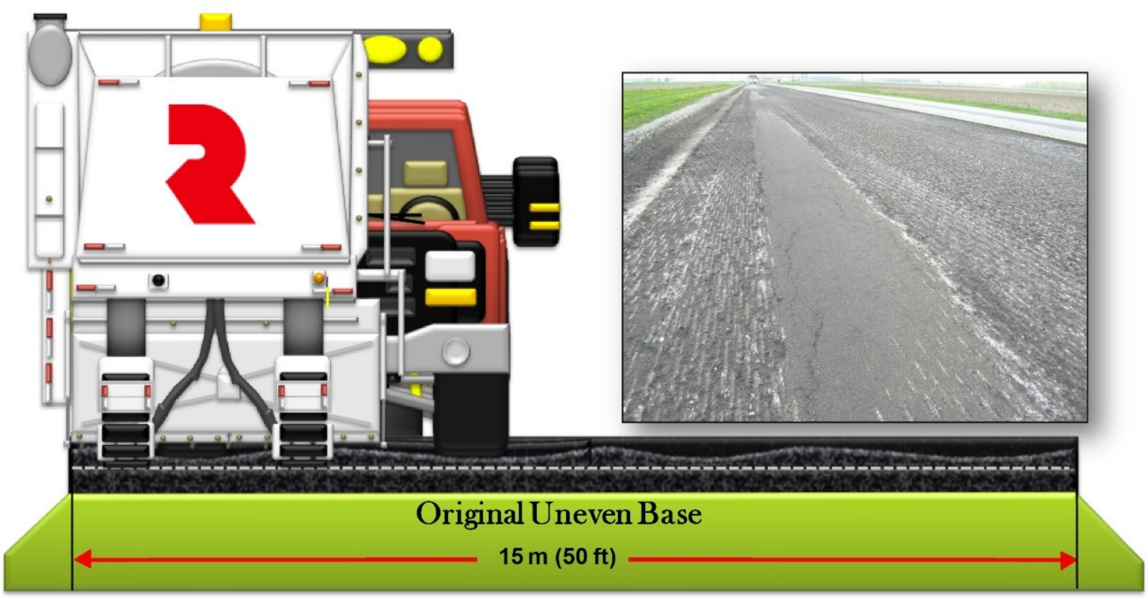


Figure 2-19 Example of Differential Compaction (Ensell, 2012)

Hung et al. (2014) analyzed a set of pavement data from California Department of Transportation (Caltrans) to evaluate the effect of milling and other repairs on the smoothness of asphalt pavements. The data included IRI, wheel path cracking, and construction quality data (such as, thickness). A total of 4,475 sub-sections were used, each ranging in length from 0.16 to 1.6 km (0.1 to 1 mile). The overlay thickness ranged from 31 to > 125 mm (1.2 to > 4.9 inch), while the majority were ≤ 60 mm (2.3 inch). For analyses, the sections were divided into categories of IRI of existing sections (poor, > 1.90 m/km, 120 inch/mile; good, < 1.90 m/km, 120 inch/mile) and thickness of overlay (> and < 60 mm, 2.3 inch), and other variables included pre-overlay condition, pre-overlay repairs (milling and dig out), surface type (open-graded, dense-graded, with and without polymer-modified or rubberized binder). The objective variables were selected as post-overlay IRI and IRI reduction. Based on multiple regression analysis, the authors concluded that milling had a significant negative effect when the pre-overlay condition is good, and no effect when the condition was poor. Their general conclusion is that milling was ineffective in contributing towards better smoothness, except for open-graded surfaces of existing pavements.

Since it was observed that milling had a negative effect on the smoothness of the mill-and-fill pavements if the existing pavement surface had a good smoothness (low IRI), it is unclear if the milling operation caused any damage, apart from creating the usual “ridge and valley” pattern, that resulted in a relatively rough surface. Such damage may be in the form of broken aggregates, displaced mastic, or deposition of fines through the above.

In a subsequent study with 23 Caltrans projects, Guada and Harvey (2018) analyzed additional considerations including: pre-overlay smoothness, thickness of the overlay, mix type and the binder type of the overlay, and the milling of entire lane width prior to overlay and the milling and patching of only wheelpaths known as digouts. Inertial profilers were used to collect the IRI data pre- and post-overlay. The IRI was measured using a standard spot laser measuring at 16 kHZ in the left wheelpath and a wide-spot laser measuring at 3 kHZ the right wheelpath. The data gathered were handled using ProVAL software and then compared to previous data compiled using the same equipment. The authors recommended that pavements having IRI less than 1.5 or 1.9 m/km (95 or 120 inch/mile) are not required to be milled prior to overlay. Note that milling did not result in a negative effect in improving the smoothness of two sections with an initial IRI of < 1.90 m/km (120 inch/mile), which indicates the need for additional data. Therefore, it appears that the impact of milling cannot be solely defined in terms of initial IRI, and is likely affected by other factors, such as existing distresses and surface type, and their interactions.

Table 2-4 Summary of Literature Review on Evaluating Milling Machine and Operations

Reference	Summary of key findings from reference
Gao et al., 2015	Skid resistance and macrotexture improved after milling using fine drums. Forward milling speed resulted in an increase in both skid resistance and macrotexture. Milling operations offer a service life up 12 months on seal coats, whereas extend the service life beyond 18 months on HMA sections.
Gallivan and Gundersen, 2005	Macrotexture testing is not complicated, quick, repeatable, and affordable. It can be correlated with visual observations of the milling operations. Plate sampling is more consistent for mixture acceptance testing.
Ensell, 2012	Worn tooth holders result in misalignment of the milling teeth. The mill should be slowed down when trying to correct slope. The milling depth should be set to prevent scabbing. Ruts need to be milled out to prevent differential compaction, which will cause rutting to quickly return. Micro-milling produces a finer tooth pattern but requires you to slow down.
Hung et al., 2014	After overlay, pavements with lower pre-overlay IRI were smoother than those with higher pre-overlay IRI. Increasing the overlay thickness significantly affected the smoothness of pavements with poor pre-overlay condition. Milling good conditioned pavements is damaging and results in lower overlay smoothness.
Guada and Harvey, 2018	It is recommended to not include milling before overlay when IRI is less than 1.5 or 1.9 m/Km (95 or 120 inches/mile).

2.3.3 Environmental and Health Concerns of Milling

According to Gadsby and Tsai (2021), conventional milling is expensive and poses a threat to the environment, compared to other milling or resurfacing methods. Micro-milling and thin overlay is a less common alternative with potential for economic and environmental alternative to remove and replace a damaged thin open-graded surface layer without altering the sublayers. Gadsby and Tsai (2021) quantified the environmental impacts of the micro-milling and thin overlay compared to the conventional milling and overlay. The pavement designs for the two methods will be used for the comparison. The new technique consists of micro-milling about 38 mm (1.5 inch) off the deteriorated open graded surface layer and inlay a thin overlay whereas the common conventional milling involves the pulverization of an additional 38 mm (1.5 inch) of the undamaged sublayer to have an adequate bond with the new open graded surface layer. Figure 2-20 represent the pavement design in terms of what layer is removed in both processes.

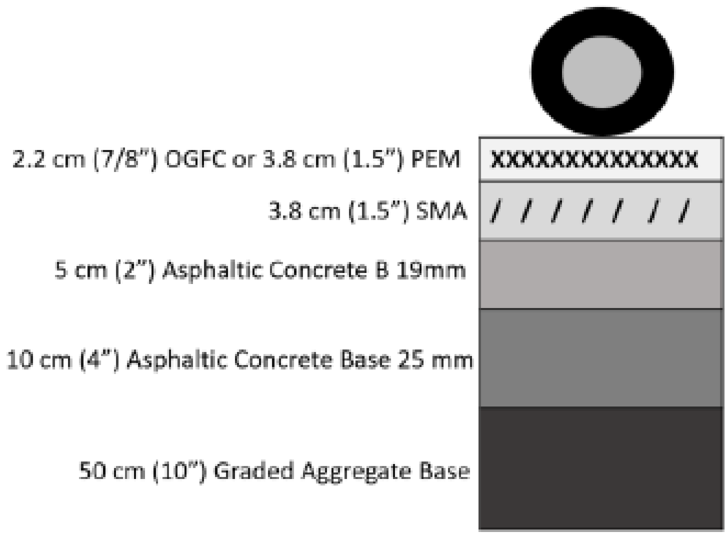


Figure 2-20 Layers Removed by Micro-Milling ("X" marking) vs Layers Removed by Conventional Milling ("X" and "/" markings)

The Pavement Life-Cycle Assessment Tool for Environmental and Economic Effect (PaLATE) is used to assess the phases of the Life Cycle Assessment (LCA). It analyzes the transportation of materials and the material life cycle from material production, initial construction/maintenance, and onsite processes to the end of life.

This study recorded a saving of more than $65,000 per lane mile by comparing the micro-filling and thin overlay to conventional milling and overlay. The results displayed that the micro-filling and thin overlay uses 30 to 40% of the materials needed for conventional milling and overlay, in addition to reduction in energy consumption, water consumption, and CO_2 emissions by 60% due to savings in the quantity of asphalt needed.

The authors mentioned some future research recommendations concerning this topic naming: (1) pavement condition suitable for micro-milling and thin overlay and pretreatments given the underlaying pavement condition be analyzed by test sections to more assess the new alternative, (2) due to the effectiveness and sustainability of the new techniques, a national standard and specification is recommended to be established, and (3) additional LCA need to be conducted once more detailed data become available in the future including the impacts of new construction techniques.

Milling generally results in fracturing of the asphalt mix, which not only involves the separation of asphalt binder-fine aggregate matrix from the coarse aggregate but also fracturing or breaking of the aggregates. The breaking of the aggregates under the action of high force at high speeds causes the release of very fine particles. Based on a study of exposure of workers to milling condition, the US National Institute for Occupational Safety and Health (NIOSH) (NIOSH, 2015) has recommended several methods of mitigation of dust during milling, which includes using proper ventilation system (such as fan and duct) and spraying of water on the milled material. Modern milling machines are sufficiently equipped to keep the worker exposure levels of respirable silica during milling well below NIOSH recommended minimum values.

While this study reported that personal breathing zone air samples during milling with the recommended practices had respirable crystalline silica content below the NIOSH recommended exposure limit (0.05 mg/m^3) and thus allays any safety concern, it does highlight the fact that dust containing crystalline silica is generated during milling as a result of crushing of aggregates. The extent to which such crushed/cracked aggregate remains on the milled surface prior to the application of the overlay is unknown.

Table 2-5 Summary of Literature Review on Evaluating Environmental and Health Concerns of Milling

Reference	Summary of key findings from reference
Gadsby and Tsai, 2021	A reduction of 60% resulted, due to savings in asphalt needed, in all environmental impacts assessed, including energy usage, water consumption, and CO_2 emissions largely.

2.3.4 Modeling and Simulation of Milling Operations

Wu et al. (2018) conducted a study on the modeling of milling of an aged asphalt mix by the Discrete Element Method (DEM). The objective of this study was to evaluate the effect of milling speed and cutting angle and depth of cut on stresses in the pavement and the cutting tool (milling tooth), using the Particle Flow Code (PFC) software for DEM. An aged (in-service for approximately 10 years) SBS modified asphalt mix, designated as AC-16 (nominal maximum aggregate size of 16 mm, 0.6 inch) was modeled, with parameters obtained from the results of uniaxial compression tests that were conducted on the aged (Rolling Thin Film Oven Test (RTFOT), for 600 minutes) mix. The aggregates were modeled as particles of different diameters, and the viscoelastic properties of the mortar were modeled as parallel bonds between the particles. For this study, the following values of the different parameters were used: (1). Milling depth – 20, 25, and 30 mm (0.8, 1, and 1.2 inch); (2) Cutting speed of the tool: 0.5, 1.0, and 1.5 m/s (1.6, 3.2, and 4.9 ft/s); and, (3) Cutting angles of the tool: 40°, 45°, and 50°. Based on the results of the study, the authors made the following conclusions: (1) the damage of the asphalt mix and the stresses on the cutting tool increase significantly with an increase in the cutting speed; (2) for the range studied, the cutting angle has relatively less effect on the damage of the mix and the stresses in the cutting tool; and, (3) both damage of the mix and stresses of the cutting tool are increased significantly with an increase in the cutting depth. For the specific mix studied, the authors recommend a low cutting tool speed (0.5 m/s, 1.6 ft/s) and a cutting angle of 45° to reduce the breaking of aggregates and stresses on the cutting tool. The authors also recommend a study of the effect of different cutting tools for different types of asphalt mixes.

Some observations regarding this study are as follows: (1) viscoelastic properties of the asphalt mix were obtained by uniaxial compression (rather than dynamic compression), which is more appropriate for the simulation of milling – however, no mention is made regarding the speed of loading, which is bound to have a significant effect on the response and hence resultant viscoelastic properties of the asphalt mix; (2) the long-term aging of the mix is conducted by RTFOT, whereas, generally, it is conducted by the Pressure Aging Vessel (PAV); (3) the range of milling depth is very small (20-30 mm, 0.8-1.2 inch) – in reality, milling depths are specified in 25 mm (1 inch) increments (unless for fine or micro-milling); and, (4) the advantage of using DEM over Finite Element Modeling (FEM) is not clear in the paper – DEM is advantageous for tracking the flow or movement of individual particles, and not for the evaluation of stresses on a relatively large area. If the DEM was used to simulate the damage of the mix, then more explanation is needed to demonstrate the method, the results, and the inferences.

Diouri et al. (2020c) presented a study in which the researchers simulated milling in the laboratory through the use of an impact testing system (Figure 2-21). The system allowed a (variably) weighted milling tooth to strike an instrumented (with strain gage) HMA sample, at different impact energies at 25^{o}C (68 ^{o}C). The resulting strain and fragmentation of the HMA sample were evaluated. The authors made the following conclusions: (1) depth of penetration was significantly affected by the impact energy of loading; (2) maximum strain showed good correlation with impact energy; (3) the number of fragments was greater and fragment sizes were larger for higher impact energies; (4) fragment size showed good correlation with impact energy levels at similar strain rates; and, (5) mean fragment size increased with an increase in impact energy.

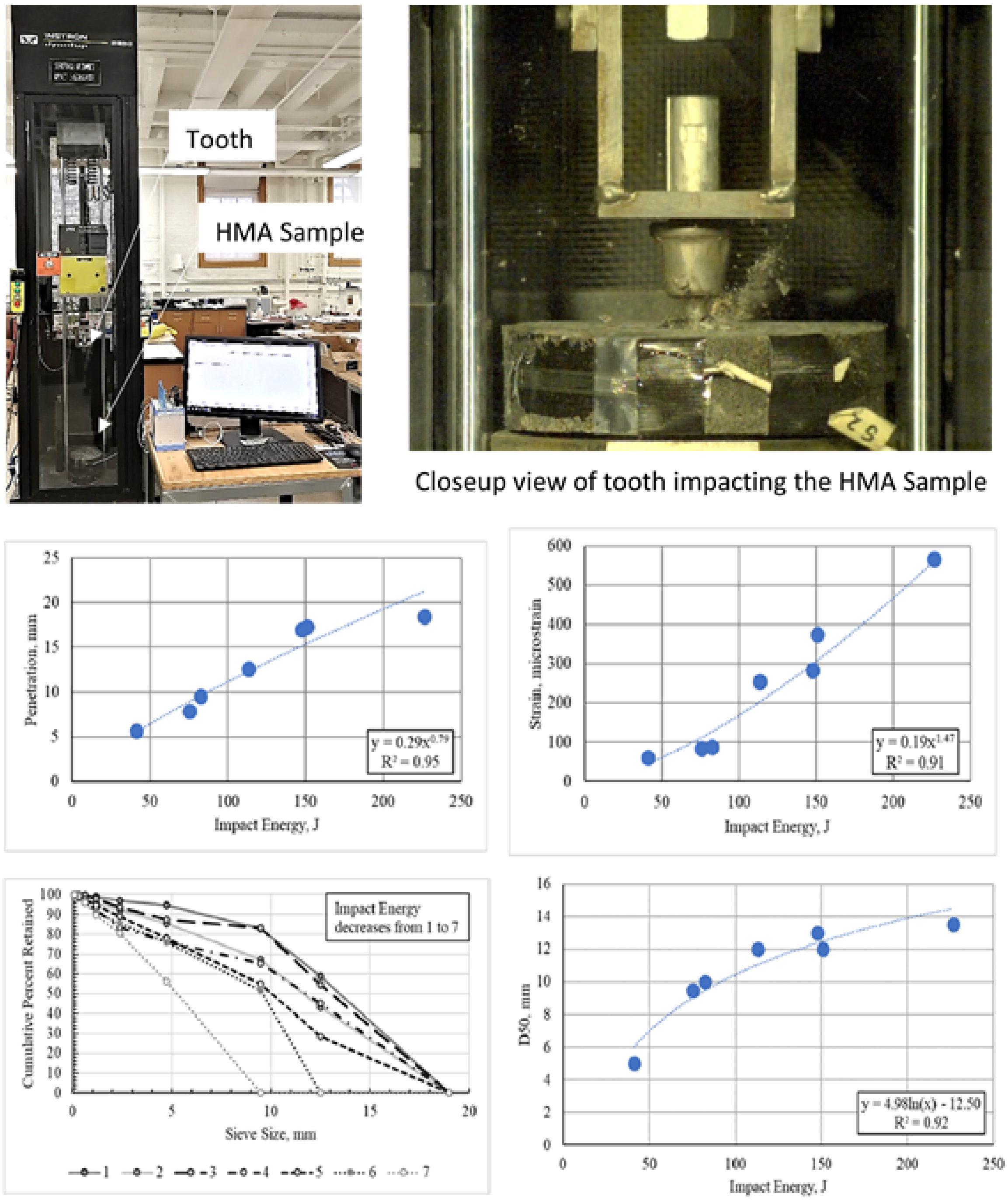


Figure 2-21 Test Set-up and Plots from Resulting Data (Diouri et al., 2020c)

Milling often results in pockets or indentations on the surface by removing stones and mastic. If there is a time interval between the end of milling and application of the overlay, and if it rains during that time, there is a potential for water accumulation in the indentations, and their entrapment under the new HMA layer. This trapped water can cause localized failures due to moisture damage.

Caution has been expressed in the literature regarding when milling depth is close but not quite all the way to an interface, that results in the existence of a portion of the milled layer after milling. These areas have been found to trigger failures in the overlay, often as isolated potholes, by debonding or delaminating from the upper layer, under traffic loading. This observation reinforces the need for the selection of an appropriate milling depth in mill-and-fill work. In addition to the importance of the selected milling depth, Diouri et al. (2021) also found that the pavement temperature while milling should be taken into consideration. They conducted a study evaluating how milling-induced stress penetration depth was impacted by the pavement temperature while milling. This study determined that cooler pavement temperatures while milling can increase the depth to which stressed induced by the milling activity penetrates into the pavement structure.

Table 2-6 Summary of Literature Review on Modeling and Simulation of Milling Operations

Reference	Summary of key findings from reference
Wu et al., 2018	Using a cutting speed of 0.5 m/s (1.6 ft/s) and cutting angle of 45 degree can reduce the amount of broken aggregates; the damage to the existing pavement is increased with the increase of cutting speed in the milling process. The cutting angle of 40 degree when the cutting depth is 25 mm at a cutting speed of 1 m/s (3.2 ft/s) should not be adopted to avoid the milling down of large pieces of old asphalt mixture.
Diouri et al., 2020c	Impacts with higher energy levels produced more fragmentation and larger fragments. Both penetration and strains showed significant effects of impact energies. The size of the fragments showed good correlation with impact energy.
Diouri et al., 2021	Milling at cooler temperatures showed an increased depth penetration of milling-induced stresses throughout the pavement structure.

2.4 Key Findings from the Literature Review

For a pavement to provide good serviceability for many years, it must be well designed and regularly maintained. However, pavements are constantly damaged due to the effect of climate and loading. Conserving, maintaining, or rehabilitating the pavement requires a procedure called milling, which is the process of grinding the pavement partially or entirely whether for functional or structural purposes. Milling is a high energy activity that may induce damage to the existing pavement during rehabilitation stages. Therefore, the need to understand, improve milling operations and see its effect on pavements and overlays performance.

To conclude, the scope of this presented state-of-the-art literature review aimed to display the importance of milling, its procedures, equipment, the different types of milling, along with the currently available research on milling detailed in the above sections. Based on information in the literature review, the following conclusions can be drawn:

- Modern milling machines utilize appropriate ventilation and stabilizing (water-spray systems) to mitigate the problem of generation of dust due to the breakdown of aggregates during milling
- There are contradictory reports regarding the effect of milling on the properties of the overlaid pavement

- Interactions of existing pavement/surface condition and milling conditions seem to be significant factors
- The effect of milling on the improvement of mill-and-fill pavements has been found to be dependent on the initial condition of the pavement, as well as the ratio of milled to remaining layer thickness
- Multiple authors have stressed the importance of maintaining specific ratios of milled to remaining layer thickness or overlay thickness to milling depth ratios to make the mill-and-fill technique effective in preventing the recurrence of distresses, such as through reflection cracking
- The macrotexture of the milled surface is dependent on milling conditions such as the speed of milling machine or the tip speed of the cutter teeth
- Stresses generated in the pavement and on the cutting teeth during milling have been researched by FEM and DEM
- Observations of cores indicates signs of crushed, cracked, and missing materials below the milling depth
- Milling stresses can penetrate to deeper depths when milling is performed at colder temperatures

Chapter 3: Survey of Current Practices for Milling Operations and Review of Milling Specifications

This chapter describes the information gathered from the survey on the current state of the practices of agencies, contractors, and equipment manufacturers with respect to milling operations. The survey is structured to document the different purposes, triggers, classifications, and limitations of asphalt milling, in addition to current approaches for determining milling depth, equipment and operational parameters specified in agency respondents' specifications. Moreover, the survey addressed pavement conditions that might influence milling specifications. Finally, the assessment tackled the quality assessment of milled surface and post milling practices. Results are segmented by agency and non-agency responses and organized into the five sections: (1) most common purposes, triggers, classification, and limitations of milling; (2) equipment and operational requirements; (3) effect of pavement condition on milling specifications; (4) milling depth; and (5) assessment of milled surface quality and post milling practices.

This section then continues to describe the review the research team conducted of the current milling and micro-milling specifications of NRRA member agencies and that of Texas Department of Transportation (NRRA associate member Transtec Group recommended that Texas DOT specifications be considered in review due to some pertinent aspects of Texas DOT specifications as they relate to current research study).

3.1 Survey of Current Practices for Milling Operations

This survey was administered in 2021. Its purpose was to gather information about the milling practices and guidelines of different state department of transportations (DOTs), other transportation agencies, and non-agency entities (consulting firms, equipment manufacturers, and contractors). All NRRA agency members (12 members) completed the survey in addition to some of the non-agency members (6 members). After establishing the current state of practice and conducting milling specification review with respect to asphalt pavement milling operations and its impacts on existing pavement, a list of parameters was generated. These parameters were then considered in the selection of field projects, material sampling, and field and lab testing. They are further discussed in section 3.3.1 of this report.

Survey respondents comprised 18 NRRA members and included agency members (different state DOTs, other transportation agencies) and non-agency (associated) entities (consulting firms, equipment manufacturers, and contractors). Out of all the respondents, 55% (10/18) were state transportation agencies, 11% (2/18) were other transportation agencies (city, county, etc.), 22% (4/18) were pavement construction equipment manufacturer, and one each (1/18) were pavement construction contractor and consultancy firm (consultant for Illinois Tollways), as shown in Figure 3-1.

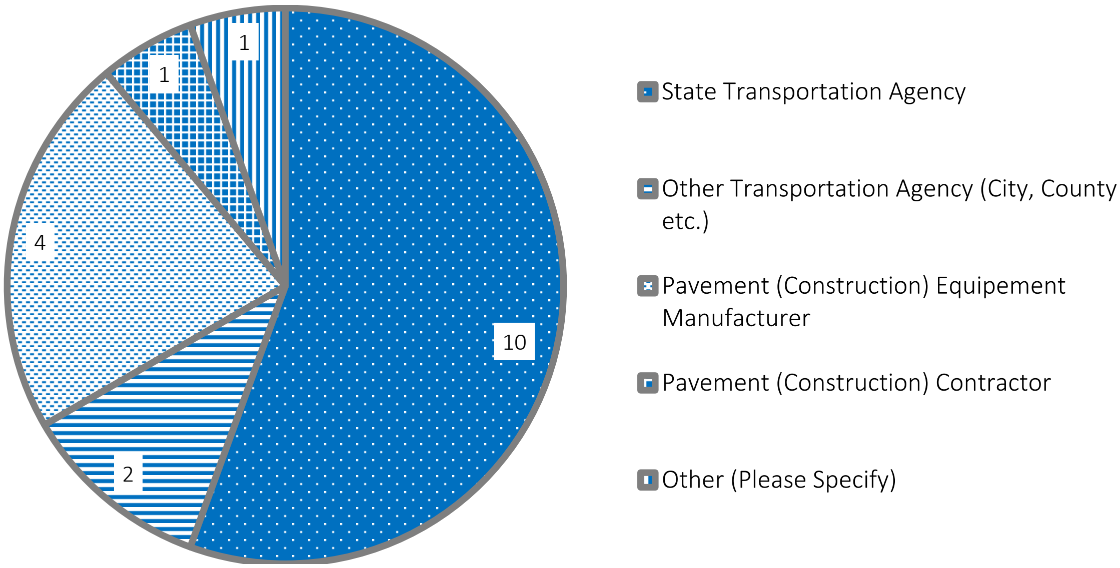


Figure 3-1 Affiliation of respondents (number of respondents, n = 18)

Chapter 3 of this report is composed of three sections. This first section, 3.1, describes the survey responses from different agencies and non-agency members. Section 3.2 provides information from existing state specifications for the different member agencies. Lastly, section 3.3 summarizes the project and highlights key findings from the survey results and the agency specifications. In addition, the survey questions are provided in Appendix A, while Appendix B and Appendix C present the corresponding survey results from the NRRA members and non-agency (associated) members, respectively.

3.1.1 Most Common Purposes, Triggers, Classification, and Limitations of Milling

State agencies were asked to rank in terms of how often milling is used/conducted for a specific purpose (0 indicates milling has never occurred and 10 designates milling has always performed); Figure 3-2 displays the average ranking provided for the different options with error bars representing the minimum and maximum respondent rankings. The most common application of asphalt milling is the removal of the asphalt layer prior to overlay placement or reconstruction. This is not entirely surprising, since use of mill and overlay as pavement rehabilitation activity is most prominent across agencies. Survey results show that use of milling to improve surface friction and skid resistance or to remove surface distresses without the application of an overlay is infrequent. This indicates that for agencies, either skid resistance is not an issue, or if it is, milling is not widely used to improve it. A wide range of rankings for profile correction were observed among respondents and indicated varied practice among agencies.

Non-agency responses (Figure 3-3) were found to be similar to agency responses in that the highest rankings were given to removal of asphalt layer for application of overlay or reconstruction. However, non-agencies indicated more frequent use of milling for friction and skid resistance improvement and for the removal of surface distresses without overlay application, and less frequently for profile correction. Only one non-agency mentioned other responses and ranked it low such as: curb reveal (rank 2) and bridge decks (rank 1).

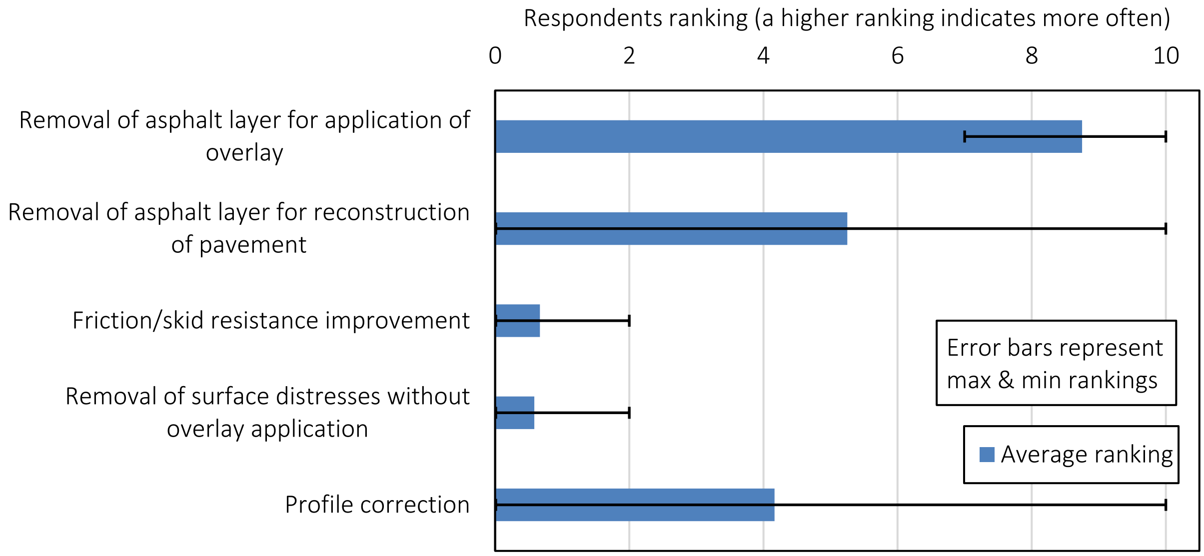


Figure 3-2 Distribution of agency rankings with respect to the purpose for asphalt pavement milling (number of respondents = 12)

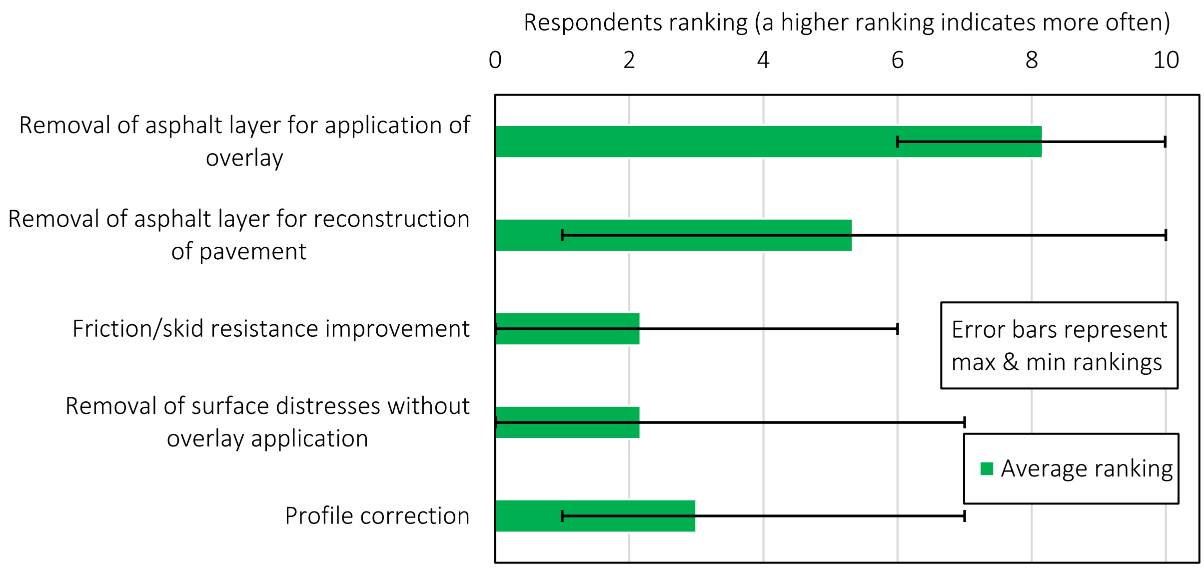


Figure 3-3 Distribution of non-agency rankings with respect to the purpose for asphalt pavement milling (number of respondents = 6)

Figure 3-4 presents the ranking of various causes that agencies reported would trigger the decision to mill an asphalt pavement, a rank of 1 indicates the most common trigger while a rank of 5 indicates the least trigger. The prevalence of the purpose for asphalt milling aligns with responses related to respondents' classification of asphalt milling activities. Agencies primarily consider milling asphalt pavements for pavement rehabilitation such as mill-and-overlay (M&O). Roughness threshold reached, pavement reconstruction, and milling of temporary pavement were less often triggers for milling decision. Finally, respondents rated the skid resistance improvements as the least likely trigger for asphalt pavement milling. Milling for overlay and reconstruction (pavement preservation, rehabilitation, and reconstruction related distinctions) was the most common purpose for asphalt milling. This result of the survey underlines the need to identify projects for this research that requires rehabilitation to further understand the stresses caused by milling, and for the selection of appropriate milling depth.

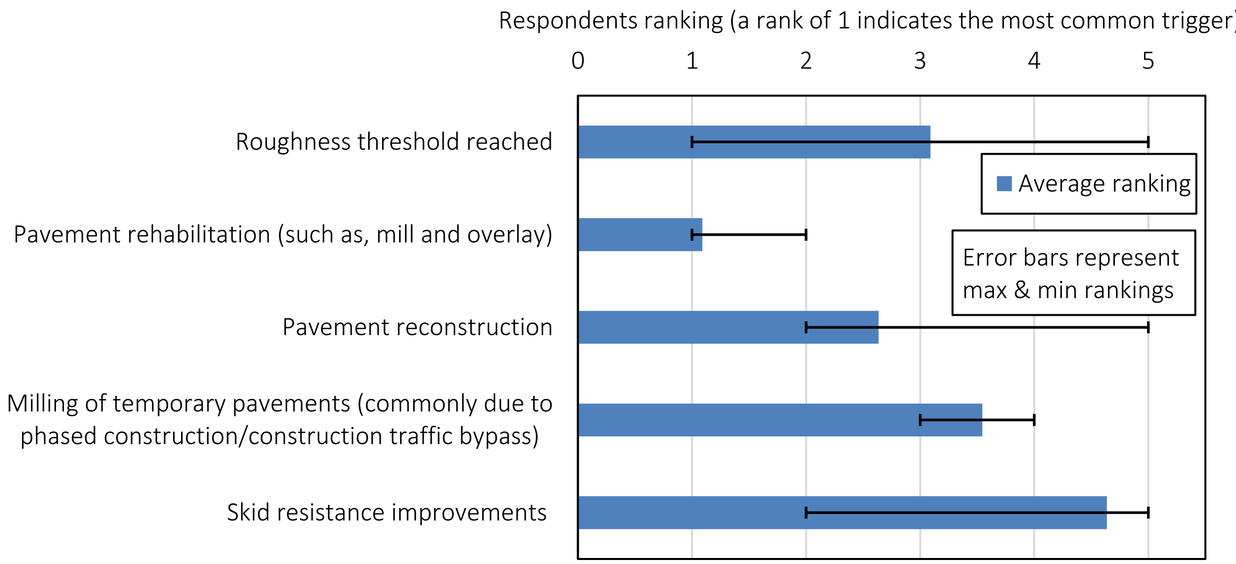


Figure 3-4 Distribution of agency rankings with respect to common triggers that are used to reach decision of milling asphalt pavement (number of respondents = 11)

The survey results helped group the various types of asphalt milling activities as classified by agencies and non-agencies; these include milling activities to remove surface irregularities, mill to a uniform depth following construction plans and specifications, adjust cross slope, or mill up to the base or subgrade. Figure 3-5 and Figure 3-6 show how milling operations are classified by agencies and non-agencies (survey requested respondents to select all options that are applicable), respectively. Figure 3-5 shows that the majority (11 out of 12) of state agencies classify asphalt milling activities with respect to purpose of construction, that is, pavement preservation, rehabilitation, and reconstruction related activities. One-quarter of the respondents classify milling activities as depth-related distinctions like micro-milling and deep milling. Milling to improve surface friction and skid resistance or to remove surface distresses without the application of an overlay (depth related distinction) is infrequent. Only one agency classified operations based on equipment and operational factors. One agency responded with “none of the above” in the “others” section.

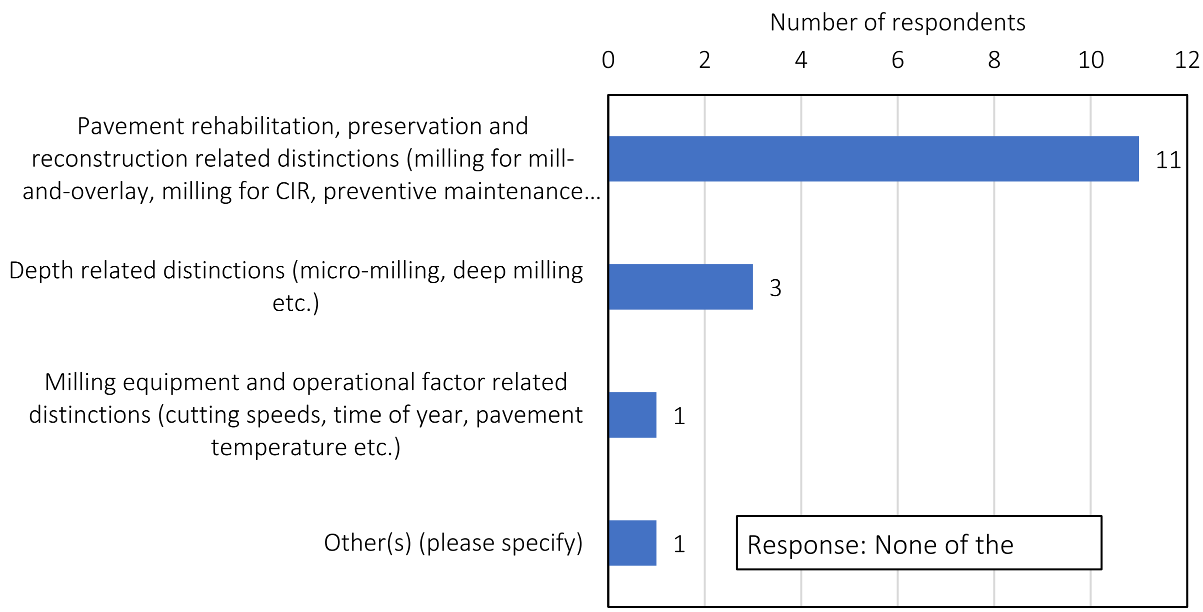


Figure 3-5 Distribution of agency responses with respect to types of asphalt milling activities (number of respondents = 12)

On the other hand, the most common milling classification that is used by non-agency respondents is with respect to depth related practices (6 out of 6), closely followed by purpose of milling (pavement rehabilitation, preservation, and reconstruction) (5 out of 6). Whereas only two categorize milling with reference to equipment and operational factor related distinctions, as presented in Figure 3-6.

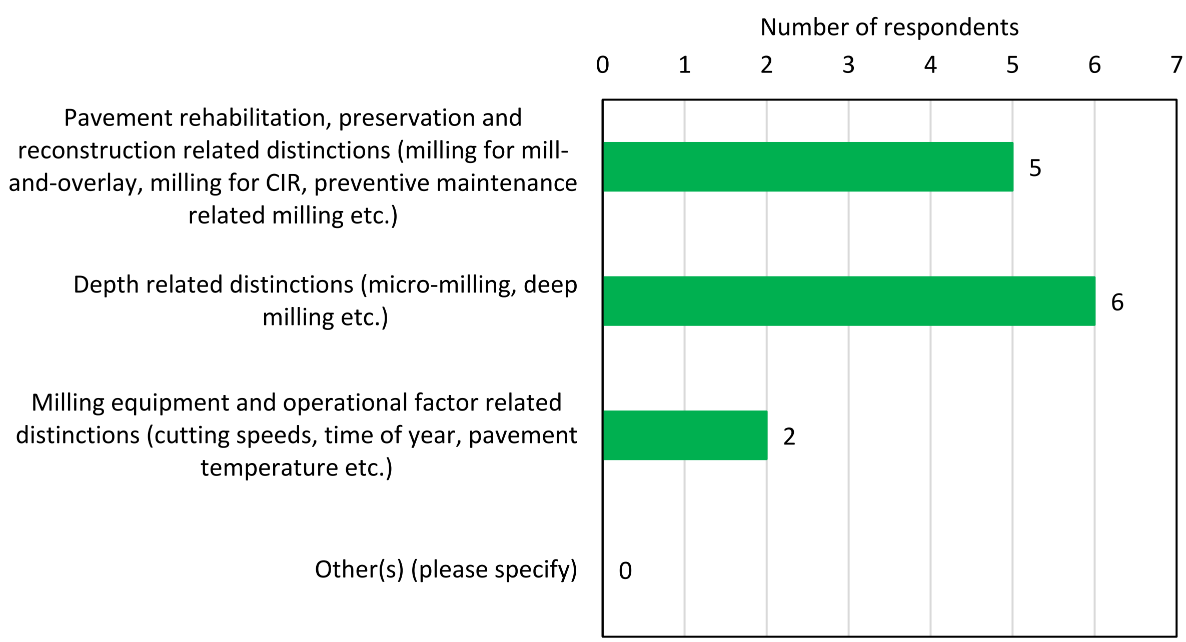


Figure 3-6. Distribution of non-agency responses with respect to types of asphalt milling activities (number of respondents = 6)

When asked about specific attributes that may restrict specifying milling operation on an asphalt pavement, half of both agency and non-agency respondents indicated that milling may be considered on any HMA pavement. The other 50% of respondents indicated that there may be specific conditions that would limit milling operations on particular pavements; these are shown in Table 3-1. Thin, distorted (pavement in bad shape), or sound pavement (pavement in good shape) are the three most common reasons of existing pavement conditions that agencies and non-agencies would not consider for asphalt pavement milling. Pavements with low asphalt layer thickness as well as structurally sound pavements (without structural distresses) occasionally require additional structure; thus, milling is not required, and an overlay is applied because milling decreases the HMA layer thickness and consequently decrease its structural capacity. Also, distorted pavements that have abundant fatigue or reflective cracking do not require milling. In these cases, the problem lies deep down in the asphalt layer where milling just the HMA layer is not substantial enough to eliminate the cracks, hence an alternative recycling practice (e.g., full depth reclamation [FDR], stabilized full depth reclamation [SFDR]) is implemented.

Table 3-1 Agency and non-agency reported attributes to not consider asphalt pavement milling

Agency	Non-agency
Existing asphalt layer thickness	Alternative recycling techniques (CIR, FDR, SFDR)
Existing pavement is distorted	Structural improvements of sound pavements (no structural distress)
Existing pavement is too thin	If milling is expected to mitigate reflective cracking after milling and overlaying, where the specified milling depth is not great enough to remove cracks in the existing layer
In most cases, reclaim and overlay projects are done	
Some pavements require additional structure; therefore, an overlay is proceeded with no milling	
Is there is room, width wise, for the overlay there may be no milling to retain the structural strength	
Thin asphalt layer over Portland cement concrete (PCC)	
Areas with PCC patching	
Additional structure is needed	

3.1.2 Equipment and Operational Requirements

All the responding agencies have a construction specification on milling of asphalt pavements including specifications for specialized milling such as micro-milling (detailed comparisons of these specifications are discussed in chapter 3). Over 90% (11/12) of the agency respondents specify milling equipment and operational parameters either through standard specifications, provisional standards or through some other mechanism (Figure 3-7). The equipment parameters specified by agencies are summarized in Figure 3-8 (survey requested respondents to select all options that are applicable), whereas, Table 3-2 summarizes the responses in the "other" category with respect to the equipment and operational parameters stated in the agencies specifications. Only one thing to specifically note is that 1/3rd of the agencies does not list any. It can be inferred that: (1) There is a lack of consistency in the equipment and operational parameters required by various agencies; (2) Teeth dimensions and drum speed are not typically specified, nor is water application rate; (3) Majority of agencies rely on final outcome of milling operation as opposed to providing specific equipment or operational requirements. Note that these outcomes are based on thickness and observations of the milled surface. An understanding of the impact of equipment and operational factors on milling can help in the development of appropriate specifications. None of the agencies reported weather limitations as an operational parameter except for one agency; but it must be noted that the weather limitations were specified for cold in-place recycling activities. That indicates that weather condition has not been recognized as a significant factor that can affect milling.

One non-agency (engineering consultant firm) reported the drum size, teeth configuration/pattern and spacing, and pavement removal accuracy as equipment parameters listed in their milling specifications.

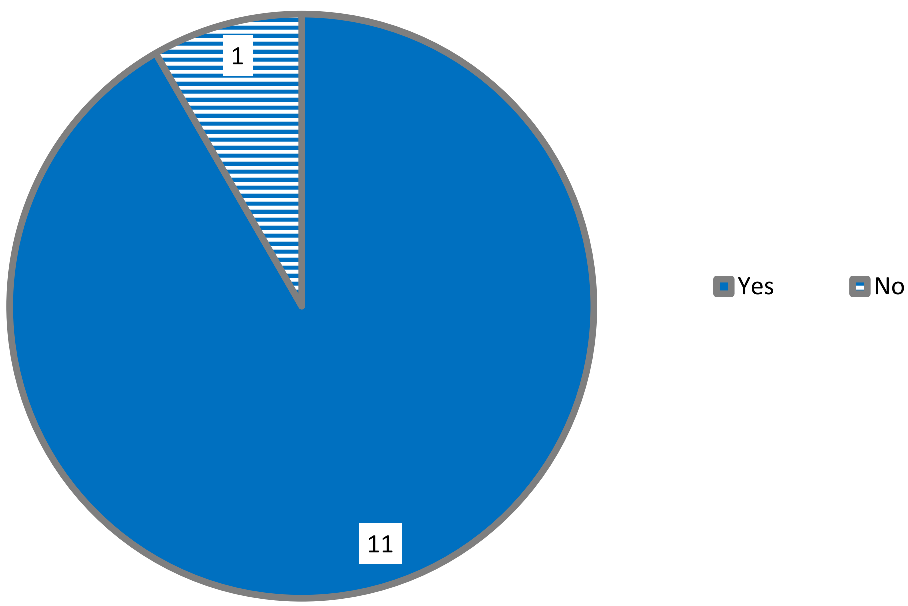


Figure 3-7 Distribution of agencies requiring milling equipment and operational parameter limits in their specifications (number of respondents= 12)

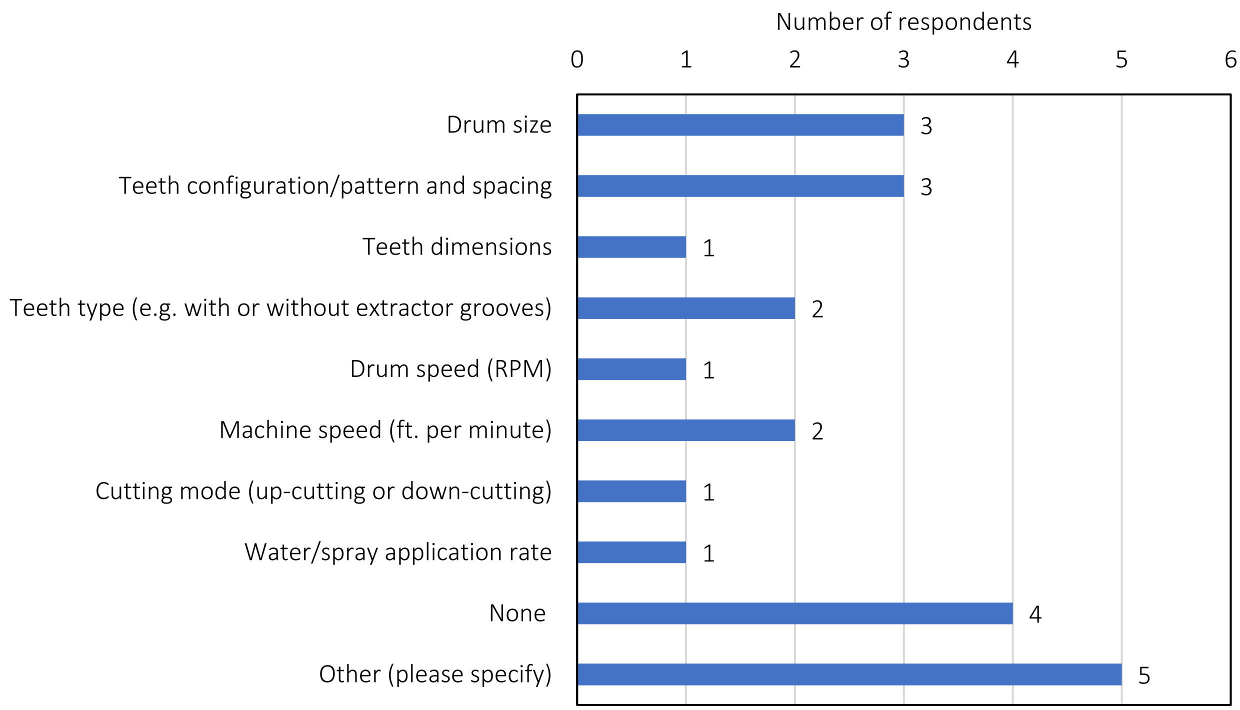


Figure 3-8 Distribution of agency responses with respect to equipment parameters specified in specifications (number of respondents= 12)

Table 3-2 Agency reported "other" equipment and operational parameters specified in specifications

Equipment parameters	Operational parameters	
Automated controlled grade leveling and slope control device	Ambient temperature	
Capability of removing the pavement surface to the necessary depth using cold planing equipment	Contractor to prevent ponding of water on milled surface	
Capability of milling the surface of one traffic lane in no more than two passes	Traffic of more than 5 days, the contractor is responsible for damage	
Milling drum with a minimum of 60 cutting teeth per foot of width with a transverse spacing of approximately ¼ inch	Weather limitations	
Cutting teeth with a cutting head face which is pointed to an angle of not more than 75 degrees		
Milling drum that produces a uniformly cut surface free of ridges		
Elevation and slope control		
Min 30 ft. skid length or rolling straightedge		
Transfer conveyors		
All other parameters can be adjusted to provide desired milled surface characteristics		
Longitudinal profile and transverse slope controls		

3.1.3 Effect of Pavement Condition on Milling Specifications

The survey asked for respondents to select factors related to the pavement condition that may impact the specification of milling operational and equipment parameters (survey requested respondents to select all options that are applicable). As shown in Figure 3-9, the amount of structural and surface distresses are the most common pavement attributes that may impact the milling specification. These are the more visible aspects of pavement condition. The less-visible aspects of pavement condition (e.g., pavement foundation stiffness/strength) are substantially less likely to impact the milling specification. Overall, more survey respondents had milling specifications for pavement structural conditions that were easily detectable upon visual inspection of the pavement surface. The underlying pavement conditions listed in Figure 3-9 do not have that important impact on the specification of milling. More specifications should include the investigation of subsurface layers condition and strength including base, subbase, and subgrade prior to milling activities by means of falling weight deflectometer (FWD). Surface distresses do not necessarily imply that the problem lays in the HMA layer only and further investigation needs to be done for subsurface layers. Milling machine weight and high energy may damage pavement in case of subsurface structural deficiency.

One non-agency stated all the options listed in Figure 3-9 as pavement condition that may impact specification of milling parameters.

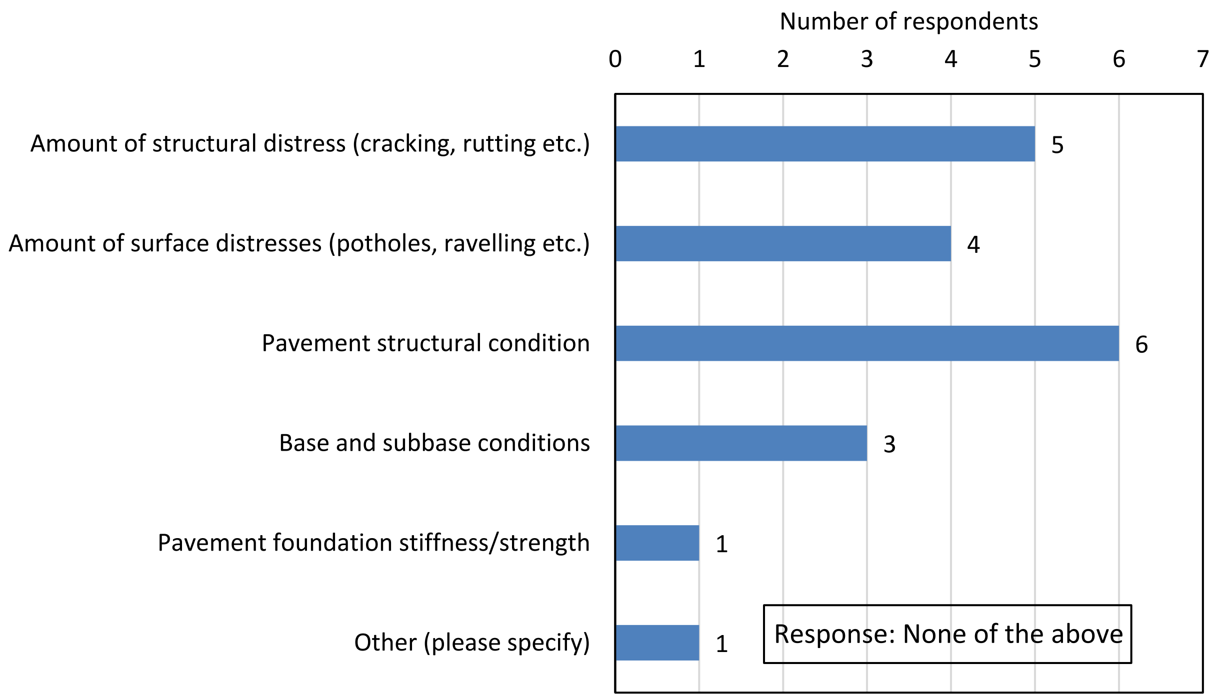


Figure 3-9 Distribution of agency responses with respect to pavement condition that may affect milling parameters specified in specifications (number of respondents= 11)

3.1.4 Milling Depth

The minimum, maximum, and most used milling depth, on the basis of projects conducted by respondents in the last two years, were surveyed. Results of this survey indicated that a range for milling depth of 0.5 to 6 in. is commonly selected by agency and non-agency respondents. The most commonly milling depths selected by agencies and non-agencies are summarized in Figure 3-10 and Figure 3-11, respectively. A milling depth of two inches is the most common among all agency and non-agency respondents. This reported number agrees with the most common pavement attributes that may impact the milling specification in terms of milling depth which is reported earlier as the amount of functional and structural distress, and with the common purpose and trigger of asphalt milling. Often, common surface distresses (e.g., raveling, potholes, rutting, and surface cracking) occur in the top couple inches of the pavement surface, therefore it may be enough to mill 2 inch to correct for surface distresses and some low to medium severity structural distresses. Agencies do not assess the extent of pavement deterioration (functional or structural) prior to determining the depth of milling but instead the selection is based on available budget and experience.

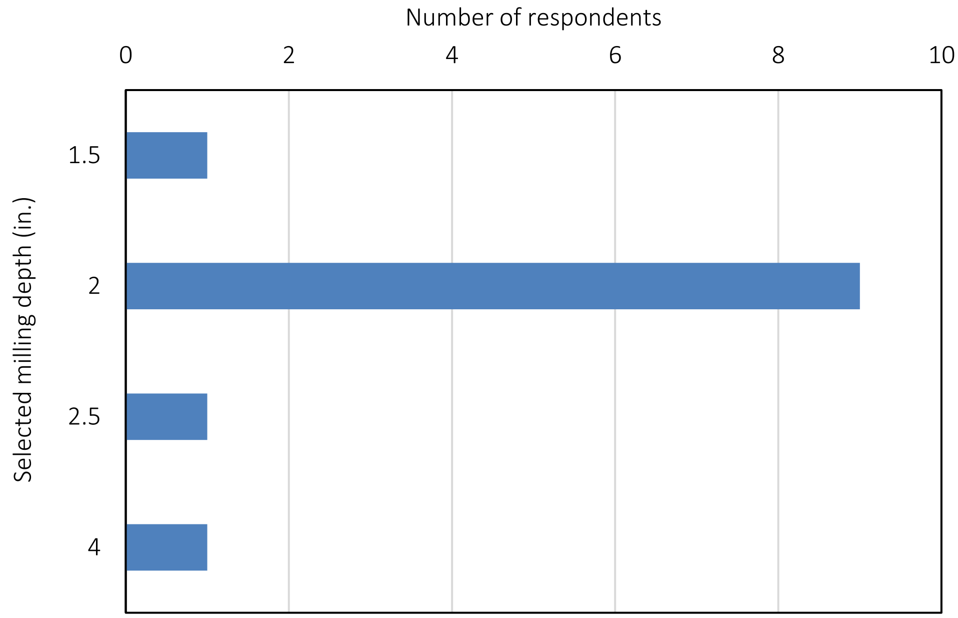


Figure 3-10 Agency responses with respect to the most common milling depth (number of agency respondents = 12)

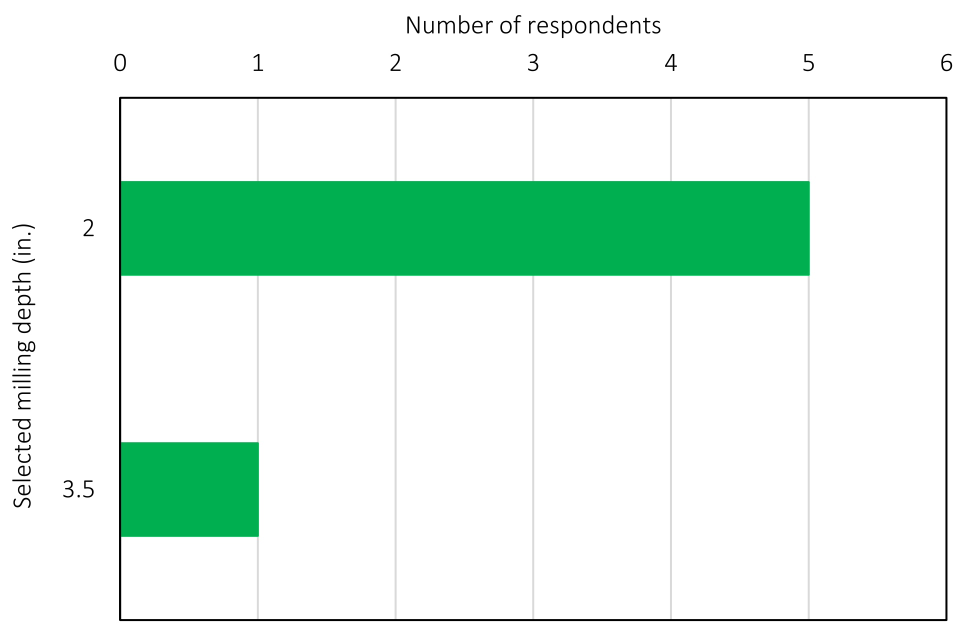


Figure 3-11. Non-agency responses with respect to the most common milling depth (number of non-agency respondents = 6)

Figure 3-12 and Figure 3-13 shows the agency and non-agency responses respectively for the factors that are used in determination of milling depth (survey requested respondents to select all options that are applicable). Half of the agencies indicated that the milling depth is determined based on the total asphalt thickness of milled pavement and the proximity of mill line to interface between two asphalt lifts, as illustrated in Figure 3-12. That statement highlights the importance of the total asphalt thickness and the proximity to lift interface in determining the milling depth. The thickness of individual asphalt lifts in the milled pavement is the second most used criteria to establish the milling depth. Approximately 1/3rd agency respondents revealed that the pavement design determines the final pavement structure after construction and therefore controls the milling depth. The bond between the asphalt lifts of existing pavement recorded the least responses (2 out of 12) in dictating the depth of milling. This last point further illustrates the importance of present study, since literature review has shown that interface condition can have significant effect on the extent of damage that milling operation can induce to the pavement below the mill line. Some agencies mentioned the importance of coring prior to milling to study the extent of stripping and deficient materials that will help selecting the milling depth. Another point that the agencies reported is that the milling depth always go somewhat beyond the interface which will eliminate the possibility of failures in overlays.

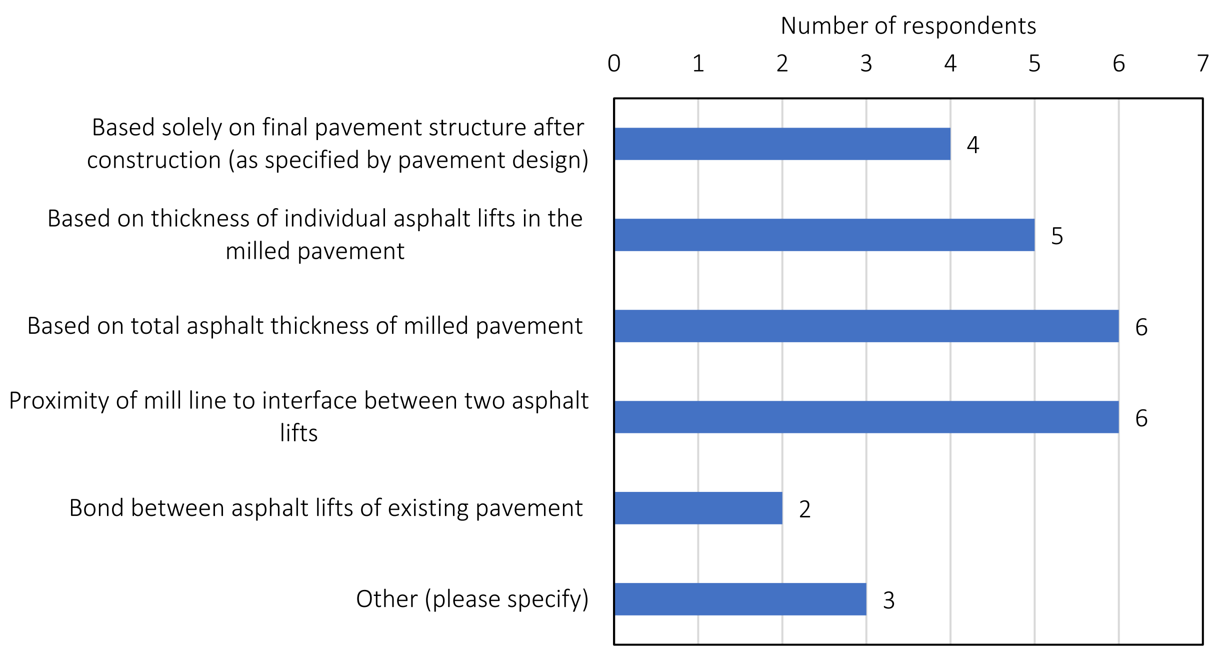


Figure 3-12 Distribution of agency responses with respect to selecting appropriate depth of milling (number of respondents = 12)

The distribution of non-agency responses matches with the agency responses, where the majority of entities (4 out of 6) determine the depth of milling based on total asphalt thickness of milled pavement and proximity of mill line to interface between two asphalt lifts, as presented in Figure 3-13. Half of the non-agency entities claim that the milling depth depends on the pavement design or on thickness of individual asphalt lifts, whereas 1/3rd of non-agencies determines the depth of milling based on the bond between asphalt lifts of existing pavement. Responses of agency and non-agency in the “other” section are summarized in Table 3-3. Non-agency reported that the selection of milling depth is part of the owner decision which brings back the point that milling depth is selected based on prevailing distress conditions and budgets.

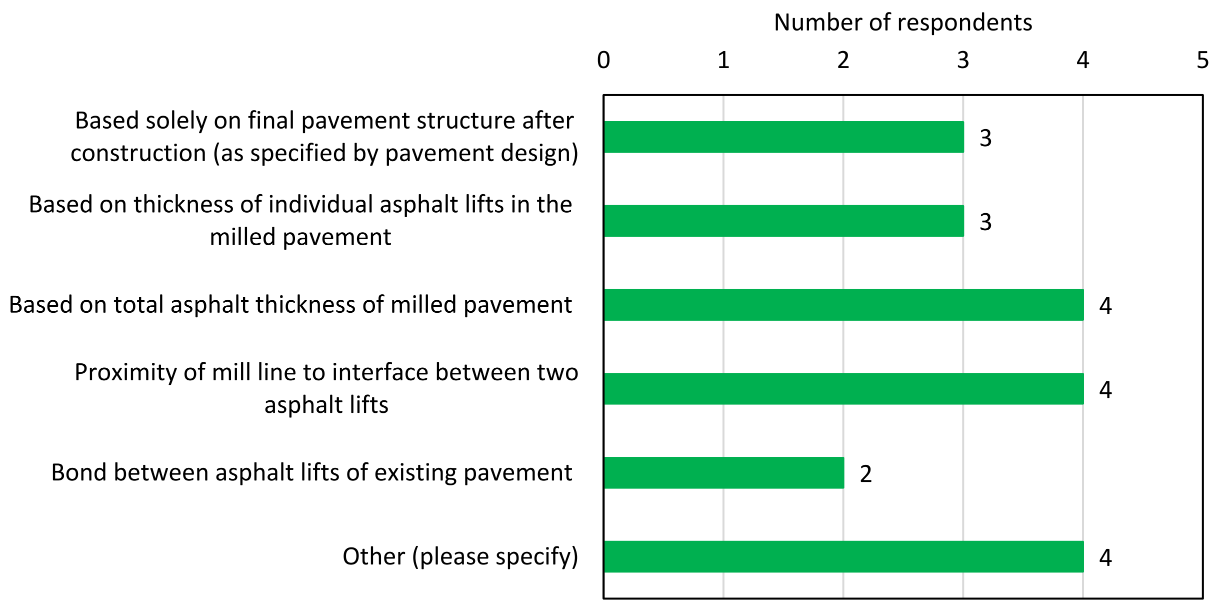


Figure 3-13 Distribution of non-agency responses with respect to selecting appropriate depth of milling (number of respondents = 6)

Table 3-3 Agency and non-agency reported "other" reasons to determine the depth of milling

Agency	Non-agency
Stripping is an issue. Coring operations are performed to determine if stripping is an issue and where that stripping may be taking place. Sometimes those results guide our decisions on how deep to mill	Depth selected by owner
Cores are cut to determine the necessary milling depth to remove deficient material	All factors are considered during evaluation stage prior to final pavement design recommendations
Mill depth would always go slightly beyond the bond interface	Based on smoothness requirement of the finished surface (to be paved back) after milling
No specific rules	Based on capabilities of available equipment

3.1.5 Assessment of Milled Surface Quality and Post-Milling Practices

After milling, the quality of the milled surface is evaluated using different measures. Figure 3-14 and Figure 3-15 show the responses of agencies and non-agencies, respectively, regarding specifications to evaluate the quality of milled surface (survey requested respondents to select all options that are applicable). Some agencies specify the quality of milled surface using the term "roughness," whereas others describe it as the "maximum vertical deviation in milled surface." The maximum vertical deviation is mostly commonly used by agencies to assess the quality of the pavement after milling (8 out of 12). The roughness of the milled pavement is considered by one-third of the agency respondents.

Three agencies take into account the amount of loose material in milled surface. Agencies need to acknowledge the importance of the amount of loose materials generated; cracked, crushed, and missing aggregate produced on the milled surface may be an indication of damage to the existing pavement due to the high stresses generated beyond the mill line or if it is due to stripping issues. Coring is critical in this case to visually assess the reason and extent of damage. One agency reported the importance of removing asphalt pavement without incorporating damages to the remaining pavement in place. However, this agency did not explicitly mention in their specifications how to quantify the extent of damage.

It can be noticed here that more than half of the agencies do not specify roughness in their milling specifications which align with the survey question about the purpose of milling, where agencies least ranked the removal of surface distress without overlay application as purpose of milling. Most agencies do not leave milled surface open to traffic and they apply an overlay; this negates the need for a roughness index.

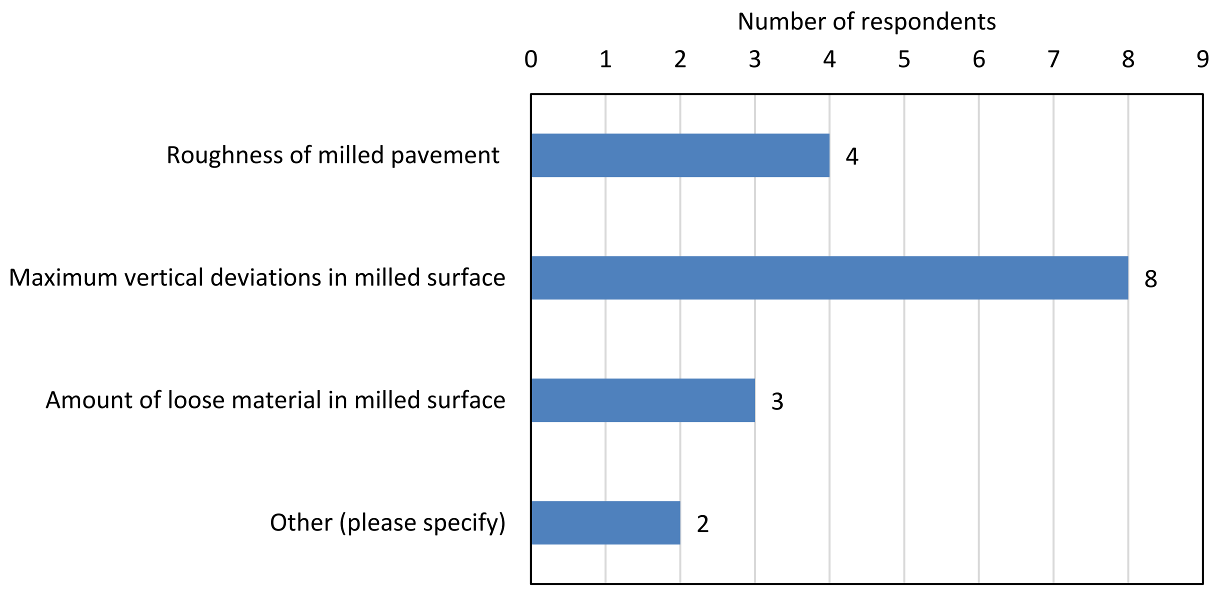


Figure 3-14 Distribution of agency responses with respect to specifying quality of milled surface (number of respondents = 12)

On the other hand, the roughness index is a measurement adopted by all non-agency respondents to evaluate the quality of milled surface. Non-agencies are beginning to introduce more end results requirements into specifications, particularly roughness, through clauses related to the quality of work and the contractor measurement and payment method in the bid project. Half of the non-agency respondents employ the maximum vertical deviations as a criterion to qualify milled surface, while only one company qualify the milled surface based on the amount of loose material in milled surface, as illustrated in Figure 3-15. Responses of agency and non-agency in the "other" section are summarized in Table 3-4.

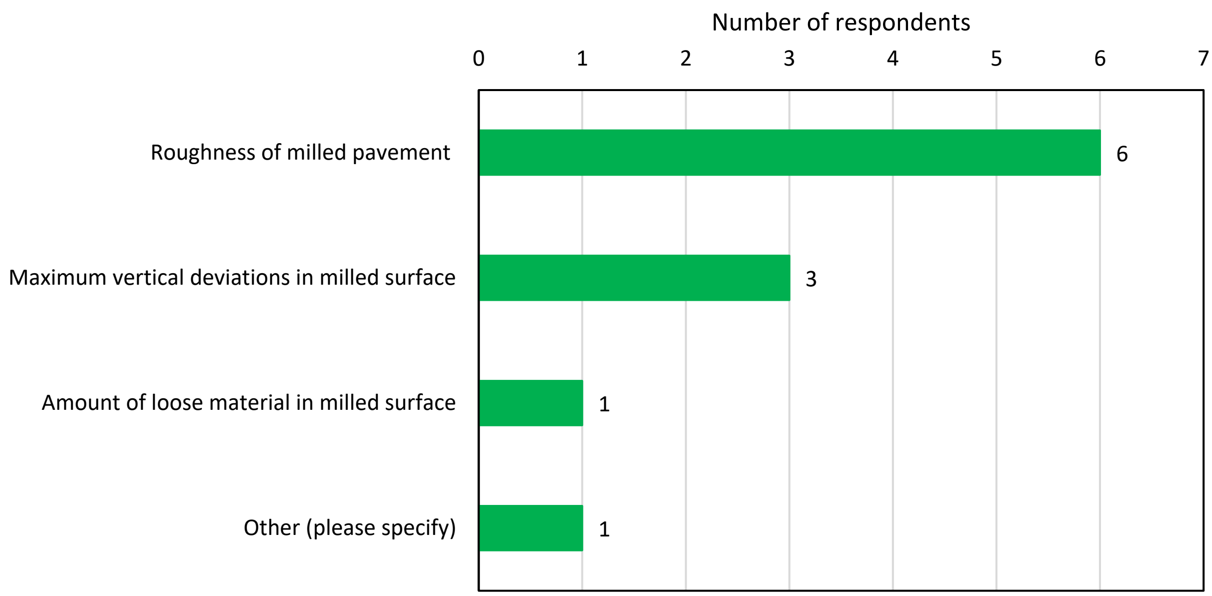


Figure 3-15 Distribution of non-agency responses with respect to specifying quality of milled surface (number of respondents = 6)

Table 3-4 Agency and non-agency reported "other" milled surface qualifications

Agency	Non-agency
Remove of existing asphaltic pavement or surfacing without incorporating or damaging underlying material that will remain in place. Provide a uniform milled surface that is reasonably plane, free of large scarification marks, and has the grade and transverse slope the plans show, or the engineer directs	Pattern design, whether it needs to be straight line or v form. This may fall under roughness, but pattern smoothness can also dictate interlocking capability of the new asphalt to the milled surface
Smoothness specification	

Asphalt milling is most often followed by the application of an overlay. Agency respondents reported a range for asphalt overlay thicknesses conducted in projects in the last two years, from 0.5 up to 6 inches each with a most common value of 2 inches for asphalt overlay. The ratio of the overlay thickness to milled depth as reported by agencies and non-agencies are shown in Figure 3-16 and Figure 3-17, respectively. Over half of the agency respondents and most of the non-agencies indicated that the milled depth is replaced by an overlay of the same thickness (ratio = 1) while the remaining indicated that an overlay thickness larger than the milled depth is used. The range of ratios larger than one vary between 1.26 - 2 for agencies and 1.5 - 2.5 for non-agencies. No respondents indicated that an overlay thickness less than the milled depth is typically used. The ratio of the overlay depth to the milling depth is specified by agencies and non-agencies based on budget, surface distresses, or pavement design.

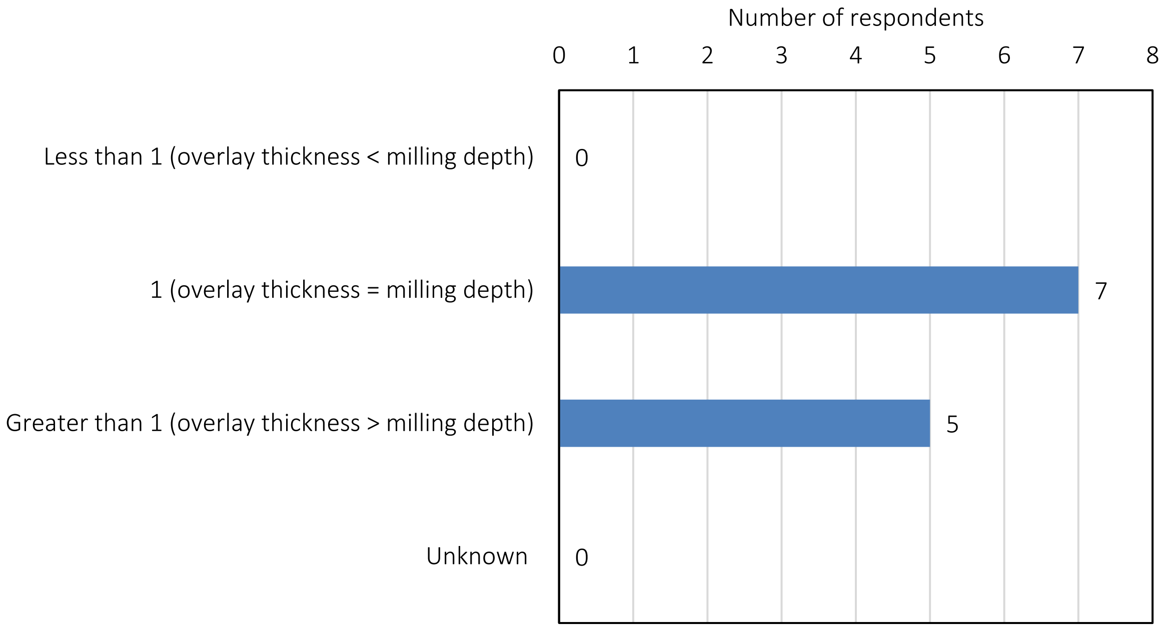


Figure 3-16 Distribution of agency responses for overlay thickness to milling depth ratio (number of respondents = 12)

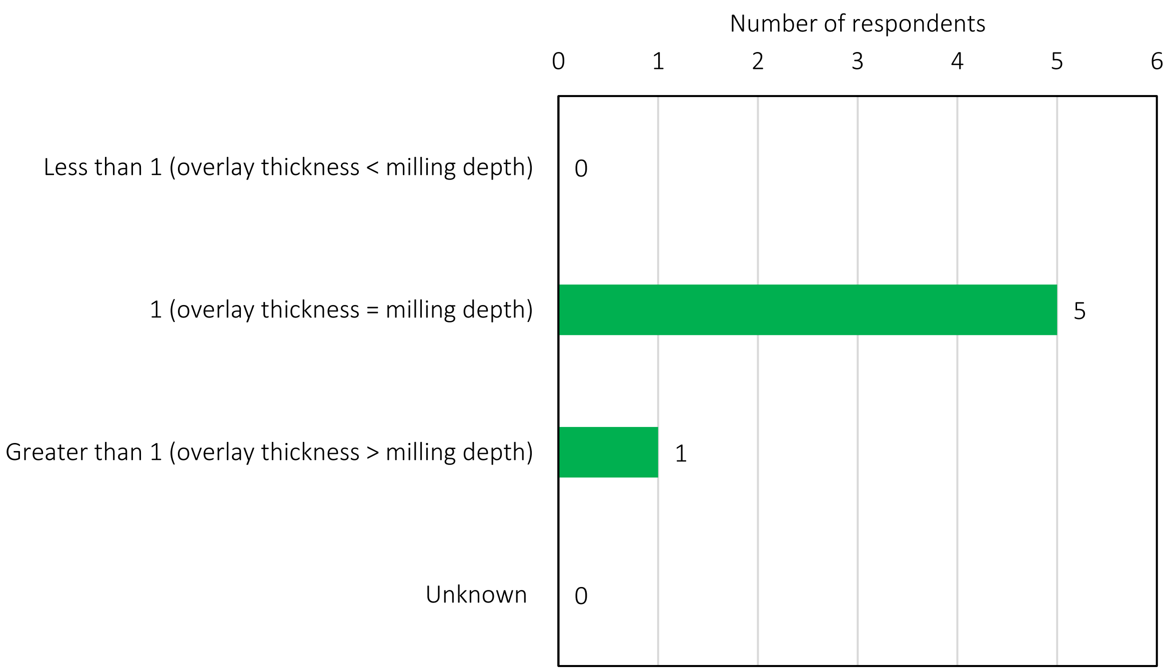


Figure 3-17 Distribution of non-agency responses with respect to selecting overlay thickness to milling depth ratio for M&O projects (number of respondents = 6)

3.1.6 Milling Survey Review Key Findings

Based on the collected responses from different agency and non-agency respondents in this survey report, the following key findings are presented:

- Almost all state highway agencies have construction specifications on milling of asphalt pavements.
- The main equipment parameters included in asphalt milling construction specifications are drum size, teeth configuration/pattern and spacing, grade leveling and slope control device.
- Ambient temperature, prevention of ponding of water on milled surface, traffic control, and weather limitations are the operational parameters that are listed in specifications.
- Pavement structural condition, amount of structural and surface distresses are the major pavement condition parameters that may impact specifications on milling projects.
- Most common asphalt pavement milling purposes are the removal of asphalt layer for overlay, reconstruction applications and profile correction.
- Improving structural capacity, using recycling techniques other than mill and overlay, and the existing pavement thickness are the principal reasons that may restrict members from milling asphalt pavements.
- Skid resistance improvements, roughness threshold reached, and milling of temporary pavements are the least common triggers that are used to reach decision for milling asphalt pavements.
- The total asphalt layer thickness of milled pavement, proximity of mill line to interface between two asphalt lifts, and thickness of individual asphalt lift are three main factors that are used to determine the depth of milling.
- Maximum vertical deviation and roughness in milled surface are the most commonly adopted criteria for assessing the quality of the milled surface.
- Asphalt milling depth and overlay thickness range between 0.5 and 6 inches, and most often the overlay thickness is the same as the milling depth.
- Agency asphalt milling specifications address parameters related to functional adjustment (e.g., smoothness, texture, milling equipment parameters) and environmental factors.
- Currently agency specifications do not address milling parameters that might cause structural damage and pre-mature failure of the overlay due to the milling related damage of the pavement below the milling line.

3.2 Review of Milling Specifications

This chapter describes the review the research team conducted in 2021 of milling and micromilling specifications of NRRA member agencies and that of Texas Department of Transportation (NRRA associate member Transtec Group recommended that Texas DOT specifications be considered in review due to some pertinent aspects of Texas DOT specifications as they relate to current research study).

Standard specifications for cold planing (CP) usually focus on several items, including general description, material requirements, equipment requirements, construction methods, inspection and quality control/quality assurance, acceptance requirements, and measurements and payment. Most of the agencies do not include all of the previously mentioned items. However, the purpose of this project is to assess the extent of damage done by the milling operation on the existing pavement. Therefore, in this review emphasis was placed on the current state of practice with respect to selection of appropriate milling depths as well as parameters associated with equipment and construction operations.

Equipment requirements section in the milling specifications can describe all equipment included in the milling process from the milling machine condition/size/production capability (self-propelled, cut width/depth, drum configuration, and cutting teeth), removal of RAP and integral loading system, dust control equipment, through automatic grade and slope controls equipped with the cold planer. All these listed parameters are recommended to be assessed in agency milling specifications due to their potential impact on the stresses generated in the existing pavement during milling operations.

Examples of specifications that can be included in the construction methods section are those that are related to the changing of cutting tooth, grade and cross slope requirements, surface texture, maximum allowable time prior to resurfacing, requirements for longitudinal edge drop-off, mill depth adjustments, amount of water used during milling, cleaning of milled surface, and opening the milled pavement to traffic. Parameters are chosen based on their effects on the quality of milled surface and structural capacity of the milled pavement during and after milling.

Specifications and construction guidance documents for each NRRA member agency were reviewed and findings were summarized. Only one agency provided specification for micro-milling of asphalt pavement. The following sections describe the equipment requirements and parameters controlled or required in construction specifications of asphalt milling and micro-milling.

3.2.1 Equipment Requirements

Table 3-5 summarizes the findings with respect to the equipment specifications used by NRRA member agencies for milling and micro-milling asphalt pavement. Appendix D includes a summary of equipment factors in each agency's specification. This information is provided in tabular format and organized by agency surveyed. A review of milling and micro-milling specifications shows that specifications do not address parameters that might cause damage to material below mill line to existing pavement (e.g., machine speed, milling depth, proximity from lift interface, and pavement temperature), but instead, the only concerns that have been addressed so far are that of safety, environmental factors, and accuracy. Most of the agencies specify a self-propelled machine to be used and all agencies require milling machine equipped with automated grade and cross slope control to minimize surface roughness and pertain accuracy.

The removal of cuttings and discharge device is specified by four agencies in term of conveyor belts and discharge of the cuttings in hauling trucks, which minimize the need for stockpiling the milled material on the side of the milled road and minimize cleaning effort. Milling operation variables such as milling depth, milling speed, drum rotational speed, drum diameter, teeth geometry and configuration, teeth condition are partially specified by one agency. This indicate that agencies tend to include parameters in their milling specifications as an end results specification to obtain a good quality milled surface (less roughness and good surface texture) instead of specifying milling equipment parameters. Higher milling (cutting) speeds results in a higher friction, good texture, and better productivity without affecting the milling pattern but it is opinion of research team (based on numerical simulations undertaken by them in previous research) that this also causes higher stresses in the existing pavement under the milling depth. Half of the agencies address environmental concerns in their milling specification by having control dust device in the cold planing machine; however, it is recommended that the amount of water used for dust control needs to be limited to avoid water infiltration in the existing layer and evade potential stripping.

Table 3-5 Equipment specifications of NRRA agency with respect to milling and micromilling of asphalt pavement

	State	Self-propelled machine	Cut width/depth	Automated longitudinal and transverse grade control	Cuttings removal and discharge device	Control dust device	Milling drum configuration	Cutting teeth
Asphalt milling	Illinois DOT	Yes	Min 6 ft./1 ½ in.	Yes	-	Yes	-	-
	Texas DOT	Yes	Min 6 ft./4 in.	Yes	Yes	Yes	-	-
	Caltrans	-	Same as planing width	Yes	-	Yes	-	-
	Iowa DOT	-	-	Yes	-	-	60 cutting teeth per ft. with transverse spacing of ¼ in.	Pointed to an angle of not more than 75 degrees
	Michigan DOT	-	-	Yes	-	-	-	-
	Minnesota DOT	Yes	-	Yes	-	-	-	-
	North Dakota DOT	Yes	-	Yes	Yes	-	-	-
	Missouri DOT	-	-	Yes	Yes	Yes	-	-
	Wisconsin DOT	Yes	-	Yes	-	Yes	-	-
	Mississippi DOT	Yes	Min 4 ft.	Yes	Yes	-	-	-
Asphalt micromilling	Texas DOT	Yes	12 ft.	Yes	Yes	Yes	60 cutting teeth per ft. with maximum tool spacing of 5/8 in.	-

3.2.2 Parameters Controlled or Required in Construction Specifications

Table 3-6 summarizes the findings with respect to the construction specifications used by NRRA member agencies for milling asphalt pavement. Appendix E includes a summary of parameters controlled or required in each agency's specification. This information is provided in tabular format and organized by agency surveyed. A review of milling and micro-milling specifications shows that smoothness criteria is specified in the construction specification by almost all the agencies. This indicates that agencies are leaning toward assessing the end product of milled asphalt by including the smoothness parameter. All agencies except one omit surface texture as a milling specification, while this parameter is important in micro-milling specifications to assess the surface of the milled pavement. This aligns with the fact that almost all agencies apply overlay immediately, obviating the need to take into consideration the surface texture of a milled road surface open to traffic. The majority of agencies do not specify maximum allowable time before resurfacing or maximum time allowed for traffic on milled surface because they apply overlay immediately. It should be noted that traffic on pavements surface subjected to micro-milling is not allowed due to the small difference between the ridge and valley in micro-milling compared to conventional milling, where traffic on the surface especially in warmer climate will cause the difference between the ridge and valley to diminish, thus affecting the bond between the existing pavement and the overlay.

Only one agency specified the mill depth adjustment. This aligns with the fact that this specification is based on project goals and that they must consider the proximity of the mill line to the interface layers and correct damage induced from breaking the aggregates. Surface cleaning is a major parameter listed by most of the agencies. Cleaning and sweeping the milled surface not only help with improved bonding from tack coat prior to overlay, it can also help in assessing the amount of damage induced by the milling operation. Quantifying the damage in terms of the loose material generated during sweeping of milled surface is not specified in agencies milling specifications. In addition, cleaning the surface from debris prior to application of overlay results in a good bond between the existing pavement and the overlayed surface. Some agencies prevent water from ponding to milled surface. Water application is important for milling application to keep the milling teeth from heating up excessively and minimize the generation of dust. However, the water application rate needs to be controlled to prevent excess water from infiltrating in the aggregate and surface causing potential stripping issue.

Only two agencies specify the check and the change of worn-out cutting teeth. This parameter is important in terms of creating a good surface texture on the milled surface for an ensuring interface bond between the milled surface and the overlay and in terms of surface texture and skid resistance specifically if the milled surface is to be opened to traffic. Another point to note is that in the case of using worn teeth, the generated pavement will have poor smoothness and surface texture which requires more passes to correct for irregularities and thus inducing more stresses in the existing pavement. Milling specifications do not state the personnel on the project. The milling project personnel must have the experience to evaluate the milled surface and authority to make field adjustments to the milling operation. Finally, the depth to milling decision is not specified and is primarily based on project goals and economics, with minimal consideration of existing pavement properties.

Table 3-6 Construction specifications (smoothness, surface texture, maximum allowable time before resurfacing and maximum adjacent lane drop-off) of NRRA agency with respect to milling and micro-milling of asphalt pavement

	State	Smoothness (straightedge)	Surface Texture	Maximum allowable time before resurfacing	Maximum adjacent lane drop-off
Asphalt milling	Illinois DOT	Max 3/16 in. in 16 ft. (longitudinal)	-	Within 10 calendar days	-
	Texas DOT	Max 1/8 in. in 10 ft. (longitudinal)	Min 0.05 in.	-	-
	Caltrans	Max 0.02 ft. in 12 ft. (longitudinal) Max 0.03 ft. in 12 ft. (transverse)	-	-	-
	Iowa DOT	Max 0.02 ft. in 12 ft. (longitudinal) Max 0.03 ft. in 12 ft. (transverse)	-	-	2 in.
	Michigan DOT	-	-	-	-
	Minnesota DOT	Max ½ in. in 10 ft. (longitudinal and transverse)	-	-	-
	North Dakota DOT	Max ¼ in. in 10 ft. (longitudinal)	-	-	-
	Missouri DOT	Max ¼ in. in 10 ft. (longitudinal)	-	On same day or night shift	-
	Wisconsin DOT	-	-	-	2 in.
	Mississippi DOT	-	-	30 days	2 ¼ in.
Asphalt micromilling	Texas DOT	Max 1/4 in. in 12 ft. (longitudinal)	0.2 in. center to center of each strike area (transverse) with max 1/16 in. difference between the ridge and valley	-	-

Table 3-7 Construction specifications (maximum time allowed for traffic on milled surface, ,mill depth adjustment, surface cleaning, water ponding and cutting teeth change) of NRRA agency with respect to milling and micro-milling of asphalt pavement

	State	Maximum time allowed for traffic on milled surface	Mill depth adjustment	Surface cleaning	Prevent water ponding on milled surface	Change of cutting tooth
Asphalt milling	Illinois DOT	-	-	-	-	-
	Texas DOT	-	-	Yes	-	-
	Caltrans	-	±0.03 ft. to achieve longitudinal and transverse smoothness ±0.05 ft. for delamination	-	-	Yes
	Iowa DOT	-		Yes	Yes	Yes
	Michigan DOT	-	-	Yes	-	-
	Minnesota DOT	-	-	Yes	-	-
	North Dakota DOT	5 days	-	Yes	-	-
	Missouri DOT	-	-	Yes	Yes	-
	Wisconsin DOT	-	-	Yes	-	-
	Mississippi DOT	-	-	-	Yes	-
Asphalt micromilling	Texas DOT	Not allowed	-	Yes	-	-

3.2.3 Milling Specification Review Key Findings

According to the review of the agency milling and micro-milling specifications, the following key findings can be drawn:

- The potential damage of the milling operation to the existing pavement material below the mill line is a new research study that has not been looked at by agencies, hence current specifications do not address parameters to prevent it and only tackle safety, environmental, and accuracy concerns.

- A self-propelled cold planing machine equipped with automated grade and cross slope control is specified in equipment specification by almost all agencies.
- Some equipment specifications require that the milling machine is equipped with removal of cuttings and discharge device.
- Milling operation variables such as milling depth, milling speed, drum rotational speed, drum diameter, teeth geometry and configuration, and teeth condition are almost not specified in any agency's' equipment specification.
- Agencies do not specify milling equipment parameters in their specifications and include an end result parameter to evaluate milled surface.
- Environmental concerns are addressed in the equipment specification of some agencies by having cold planing machines equipped with dust device control.
- Smoothness criteria of the milled surface is specified in the construction specification by almost all the agencies.
- Surface texture of the milled surface is addressed by only one agency as construction specification.
- The majority of agencies do not specify maximum allowable time before resurfacing or maximum time allowed for traffic on milled surface.
- At present, agencies do not always specify the proximity of the mill line to the interface layers in determining the milling depth, which is specified based on project goals; therefore, agencies specify the mill depth adjustment to correct for irregularities.
- Cleaning of the milled surface is a major construction parameter listed by the majority of the agencies.
- Agencies do not quantify in their construction specification the damage induce by the milling process in terms of the generated loose material.
- Prevention of water from ponding on the milled surface is specified in construction specification of some agencies,
- The application rate of the water spray on cutting teeth is not included in the milling construction specification.
- The change of worn cutting tooth prior to milling operation is only specified in the construction specification of a minority of agencies.
- Micro-milling of asphalt pavement is a substitution technique for conventional milling. Only few agencies have developed mature micro-milling specifications.
- Traffic is typically not allowed on micro-milled pavement.

3.3 Summary

The scope of this presented state of practice survey and review of agency specifications aimed to document the current approaches in determining milling depth and equipment, and parameters required of different state highway agencies, contractors, and equipment manufacturers. Survey respondents were a total of 18 NRRA members including 12 agency members from different state Department of Transportations (DOTs) and other transportation agencies, and 6 non-agency (associated) entities from various consulting firms, equipment manufacturers, and contractors. The survey review is complimented by a review of milling operations criteria available in milling specifications of different agency respondents.

Based on a review of research data and literature, and the current survey and specifications, the research team identified specific items which are not currently considered by some of the agency specifications:

1. Consideration of the effect of milling parameters on the pavement layers below the milling line.
2. Replacement of worn-out cutting teeth beyond a threshold wearing.
3. Appropriate qualifications of the milling personnel in order to evaluate milling.
4. Watering of cutting teeth.
5. Ponding of sprayed water on the milled surface.
6. Type of interface bonds between the milled and remaining layer (which dictates stress penetration).
7. Assessing of the underlaying pavement condition prior to milling.
8. The time between milling and the overlay, especially when the pavement will be open to traffic.
9. Cleaning and sweeping after milling operation to assure a durable bond with the overlay.
10. Assessing the damage to the existing pavement in terms of loose material generated.
11. Proximity of the mill line to the lift interface in determining the milling depth.

3.3.1 List of Parameters to be Considered in Selection of Study Sites

In this subsequent task, testing and sampling plans for both in-situ and laboratory testing were established to quantitatively assess the impacts of milling operation on mechanical integrity of the milled asphalt pavement by selecting suitable projects to include in this study. The outcome of this task will help researchers establish a list of projects that require rehabilitation (e.g., mill and overlay) in order to study the impacts of asphalt milling operations on existing pavement. Synthesis of various agency practices as well as industry preferences provided information to the researchers that is helping guide the project selection process. An initial list of significant parameters is established based on the asphalt milling operations literature review, survey and milling specification review. This list will help in the selection of sufficiently varied projects and will be finalized with input from the project Technical Advisory Panel (TAP). Age of pavement, structure of existing pavement, type and condition of pavement, depth of milling and its proximity to the mill line, operational and equipment parameters, pavement temperature ability to obtain ride-quality and texture information on the milled surface, and timing between milling and post-mill overlay construction sum up the list of parameters that is believed to have significant impacts on the post-milled pavement condition and will be used to guide the activities in other tasks. Each variable is described next.

- Age of pavement:
  Asphalt durability is another measure for age hardening, which refer to how the asphalt binder physical properties change with age. A number of factors results in aging of asphalt binder, the principal ones being oxidation, volatilization, polymerization, thixotropy, syneresis, and separation. In general, as the asphalt binder ages, its viscosity increases, and it becomes stiffer and brittle. As a result, asphalt pavements age with time and become stiffer. The stiffer the

asphalt pavement the more it will resist rutting, but the more it will be susceptible to cracking. Aging of asphalt pavement may also have an effect on the strength of bond between the asphalt lifts. As pavements age, it is expected that more damage below the mill line may be generated from milling activity.

- Structure of existing pavement (lift and their thicknesses):
  It is important to identify the structure of existing pavement, which consists of the number of different lifts of an HMA layer and their thicknesses. Coring at full depth prior to milling will help identify this matter. Recognizing the structure of existing pavement would help select the milling depth by first knowing the extent of distress on the pavement surface and by knowing the proximity of the mill line to the interface. The closer the distance, the more damage will be induced under the mill line in the case of a strong bond between the lifts.
- Type and condition of pavement subsurface layers (base/subbase/subgrade):
  Condition of underlaying layers needs to be assessed by means of FWD testing prior to milling operation just to test the structural capacity of the layers below the asphalt layer. The milling process is a high energy process in addition to the heavy weight of the milling equipment used; any structural deficiency in the base, subbase, or subgrade layers will result in the failure of the pavement and defeat the purpose of milling.
- Depth of milling (especially proximity of existing pavement layer interface to milling line):
  Milling at any depth provoke the development of high stresses below the milling line. Stresses higher than the tensile strength of HMA are generated underneath the milling depths and will be affected by the bonding between the different asphalt layer lifts. Milling at a depth close to the interface depth will trigger failures in the overlay often as isolated potholes, debonding from upper layer, and delamination of upper layer, under traffic loading.
- Operational/equipment parameters: Drum diameters, speed (rotational speed of drum and longitudinal speed), teeth wrap patterns, teeth density, teeth condition, etc.:
  Operational and equipment parameters have a significant impact on the damage induced below the mill line during milling operation. Increase in the machine and the drum speeds result in higher friction and texture of the milled surface and in less chunking of the material and better productivity without affecting the milling pattern. However, the damage to the existing pavement is increased with the increase of cutting speed (machine or drum speed) in the milling process. The maximum stresses and stress distributions below the mill line is highly affected by the milling drum speed.
- Pavement temperature:
  Milling of pavement will be considered in two different time of the day, one early in the morning where the asphalt pavement is relatively stiffer due to the low temperature and one during the evenings where the pavement is considerably to be relatively less stiff due to the high temperature during the day. Milling when the pavement is less stiff creates less damage to the existing pavement. Pavement temperature is a variable constant during the milling process; it can vary daily (during the day between day and night) or changes between projects, and also between season and another (month of July vs. month of October). Milling on the same project or during the same time of the day results in limiting the variability of pavement temperature which must be considered in the analysis.

- Ability to obtain ride-quality and texture information on the milled pavement:
  The milled asphalt pavement surface needs to be assessed in term of ride-quality and texture information to evaluate the milling process. A good ride-quality and surface texture indicates the success of the milling process and operation. Another aspect of having good and consistent milled surface texture is to assure a good bonding between the existing pavement and the overlayed asphalt layer. A more consistent way to assess surface texture is to measure macro texture depth (using methods such as sand patch test).
- Timing between milling and post-mill overlay construction:
  Timing between milling and post-mill overlay construction is important to be studied because the milled pavement would be open to traffic for few days prior to overlay. During this time, the milled pavement would be exposed to traffic which, depending on the loading/volume of traffic, might induce some damages and distresses to the existing pavement especially when the purpose for milling is to add structure to the pavement. Another aspect is that cracks in the exposed milled asphalt pavement would heal during warmer time under traffic.

Based on the parameters discussed above, the research team worked with NRRA member agencies and associate members and the project TAP and identified rehabilitation sites and selected five suitable milling parameters to be evaluated. A 500 ft. long study section for each parameter (or multiple 500 ft study sections for each parameter) were identified. These sections were selected to represent uniform conditions from the perspective of pavement and construction operations.

Chapter 4: Project Identification and Sampling

This section discusses the process of identifying and selecting the milling parameters that were evaluated through this study. It further details the material sampling methods used to conduct this project, along with the sampling plans. It also describes the structures of the pavement study sections that were established at the MnROAD research facility where pre- and post-milling cores were collected to evaluate the impact of milling. Five different operational and pavement parameters were studied, each with multiple variations to provide a balanced evaluation of the impact that milling and different milling parameters can have to the asphalt layer that remains directly below the mill line.

4.1 Project Methods

As discussed in Section 1 of this report, the overall objective of this project is to evaluate if the high-stress activity of milling has an impact to the asphalt layer that remains directly below the mill line. Five different operational and pavement parameters were evaluated under variations of milling parameters to evaluate if different parameters impacted the asphalt that remained below the mill line differently. To conduct this study, pre-milling cores were collected, milling was performed under different parameter variations, and then post-milling cores were collected directly adjacent to where the pre-milling cores were collected. The pre-milling cores were trimmed to represent the pavement layer just below the mill line, as depicted in Figure 4-1 below. Without trimming, the post-milling cores represented the pavement layer just below the mill line, but were trimmed minimally to create a smooth surface, eliminating the indentations from the teeth on the milling drum. All cores were trimmed using a circular saw under the same parameters, and it was therefore assumed that the trimming effect was equally applied to both the pre- and post-milling cores. The average thickness of both the pre- and post-milled cores after trimming was between 38 – 51 millimeters (1.5 – 2 inches). The trimmed cores were then evaluated in the laboratory to evaluate potential impacts from milling.

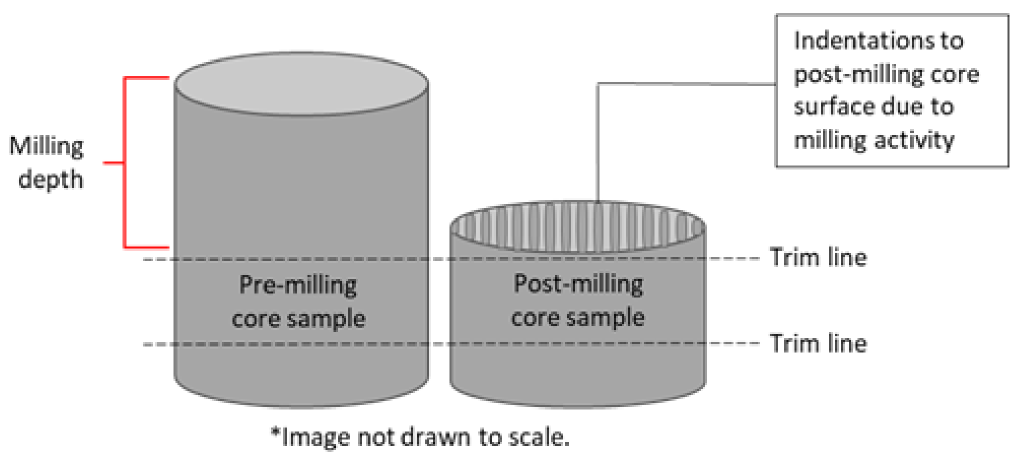


Figure 4-1 Core Trimming Sketch

4.2 Study Parameter Prioritization and Identification

This section focuses on the identification, prioritization, and selection of the testing parameters determined by the research team. There are multiple parameters that fluctuate between and within milling operations. Different pavement sections can feature different structural designs and conditions of the pre-milled pavement. Additionally, different milling equipment plans can offer different operational parameters, such as, mill drum rotational speed and cutter bit patterns for milling the asphalt. These parameters can affect properties and structural condition of the post-milled pavements. Each parameter may or may not have an effect on the post-milled pavement properties. Thus, it is important to evaluate these parameters in a controlled field setting. The previous sections of this report present the comprehensive literature review and survey of agencies that were the initial steps of this project. The literature review along with the survey results were utilized by the research team to identify relevant study parameters.

The research team at the University of New Hampshire worked with the project TAP, MnROAD personnel, and the milling contractor to select eight milling or existing pavement parameters that could be studied to determine if they impacted the asphalt layer that remained below the mill line: the age of the pavement, the structure of the existing pavement, the type and condition of the pavement's subsurface layers, the depth of the milling relative to the interface layers, the operational and equipment parameters of the milling machines and the crew, the pavement temperature both before and after the milling process is complete, and the timing between the milling operation and the post-mill overlay construction. Further, the ability to obtain ride-quality information on the milled surface was also considered as a criterion in selection of study site location. The parameters were then utilized in the field sampling and testing conducted at the MnROAD research site. Figure 4-2 shows milling underway at the MnROAD test site. Each variable was mapped to a specific section of the MnROAD site. In-situ testing was conducted by MnROAD staff, cored samples were obtained before and after milling and samples of milled materials were taken from each test cell. Each cored specimen was assigned a study parameter specific designation code.

Figure 4-2. Milling Operation at MnROAD Research Facility in May 2022

4.2.1 Brief Description of Study Parameters

The initial study parameters were prioritized, and five were selected to be studied through this project. Table 4-1 provides the finalized list of selected study parameters along with a brief rationale of their selection. These parameters were internally prioritized by the research team to ensure that those with highest potential for impact to study objectives would be considered in the field experiment design. The main factors considered include importance to test, ease of controlling the parameter between study sections, and ease of controlling the parameters within a test section. The team had determined that resilient modulus (Mr) and the indirect tensile strength (ITS) tests on pre-milled and post-milled specimens would be primary indicators of the effects of milling. Further, gravimetric and permeability testing would also be employed on both pre- and post-milled specimens. Lastly, in-situ deflection testing was performed on some of the study sections by the MnROAD staff to supplement the laboratory evaluated properties. Multiple variations of each milling or pavement parameter listed in Table 4-1 were evaluated and are described in later sections of this report. As each parameter that was being studied was varied, all other milling parameters were held constant; this includes the milling machine, the forward-moving speed of the milling machine, the type of teeth used to perform the milling, and all other variables, other than the one being evaluated at that time.

Table 4-1 Selection of Study Parameters

Parameter Name	Reasoning
Structure of Existing Pavement	Allows to study different types of materials and pavement conditions at time of milling. This parameter requires use of different pavement sections.
Timing between Milling and Post-mill Overlay Construction	Damage or healing can occur in post-milled pavements when it is left exposed to environment (and traffic) prior to overlay application.
Depth of Milling Relative to the Interface Layer	Proximity of mill line to asphalt layer interface has been shown in lab and computer simulations to strongly impact properties of post-milled pavements from milling. This parameter can be studied within a same pavement section by changing location/depth of mill line.
Operational and Equipment Parameters	Energy input changes drastically with the change of operational and equipment parameters and hence the potential for damaging post-milled pavements. These parameters can be studied within a pavement section by changing operational and equipment parameters at specific interval.
Pavement Temperature	Pavement temperature changes asphalt mixture's mechanical properties and thus can impact effects of milling on pavement. This parameter can be studied within same pavement section by altering time of milling (either seasonally or over course of day).

4.3 Test Section Plans

The research team worked with MnROAD staff and Caterpillar milling crews to determine how each milling parameter would be tested at the MnROAD test site. The research team collaborated with MnROAD staff to determine what areas of the MnROAD site were in acceptable condition for inclusion in this study. Then, the team determined which milling parameters would be tested within each section; this was guided by the pavement structure in each of the cells and the area needed for the testing of each milling parameter. The map of the test site, shown in Figure 4-3 and Figure 4-4, shows the various test sections and planned total milling depths that were available for the team. The areas selected for evaluated each milling parameter are further shown in Figure 4-5, while Table 4-2 summarizes the MnROAD cells used for evaluating each milling parameter.

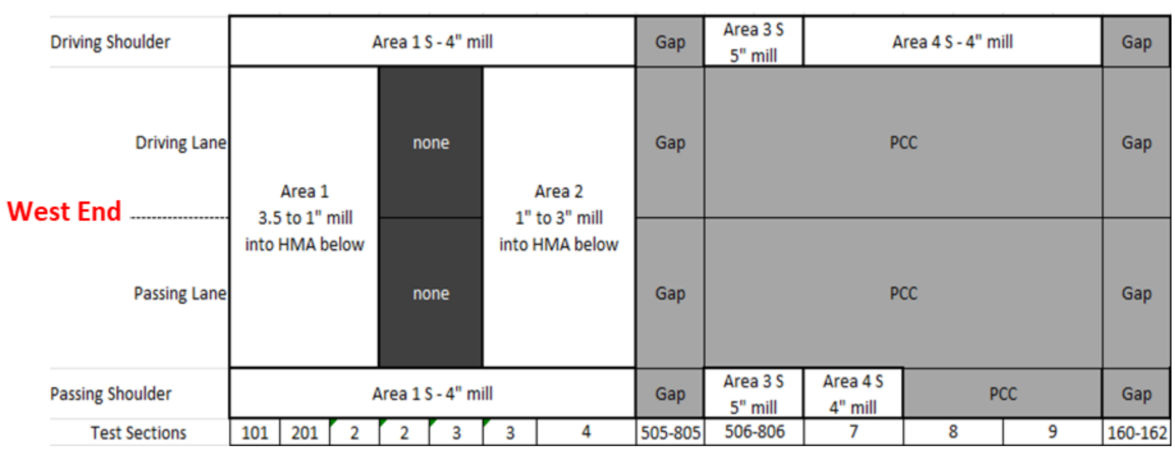


Figure 4-3 Map of MnROAD Test Site, West End (areas shown that were milled in 2022, not to scale)

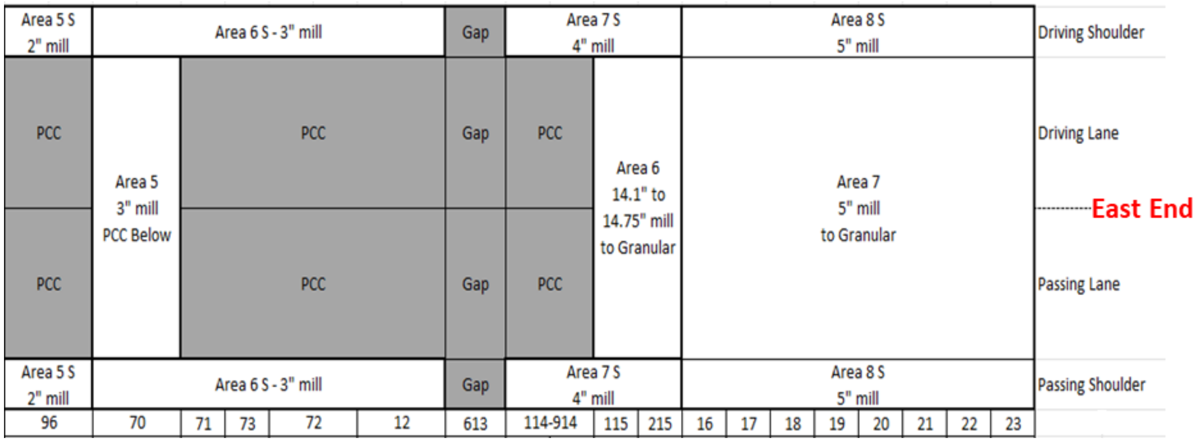


Figure 4-4 MnROAD Test Site East End (highlighted areas were used in this study, not to scale)

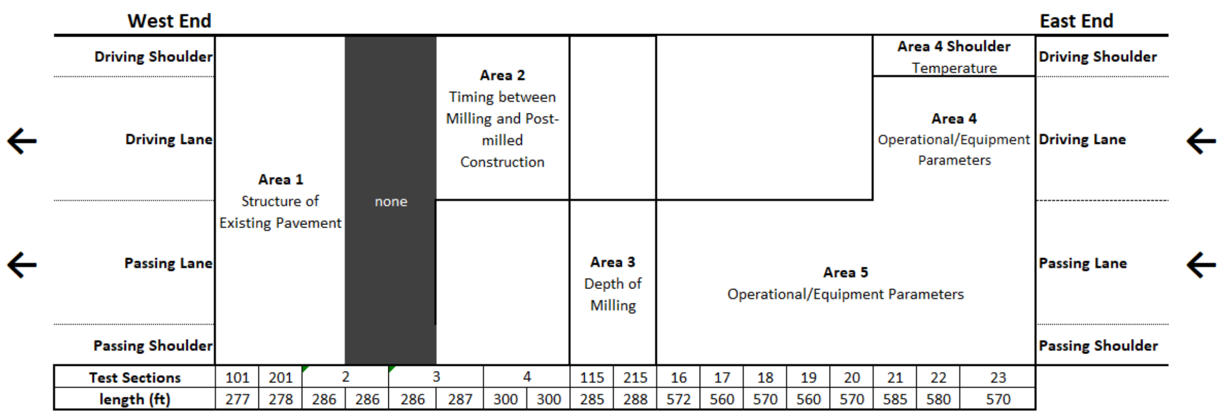


Figure 4-5 Map of MnROAD Test Site, Milling Areas Map, Plan View (not to scale)

Table 4-2 Mapping of Parameters to MnROAD Milling Areas and Cells

MnROAD Cell	Designated Lane/Shoulder	Variable to Evaluate
16-23	Passing Lane	Operational and Equipment Parameters
20-23	Driving Shoulder	Pavement Temperature when Milling
115-215	Passing Lane	Depth of Milling
3, 4	Driving Lane	Time between Milling and Post-Mill Construction
101, 201, 2	Passing and Driving Lane	Structure of Existing Pavement

4.4 Material Sampling

Cores of the pavement structures were collected at thirty-foot intervals, with one foot spacings between pre-milling samples and their post-milling counterparts (detailed sampling plans for each study section are presented later in this section). This ensured minimal variation between the pre- and post-milling core material properties. If a post-milling core was to be taken in an area that had excessive distresses present in the pavement, such as along an existing longitudinal crack, the core was instead collected from either one foot to the side of the pre-milling sample, or further along the test cell until it was able to be collected, clear of distresses.

Multiple cores were collected in each section, labelled using the system shown in Figure 4-6. This naming scheme utilized abbreviations to describe the milling parameter being evaluated, the test section and lane location, whether it was a pre- or post-milling core, and the core number for each core collected. These abbreviations are described in Table 4-3 below. This naming scheme is utilized throughout the remainder of this report to differentiate between each of the cores and milling parameters evaluated.

PS1P-B1

Milling Parameter	Milling Parameter Variation	Lane	Before/After Milling	Core Number
[PS,TM,DM,OP,TP]	[1,2,3,4,5]	[P,D,S]	[B,A]	[1,2,3,4]

Figure 4-6 Example of Core Sample Identification Code

Table 4-3 Abbreviations for Core Labelling

Milling Parameter / Core Collection Location	Abbreviation
Structure of Pavement	PS
Time between Milling and post-mill Overlay Construction	TM
Depth of Milling Relative to the Interface	DM
Operational and Equipment Parameters	OP
Temperature of Pavement at time of Mill	TP
Driving Shoulder	DS
Driving Lane	DL
Passing Lane	PL
Passing Shoulder	PS

4.4.1 MnROAD Cells 101, 201, 2 (Existing Pavement Structure)

Shown below in Table 4-4 is the summary of the MnROAD cells in which the cores were collected to evaluate the existing pavement structure parameter. These cores were collected form MnROAD cells 101, 201, and 2.

Table 4-4 Summary of PS Parameter Variations and Cells

Milling Variable Evaluated: PS (Pavement Structure)

Parameter Variations	MnROAD Cells	Pavement Structure
1	101	Structure 1
2	201	Structure 2
3	2	Structure 3

The sampling plans for the three MnROAD cells used to study the effect of the existing pavement structure when milling are shown in Figures 4-7, 4-8, and 4-9 below. Cored samples were taken from both lanes and at various lateral offsets to capture differences in traffic volume and wheel location. The pavement cross-sections for these cells are shown in Figure 4-10. MnROAD cells 101 and 201 are very similar, composed of identical structures, except for their surface layer material. Comparatively, MnROAD cell 2 has a significantly different pavement structure as compared to the other two cells.

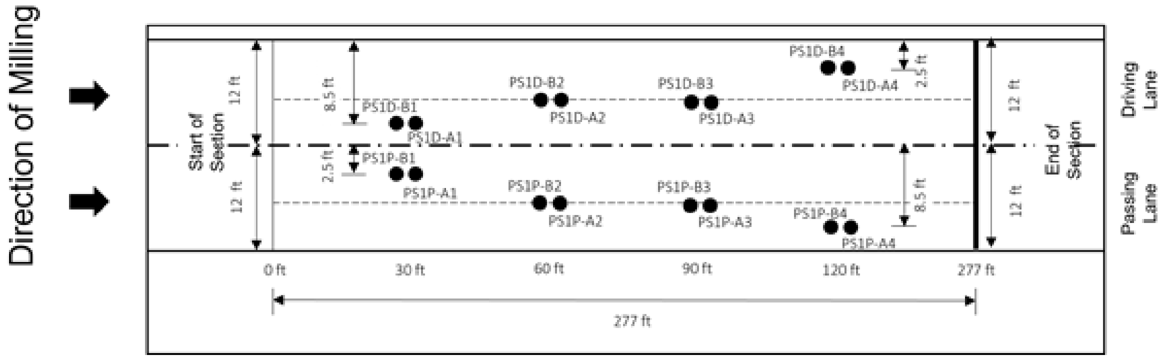


Figure 4-7 Cell 101 Sampling Plan (not to scale)

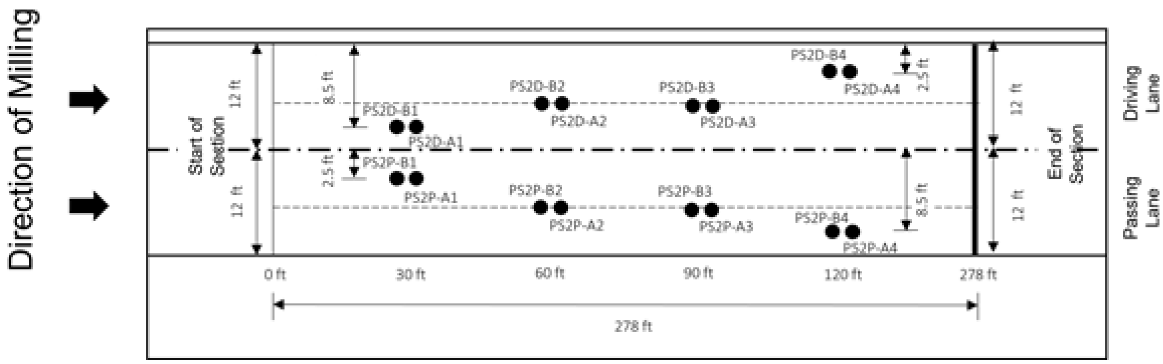


Figure 4-8 Cell 201 Sampling Plan (not to scale)

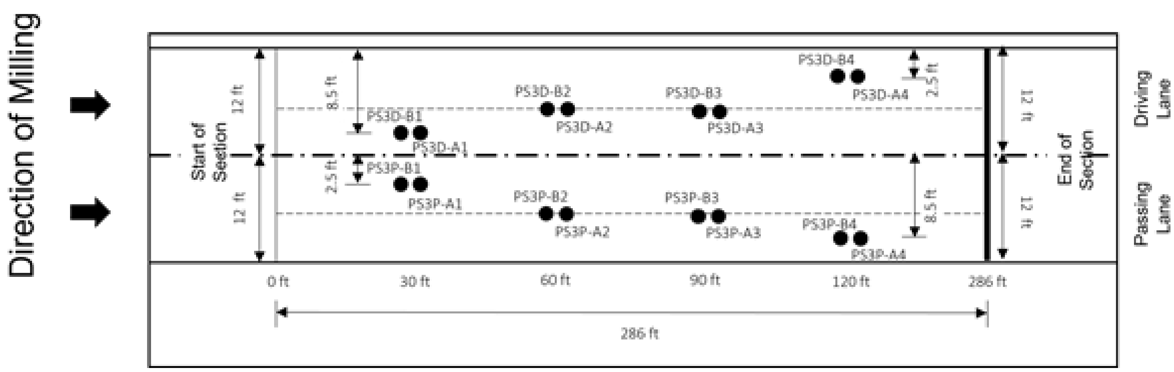


Figure 4-9 Cell 2 Sampling Plan (not to scale)

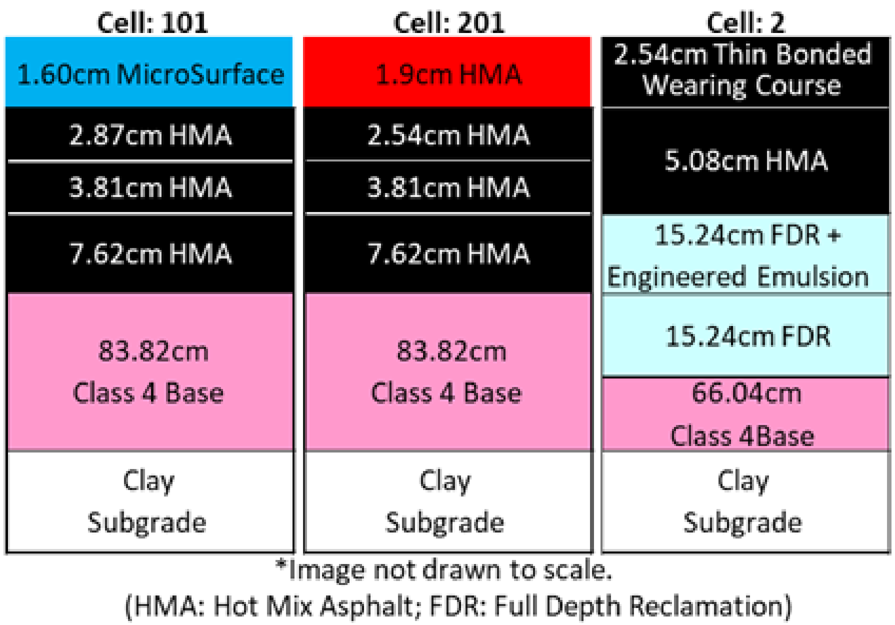


Figure 4-10. Pavement Cross-Section of Cells 101, 201, & 2

4.4.2 MnROAD Cells 3 and 4 (Time between Milling and Post-Mill Construction)

Shown below in Table 4-5 is the summary of the MnROAD cells in which the cores were collected to evaluate the time between milling and post-mill overlay construction parameter. These cores were collected from MnROAD cells 3 and 4.

Table 4-5 Summary of TM Parameter Variations and Cells

Milling Variable Evaluated: TM (Time between Milling and Post-Mill Overlay Construction)		
Parameter Variations	**MnROAD Cells**	**Parameter Variation Description**
1	3	Cores collected directly after Milling
2	4A	Cores collected 1 week after Milling
3	4B	Cores collected 2 weeks after Milling

MnROAD Cells 3 and 4 were utilized to evaluate how changes in the time between milling and post-mill overlay construction may impact the HMA directly below the mill line. This was researched by delaying the sampling of the post-milling cores for various periods of time: immediately after milling, 1 week after milling, and 2 weeks after milling. Cores were only collected from the driving lanes of these MnROAD cells due to extensive damage in the passing lanes of the existing pavements. The cores collected to study the first variation of this parameter were collected from the second half of MnROAD Cell 3, as shown in Figure 4-11.

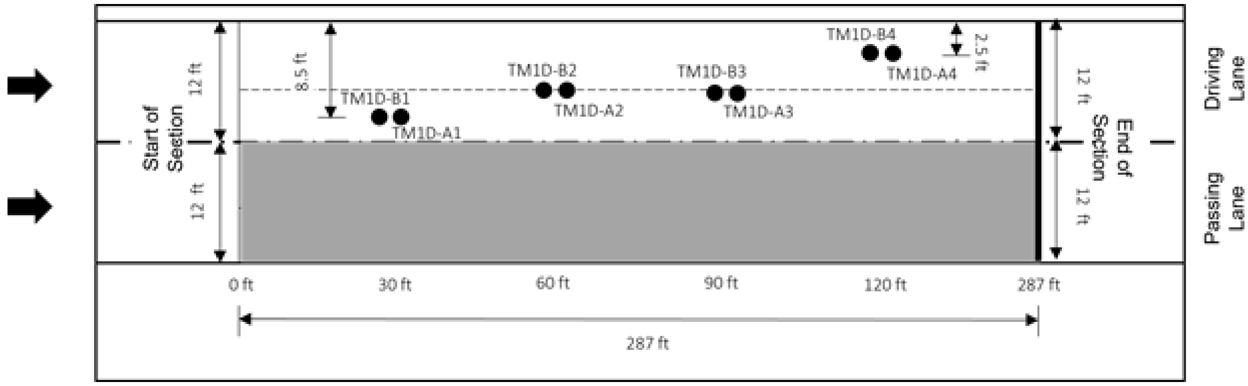


Figure 4-11 Cell 3 Sampling Plan (not to scale)

The second and third variations of this parameter were collected from MnROAD Cell 4. This cell was split into two halves, 4A and 4B. The post-milling cores collected from each half of MnROAD Cell 4 were collected at 1 week and 2 weeks after milling had been performed, respectively. It was initially planned that the post-milling cores from these sections would be collected 2 weeks and 1 month after milling. However, slight changes to the sampling plans occurred, and thus the cores were collected at 1 week and two weeks post-mill. The sampling plans for the collection of cores from MnROAD cell 4 are depicted in Figure 4-12 and Figure 4-13 below.

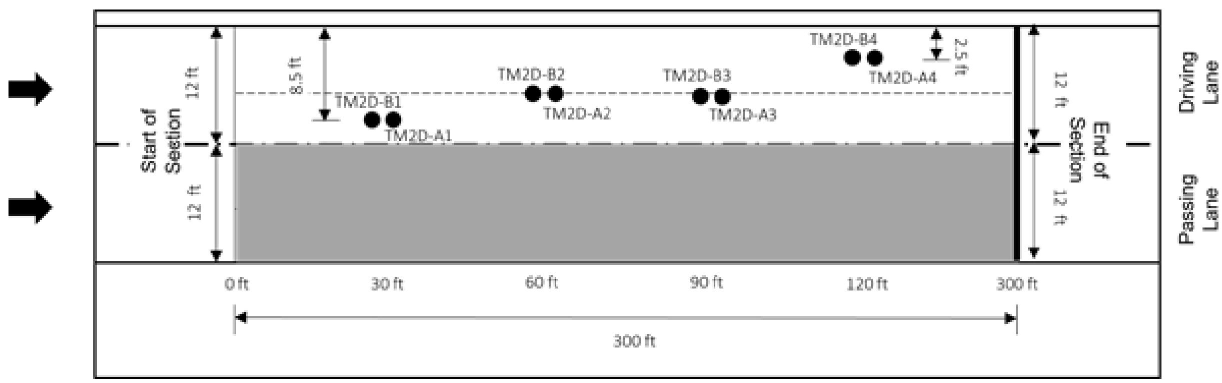


Figure 4-12 Cell 4A Sampling Plan (not to scale)

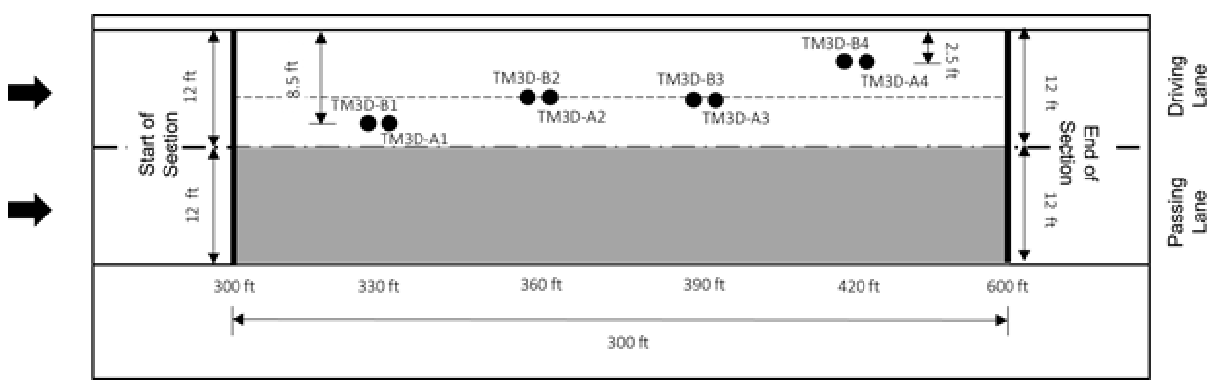


Figure 4-13. Cell 4B Sampling Plan (not to scale)

The pavement cross-sections for both MnROAD cells 3 and 4 are depicted in Figure 4-14 below.

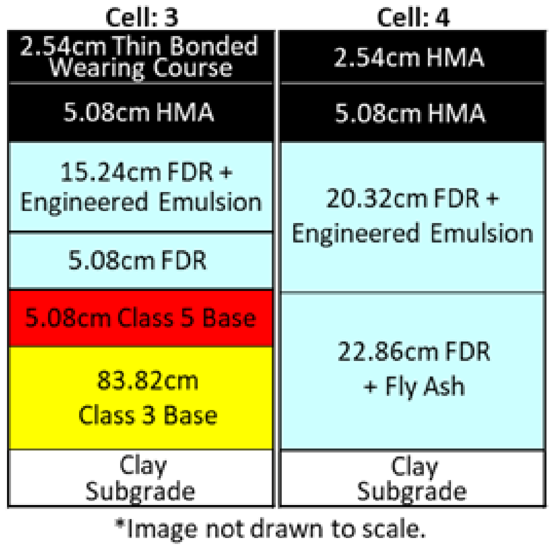


Figure 4-14 Pavement Cross-Section of Cells 3 and 4

4.4.3 MnROAD Cells 115, 215 (Depth of Milling)

Shown below in Table 4-6 is the summary of the MnROAD cells in which the cores were collected to evaluate the depth of milling relative to the layer interface parameter. These cores were collected from MnROAD cells 115 and 215.

Table 4-6 Summary of DM Parameter Variations and Cells

Milling Variable Evaluated: DM (Depth of Milling)		
Parameter Variations	**MnROAD Cells**	**Parameter Variation Descriptions**
1	115	At Layer Interface
2	115 - 215	Halfway through lift (1" Deeper)
3	215	Three-quarters through lift (1.5" Deeper)

MnROAD cells 115 and 215 were utilized to evaluate how milling to different depths relative to the layer interface may impact the HMA directly below the mill line. This was researched by milling to three different depths within the pavement structure: to the layer interface, to halfway through the lift, and to three quarters of the way through the lift. These variations in milling depth were evaluated over two MnROAD cells: 115 and 215. Due to damage in the passing lane of both of the cells, cores were only collected from the driving lanes. The sampling plans for these cells are shown in Figures 4-15, 4-16, and 4-17 below.

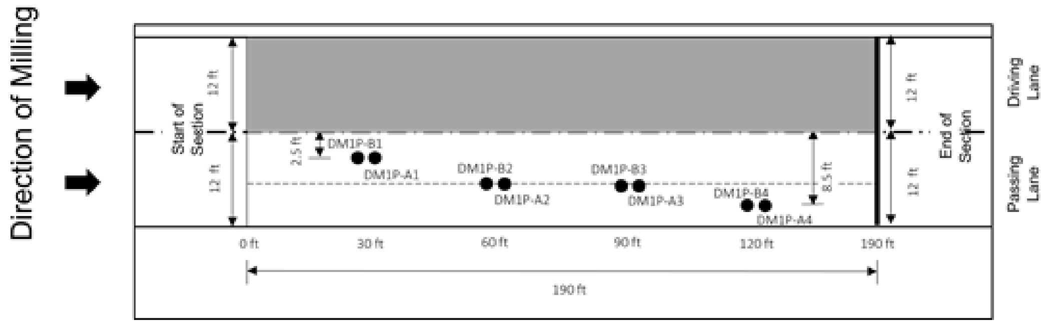


Figure 4-15. Cell 115 Sampling Plan (not to scale)

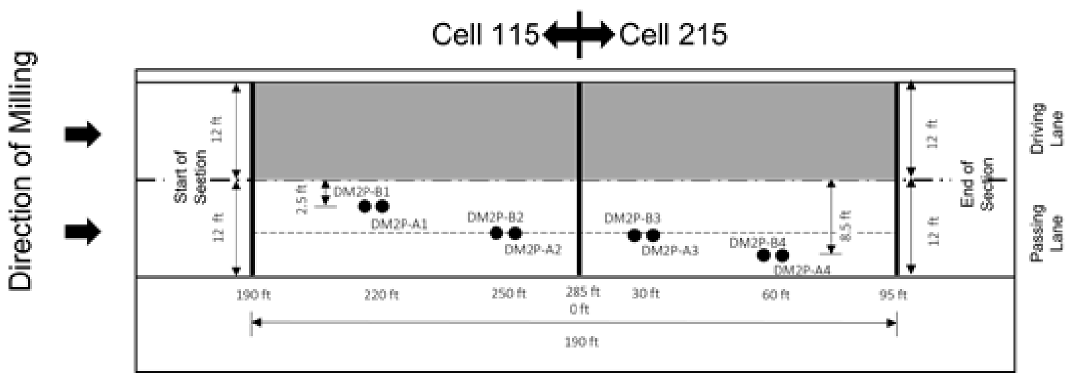


Figure 4-16. Cell 115-215 Transition Zone Sampling Plan (not to scale)

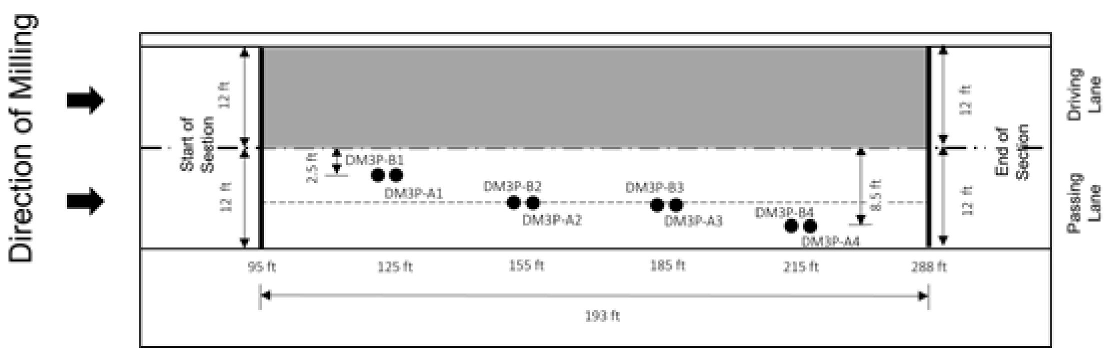


Figure 4-17 Cell 215 Sampling Plan (not to scale)

The pavement cross-sections for both MnROAD cells 115 and 215 are depicted in Figure 4-18 below, while Figure 4-19 shows the milling depths relative to the interfaces.

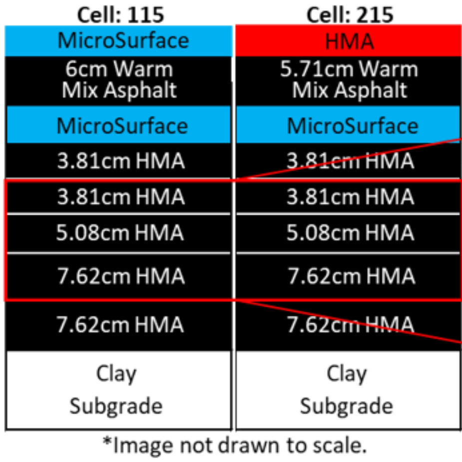


Figure 4-18 Pavement Cross-Section Cells 115 and 215

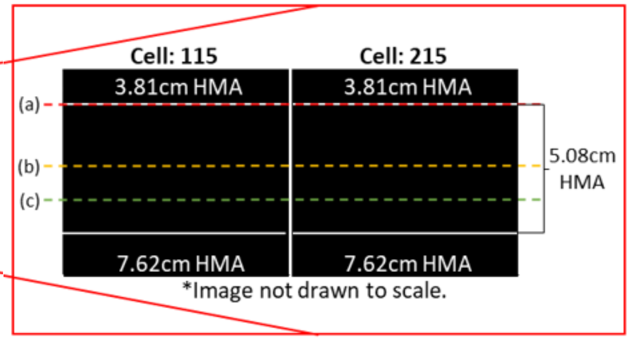


Figure 4-19 Depth of Milling Cross-Sections; (a) to Layer Interface, (b) to Halfway through Lift, (c) to Three-Quarters through Lift

4.4.4 MnROAD Cells 16, 21, 22, & 23 (Operational Parameters and Pavement Temp.)

MnROAD cells 16, 17, 18, and 19 were initially intended to be used to evaluate the impact of changing operational and equipment parameters while milling, while MnROAD cells 21, 22, and 23 were intended to be used solely to evaluate the impact of the pavement temperature at the time of milling. The initial sampling plan for cells 16, 17, 18, and 19 included collecting cores across the passing and driving lanes. This method would have allowed for comparison between cells in case of differences in pavement structure between test cells. Unfortunately, as the construction process in these cells began, it was evident that using some of these cells would not be possible due to the significant number and severity of distresses that existed in the pavement structures. This damage included delamination in the intermediate layers and severe transverse cracking. The delamination is shown in Figure 4-20, where the first run of milling occurred in the driving lane of cell 16.

Figure 4-20 Mid-layer Delamination in MnROAD Cell 16 Driving Lane

As shown in the figure above the distresses present in the driving lane of cell 16 made this lane of this cell unable to be used for the purposes of this study. Similarly, it was determined that due to the delamination and severe distresses present throughout MnROAD cells 17, 18, and 19, that no part of these three cells were able to be used for the purposes required in this study. Thus, it was determined that out of cells 16, 17, 18, and 19, only the passing lane of cell 16 was able to be used in this study. Because of that, the UNH research team worked with the Caterpillar crew and the MnROAD staff to alter the sampling plans.

Together, the team devised a plan using the passing lane of cell 16 along with the passing lanes of cells 21, 22, and 23 to collect cores to evaluate the operational and equipment parameter variations. Because of this, the initial sampling plans to evaluate the pavement temperature at the time of milling was also adjusted. The sampling plan was reorganized such that the operational and equipment parameter cores were collected from the passing lanes of the cells, while the pavement temperature cores were collected from the driving shoulders of the cells. Tables 4-7 and 4-8 below present the summary of these two parameters and their corresponding MnROAD cells. Further, the layouts of the finalized sampling plans that were carried out are depicted in Figures 4-21, 4-22, 4-23, 4-24, 4-25, and 4-26 below.

Table 4-7 Summary of OP Parameter Variations and Cells

Milling Variable Evaluated: OP (Operational and Equipment Parameters)					
Parameter Variations	**MnROAD Cell**	**Variable ID**	**Rotor Speed**	**Cutter Bit Spacing**	**Rotor Type**
1	16	3-8-K	Speed 3	8 mm	K Rotor
2	16	3-8-G	Speed 3	8 mm	G Rotor
3	21	1-15-K	Speed 1	15 mm	K Rotor
4	22	2-15-K	Speed 2	15 mm	K Rotor
5	23	3-15-K	Speed 3	15 mm	K Rotor

Table 4-8 Summary of TP Parameter Variations and Cells

Milling Variable Evaluated: TP (Temperature of Pavement)				
Parameter Variations	**MnROAD Cells**	**Parameter Variation Description**	**Air Temperature**	**Pavement Temperature**
1	21-22	Cool Temperature	47 °F	54 °F – 60 °F
2	22-23	Warm Temperature	65 °F	92 °F – 117 °F

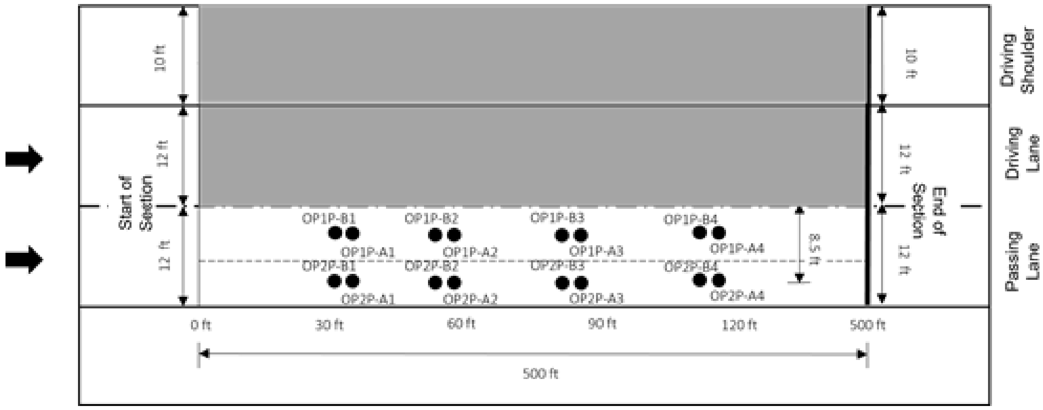


Figure 4-21 Cell 16 Sampling Plan (not to scale)

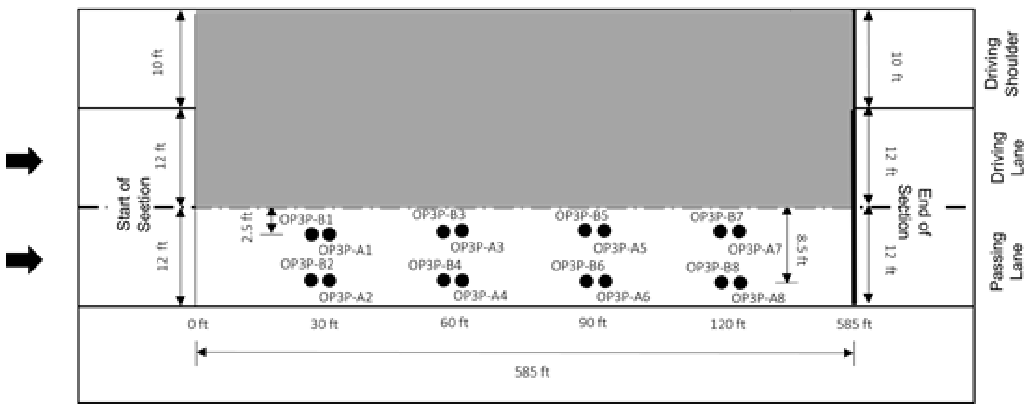


Figure 4-22. Cell 21 Sampling Plan (not to scale)

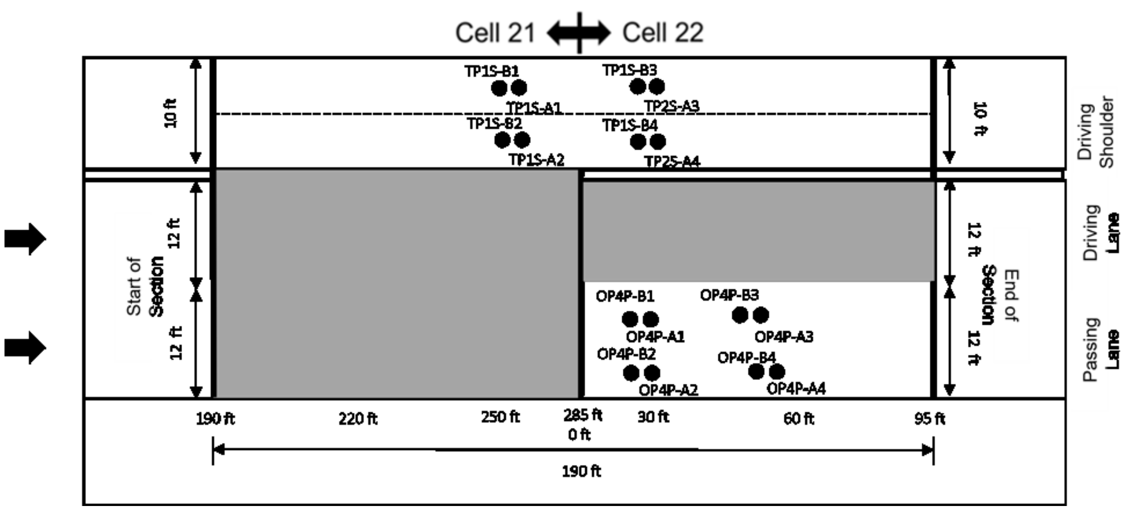
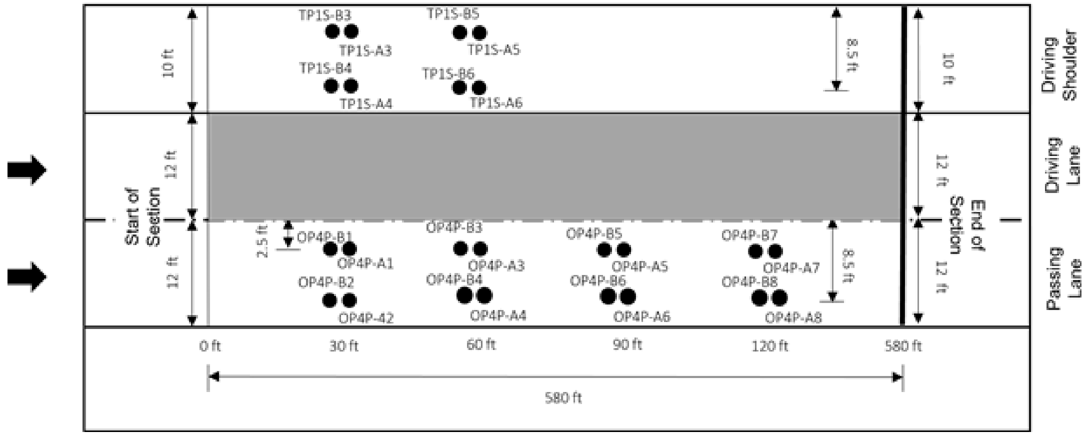
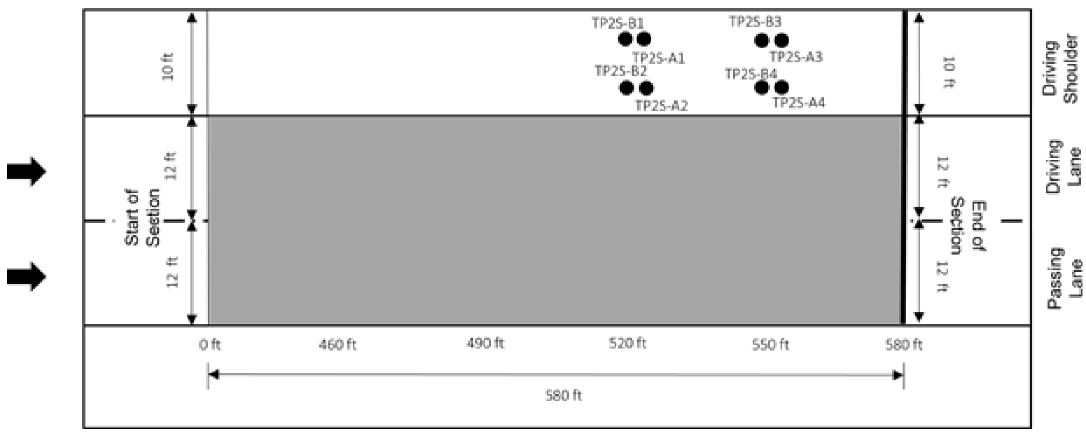


Figure 4-23. Cell 21 to 22 Transition Zone Sampling Plan (not to scale)



(a)



(b)

Figure 4-24 Cell 22 Sampling Plan (not to scale)

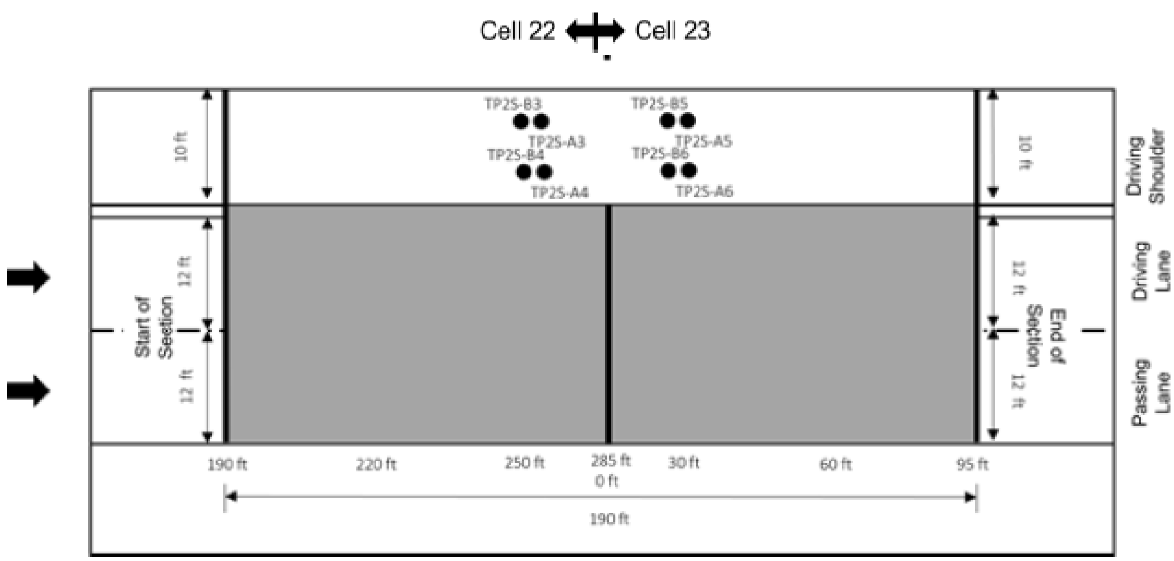


Figure 4-25. Cell 22 to 23 Transition Zone Sampling Plan (not to scale)

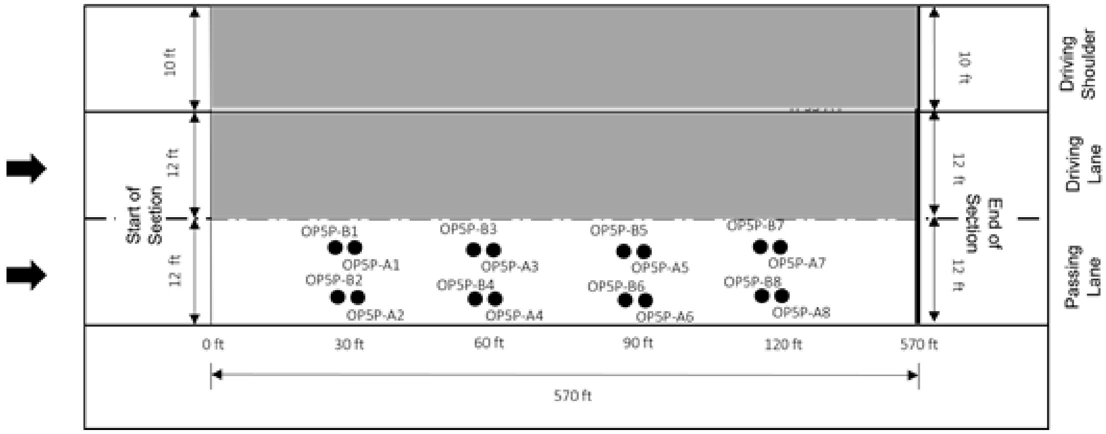


Figure 4-26. Cell 23 Sampling Plan (not to scale)

The pavement cross-sections for MnROAD cells 16, 21, 22, and 23 are depicted in Figure 4-27 below.

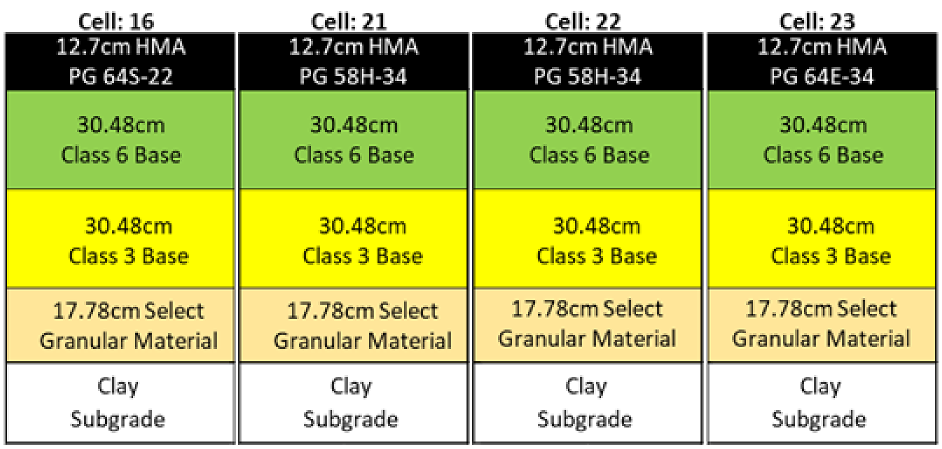


Figure 4-27 Pavement Cross-Sections Cells 16, 21, 22, & 23 (not to scale)

4.5 Summary

This section documented the process used in establishing test sections and sample collection of pre- and post-milling cores for laboratory testing. This included the milling parameter identification, sampling plans, and use of those sampling plans to obtain both the pre- and post-mill samples at the MnROAD research facility.

As described in the above sections, initial sampling plans required slight alterations as construction began and not all the cells that were intended to be used were able to be used in this study. There were significant efforts in place to collect both the pre- and post-milling cores used to study the same milling parameter from cells with as similar of pavement structures as possible.

The following sections of this report describe the evaluation of these cores and the impact of each of the milling parameters. Section 5 describes both the laboratory testing and data analysis methods, while Section 6 presents the laboratory testing results and analysis of both the pre- and post-milling cores.

Chapter 5: Laboratory and Field Testing and Data Analysis Methods

Laboratory tests were performed on each of the pre- and post-milling field cores to better understand how changing different milling parameters impacts the pavement immediately below the mill line. There were four laboratory measurements collected for each of the field cores: bulk specific gravity, permeability, resilient modulus, and indirect tensile strength. The team had determined that resilient modulus and the indirect tensile strength tests on the pre- and post-milling cores would be the primary indicators of the effects of milling. Further the bulk specific gravity and permeability testing would also be employed on the pre- and post-milling cores to determine any possible impacts to the physical properties of the remaining HMA due to milling. These four laboratory testing methods are described further in the sections below.

5.1 Laboratory Testing Methods

The four laboratory testing methods used to evaluate the pre- and post-milling cores are presented in the sections below.

5.1.1 Bulk Specific Gravity Measurement

The bulk specific gravity of each specimen was determined in accordance with the ASTM Standard Test Method for Bulk Specific Gravity and Density of Non-Absorptive Compacted Asphalt Mixture (Designation: D2726/D2726M-21). During this measurement, the mass of each specimen in a dry state, in water, and in saturated surface dry condition was recorded. The bulk specific gravity was then calculated using these three values as displayed in equation (5-1) below.

$$Bulk\ specific\ gravity = \frac{A}{(B - C)} \tag{5-1}$$

Where:

A = Specimen dry mass in air, g
B = Specimen saturated surface-dry mass in air, g
C = Specimen mass in water, g

5.1.2 Permeability Test

The permeability test was used to assess the field core permeability, as determined by Darcy's Law. The permeability of the cores was evaluated using the Florida Department of Transportation Method of Test titled Measurement of Water Permeability of Compacted Asphalt Paving Mixtures (Designation: FM 5-565). During this testing procedure, the specimen is placed into a sealing tube and pressurized to prevent water from travelling around the specimen, as shown in Figure 5-1 below. Next, the rate that water is able to flow through the specimen is recorded and used to calculate the coefficient of permeability by equation (5-2) below.

$$k = \frac{aL}{At} \ln\left(\frac{h_1}{h_2}\right) * t_c \qquad (5\text{-}2)$$

Where:

k = coefficient of permeability, cm/sec
a = inside cross-sectional area of the buret, cm^2
L = average thickness of the test specimen, cm
A = average cross-sectional area of the test specimen, cm^2
t = time elapsed between h_1 and h_2, seconds
h_1 = initial head across the test specimen, cm
h_2 = final head across the test specimen, cm
t_c = temperature correction for viscosity of water
A temperature of 20°C (68°F) is used as the standard.

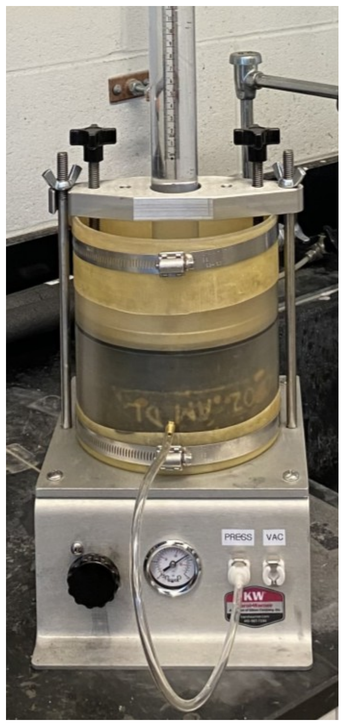


Figure 5-1 Permeability Test Setup

5.1.3 Resilient Modulus Test

The resilient modulus (Mr) test was performed in accordance with the ASTM Standard Test Method for Determining the Resilient Modulus of Asphalt Mixtures by Indirect Tension Test (Designation: D7369 – 20) to determine the stiffness of each of the field cores. During this test, cyclic compressive forces are loaded onto the diametric axis of the test specimen and the horizontal and vertical deformations are recorded. The measurements are then used to calculate the Poisson's ratio, as in equation (5-3) and the resilient modulus, as in equation (5-4).

$$\mu = \frac{I4 - I1 * (\frac{\delta_v}{\delta_h})}{I3 - I2 * (\frac{\delta_v}{\delta_h})} \quad (5\text{-}3)$$

$$M_R = \frac{P_{cyclic}}{\delta_v t}(I1 - 12\mu) \quad (5\text{-}4)$$

Where:

M_R	=	resilient modulus, MPa
δ_v, δ_h	=	recoverable vertical and horizontal deformation, mm
μ	=	Poisson's ratio
P_{cyclic}	=	cyclic load applied to specimen, N
t	=	thickness of specimen, mm
I1, I2, I3, and I4	=	gauge length constants

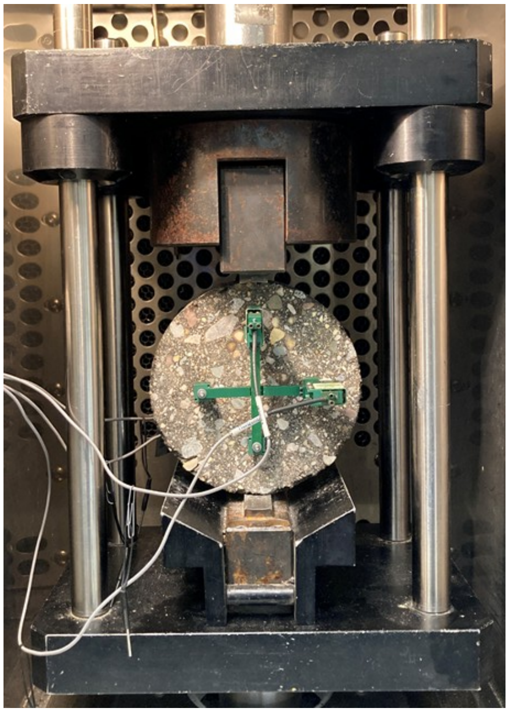


Figure 5-2 Resilient Modulus Test Setup

5.1.4 Indirect Tensile Strength Test

The indirect tensile strength test was performed in accordance with the ASTM Standard Test Method for Indirect Tensile (IDT) Strength of Asphalt Mixtures (Designation: D6931-17) to determine the strength of each of the field cores. During this laboratory test, specimens experienced loading on their diametric axis at a loading rate of 50mm/min. The loading is applied until the specimen fails. The maximum load is recorded and is used to calculate the indirect tensile strength, as displayed in equation (5-5) below.

$$IDT = \frac{2000 * P}{\pi * t * D} \tag{5-5}$$

Where:

IDT	=	indirect tensile strength, kPa
P	=	maximum load, N
T	=	specimen height, mm
D	=	specimen diameter, mm

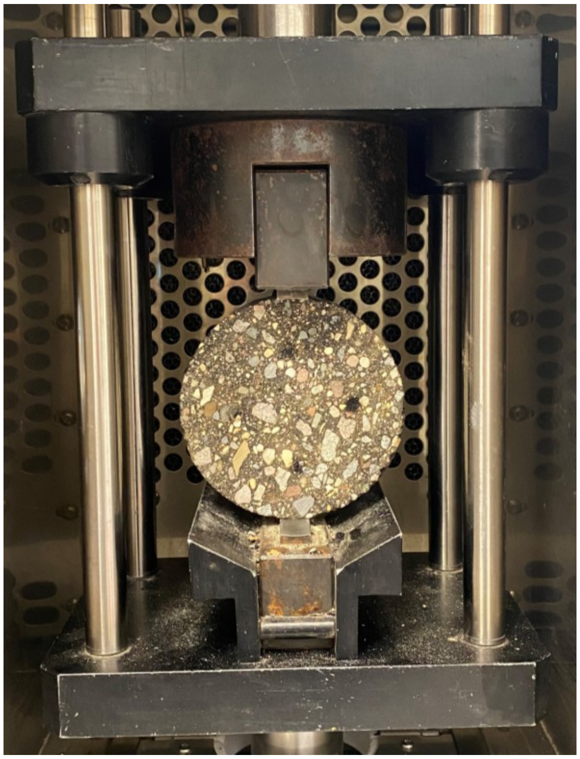


Figure 5-3 Indirect Tensile Strength Test Setup

5.2 Data Analysis Methods

Four laboratory tests and one field test were performed on the pre- and post-milling cores/pavement structures to better understand how changing different variables or parameters while milling impacts the physical and mechanical properties of the pavement layer immediately below the mill line. After the laboratory and field testing was completed, different methods were used to analyze the data to compare the properties of the pre- and post-milling core properties and to evaluate the overall impact that milling under the various milling parameters has on the HMA layer directly below the mill line. The description of each of the data analysis methods are presented in the sections below.

5.2.1 Percent Difference Calculations

One data analysis method used to compare the properties of the pre- and post-milling cores was by percent difference calculations. The percent difference between the average value of each property of the pre- and post-milling cores under each variation of each milling parameter was found, where:

$$\%\,diff = 100 * \left(\frac{post\ milling\ core\ average - pre\ milling\ core\ average}{pre\ milling\ core\ average}\right) \quad (5\text{-}6)$$

5.2.2 Statistical Significance Testing

Statistical significance testing using student's t-test was also performed on the laboratory test results to determine if there was a significant difference between the evaluated properties of the pre- and post-milling cores. The test performed was a two-tailed t-test for unequal variances. The results from the t-tests are presented in the form of a p-value, where a p-value less than or equal to 0.05 represents that there is a statistically significant difference between the pre- and post-milling core values. The value of p=0.05 is corresponding to a 95% confidence interval.

5.2.3 Pavement Life Analysis

The objective of this analysis was to determine if a statistically significant decrease in the mechanical properties of the HMA layer below the mill line also displayed an impact to the expected life of the overall pavement. In other words, was there a difference in the expected life of a pavement that was designed as if it had been impacted by milling versus the expected life of a pavement that was designed as if it had not been impacted by milling.

Minnesota Department of Transportation's MnPAVE flexible pavement analysis and design system version 6.4 (MnPAVE) was utilized to calculate the expected pavement life of two pavement structures, one thin and one thick, that are presented in Figure 5-4 below. In the pavement structures, the old HMA layer represented the layer of HMA directly below the mill line and thus the laboratory-measured modulus values of the pre- and post-milling cores were entered as the old HMA modulus values, while all other values were held constant. The difference in the expected pavement life when the pre-milling core modulus was used, versus the expected pavement life when the post-milling core modulus was used demonstrates the difference in designing a pavement as if the HMA below the mill line had been impacted by milling versus designing a pavement as if the HMA below the mill line had not been impacted by milling. This analysis was conducted using the average Mr values for each of the milling parameters evaluated. The other inputs (climate, seasonal impacts, and traffic) used in the MnPAVE analysis are outlined in Appendix A.

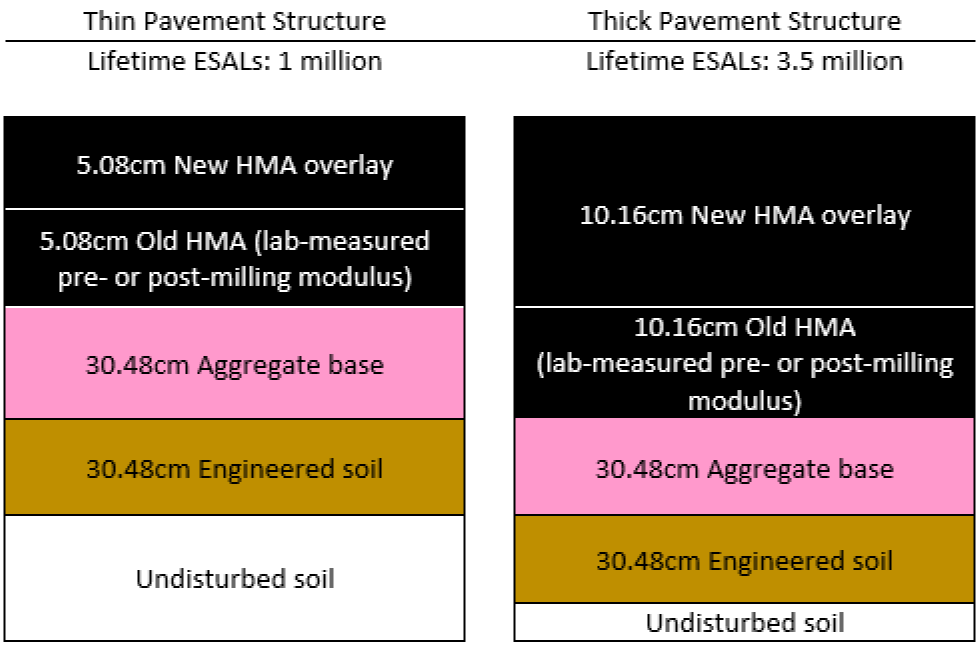


*Figure not drawn to scale.

Figure 5-4 Pavement Structure Cross-Sections for Pavement Life Analysis

This analysis was only performed on the milling parameters that indicated a statistically significant difference between the mechanical properties (Mr or ITS) of the pre- and post-milling cores. Although this analysis was performed for parameters that had a statistically significant difference in ITS values, it is important to note that this analysis does not directly consider changes to the ITS values. This property was just used as a baseline to determine which parameters this analysis would be performed on. But, this analysis solely takes layer modulus values into account, and not strengths. Despite that, the analysis was performed on milling parameters that displayed significant changes to the Mr or ITS values of the HMA below the mill line. If there was only a significant change in the measured ITS values, the analysis was still performed, and the modulus values were entered as the old HMA modulus in the MnPAVE software.

5.2.4 Falling Weight Deflectometer

In addition to the laboratory testing that was performed on the field cores, falling weight deflectometer (FWD) testing, was employed to further evaluate the pavement structures pre- and post-milling. The falling weight deflectometer (FWD) is a non-destructive deflection measurement test. It was performed on some of the MnROAD Cells that were evaluated in this study pre-milling, and post-milling/pre-overlay. During the test, loads were dropped ('falling weight') onto the pavement and the deflections of the pavement under the load at different distances away from the load, were measured. Three different loads were used in the testing of these cells, but only the deflection values under the second drop of 40kN was used in this analysis.

The deflection basins are presented throughout this report for some of the cells that the FWD testing was performed on. To compare the deflections of the pre- and post-milling pavement structures, the measured deflections were adjusted based on the temperature that they were performed at. All of the pre- and post-milling deflections were normalized to 25^{o}C. The deflections were normalized for temperature using the following equation (Kim and Park, 2002):

$$D0_{adj} = D0 * 10^{(-C_0 + Ar)*(H_{ac})(T - T_0)}$$

Where,

$D0_{adj}$	=	Adjusted deflection measurement
$D0$	=	Measured deflection measurement
C_0	=	4.65E-05
A	=	-5.47E-08
r	=	Radial distance from load to deflection measurement location
H_{ac}	=	Thickness of the asphalt layer
T	=	Temperature 1/3 of the depth into the asphalt layer at time of testing
T_0	=	Normalized temperature, 25^{o}C

In addition, the measured deflections from the FWD testing that was performed were used to backcalculate the stiffness of each layer of the pavement structure. Backcalculations were performed using the Dynatest Elmod6 software to approximate the modulus values of the asphalt layer pre- and post-milling. The purpose of performing this analysis was to provide an additional method of comparing the pavements to further evaluate possible impacts that milling may have to the HMA layer below the mill line. In this analysis it was assumed that the modulus values of all layers below the HMA layer were constant both pre- and post-milling. To simulate this, the following steps were taken to perform the backcalculations:

1. Initial backcalculations were performed on both the pre- and post-milling structures.
    - The structures of each of the pre- and post-milling cells were entered and the backcalculation was performed through the Elmod software.
2. The resulting backcalculated modulus values from Step 1 for all layers below the HMA were averaged between the pre- and post-milling structures for each cell.
    - For example, the pre-milling backcalculated base modulus for MnROAD Cell 2 was averaged with the post-milling backcalculated base modulus for MnROAD Cell 2. This resulted in a single, average, base modulus value to assume for the cell. This was conducted for each layer below the HMA, for each MnROAD Cell.
3. Then, the average backcalculated modulus value of each layer below the HMA that was found in Step 2 was used as modulus in the Elmod software so that modulus values for both the pre- and post-milling pavement structures (except for those of HMA layers) was same.
4. Next, a second backcalculation was performed during which the modulus values for all layers below the HMA layer were 'fixed' (as described in Step 3), so that they remained constant

during the backcalculations. This allowed for the backcalculation to only determine the modulus values of the HMA, while holding the modulus values of all other layers constant between the pre- and post-milling structures of each cell.

5. Finally, the HMA modulus values for the pre- and post-milling structures underwent temperature correction that was dependent on the time of day, air temperature, and pavement temperature at the time the FWD testing was performed. The equation used to perform the temperature correction (FHWA-RD-98-085) was:

$$T_d = 0.95 + 0.892 * IR + \{\log(d) - 1.25\}\{-0.448 * IR + 0.621 * (1 - day) + 1.83 * \sin(hr_{18} - 15.5)\} + 0.042 * IR * \sin(hr_{18} - 13.5) \quad (5\text{-}7)$$

Where,

T_d	=	Pavement temperature at depth d, ^{o}C
IR	=	Pavement surface temperature, ^{o}C
Log	=	Base 10 logarithm
d	=	Depth at which mat temperature is to be predicted, mm
1-day	=	Average air temperature the day before testing, ^{o}C
Sin	=	Sine function on an 18-hour clock system, with 2(pi) radians equal to one 18-hr cycle
hr_{18}	=	Time of day, in a 24-hr clock system, but calculated using an 18-h4 asphalt concrete (AC) temperature rise-and-fall time cycle, as indicated in Figure 6

The above T_d value was found as the pavement temperature at one-third of the depth of the asphalt. Once the T_d value was calculated, the temperature correction coefficient was found using the following equation (FHWA-RD-98-085):

$$Temperature\ Correction\ Coeff. = 10^{slope(reference\ temperature - T_d)} \quad (5\text{-}8)$$

Where the slope was assumed to be -0.021 and the reference temperature was assumed to be 21^{o}C. The backcalculated modulus values of the HMA layer were then multiplied by the temperature correction coefficient to produce the temperature corrected HMA modulus values.

- This allowed for comparison of the backcalculated modulus values of the HMA layer pre- and post-milling from each of the evaluated MnROAD cells, while assuming that the layers below the HMA were not impacted by the milling activity.

Note: The FWD data is presented in terms of MnROAD cell number, wheel path, and lane, where:

OWPD = Outer Wheel Path Driving Lane

OWPP = Outer Wheel Path Passing Lane

The pre- and post-milling FWD data was targeted to be collected from the same season to eliminate additional differences between the two structures. Data collected from the same month both pre- and post-milling was used in this analysis, when possible, but for a couple of cells, the next closest available pre- or post-milling data was used. Table 5-1 presents the FWD results that were backcalculated and are detailed in this report:

Table 5-1 FWD Data per MnROAD Cell

MnROAD Cell	Lane and Position	Date	Pre/Post Milling
2	OWPD	07/26/2021	Pre-milling
	OWPD	07/12/2022	Post-milling
	OWPP	07/26/2021	Pre-milling
	OWPP	07/12/2022	Post-milling
3	OWPD	Pre-milling	07/26/2021
	OWPD	Post-milling	07/12/2022
	07/26/2021	OWPP	Pre-milling
	07/12/2022	OWPP	Post-milling
101	OWPD	Pre-milling	07/26/2021
	OWPD	Post-milling	07/12/2022
	07/26/2021	OWPP	Pre-milling
	07/12/2022	OWPP	Post-milling
115	OWPP	07/26/2021	Pre-milling
	OWPP	05/26/2022	Post-milling
201	OWPD	Pre-milling	07/26/2021
	OWPD	Post-milling	07/12/2022
	07/26/2021	OWPP	Pre-milling
	07/12/2022	OWPP	Post-milling
215	OWPP	07/26/2021	Pre-milling
	OWPP	05/26/2022	Post-milling

In addition to the backcalculation of each layer modulus from the FWD testing, the surface modulus for each structure was evaluated and compared, pre- versus post-milling. The surface modulus is representative of a stiffness of the overall pavement structure, under the given load. In this analysis, the average surface modulus directly under the second drop (40kN load) for both the pre- and post-milling structures was used for comparison.

The percent difference between the pre- and post-milling HMA backcalculated modulus values and the surface modulus values were calculated using the following equation:

$$\%\,diff = 100 * \left(\frac{post\ milling\ modulus - pre\ milling\ modulus}{pre\ milling\ modulus}\right) \tag{5-9}$$

5.3 Summary

The four laboratory tests, one field measurement, and all data analysis methods were described in this section. These methods were performed on the pre- and post-milling pavements. The results from these testing and analysis methods are presented in the following section of this report.

Chapter 6: Testing and Data Analysis Results

This section presents the results of the laboratory testing and data analysis that was performed on the collected field cores. All field cores for this study were collected from the MnROAD facility to study five milling variables. The bulk specific gravity, permeability, resilient modulus, and indirect tensile strength of each of the pre- and post-milling cores were measured. The permeability test was unable to be performed on all the samples as many were collected using a coring device with a diameter of 158.75mm (6.25in.), while the permeability device used in this study cannot be used on specimens with a diameter larger than 152.4 (6in.). The intention was to use a 152.4mm (6in.) core barrel to collect all the cores in this study so that they could all be tested for permeability, but due to supply chain issues in receiving a 152.4mm (6in.) core barrel within a timely manner while sampling, a 158.75 (6.25in.) core barrel was used to collect some cores until the team was able to obtain a 152.4mm (6in.) core barrel. Further, some of the cores collected for this study were unable to be tested in the laboratory at all. This is because they cracked during their transit from the MnROAD facility to New Hampshire. The cracked field cores were primarily the cores that were relatively thin to begin with.

The laboratory testing results for the cores that were able to be evaluated are presented in this section in the form of box and whisker plots. In the box and whisker plots, the median of each data set is represented by the middle line in each box, while the upper and lower quartiles of the data are represented by the bounds of each box. The maximum and minimum values of each data set are represented by the whisker ends, while the circles outside each of the boxes represent any outliers within the data set. In the box and whisker plots presented, the outliers were determined as any data point that was greater than the upper quartile by 1.5 times the inter quartile range (IQR), or any data point that was less than the lower quartile by 1.5 times the IQR, where the IQR is equal to the upper quartile minus the lower quartile.

The results from the data analysis methods that were performed on the collected laboratory data are also presented in this section. The percent differences between the pre- and post-milling cores along with the results from the statistical tests that were performed are presented for each of the evaluated milling parameters. Further, the pavement life analysis results and the results from the FWD testing are also presented in this section.

6.2 Structure of Existing Pavement

The first parameter evaluated in this section was used to determine if the structure of the existing pavement that is being milled has an influence on the impact that the milling has, or does not have, on the layer directly below the mill line. Three different pavement structures were evaluated for this study and are presented in Table 6-1 below, along with the cross-sections of each of the three structures presented in Figure 6-1. The laboratory testing results of the cores from Cell 101 are presented in Table 6-2 and Figure 6-2, while the results from Cell 201 are presented in Table 6-3 and Figure 6-3, while lastly the results from Cell 2 are presented in Table 6-4 and Figure 6-4, below.

Table 6-1 Summary of Pavement Structure Variable

Test Section	Core ID	MnROAD Cell and Parameter Variations
1	PS1D and PS1P	101- Driving and Passing Lanes
2	PS2D and PS2P	201- Driving and Passing Lanes
3	PS3D and PS3P	2 – Driving and Passing Lanes

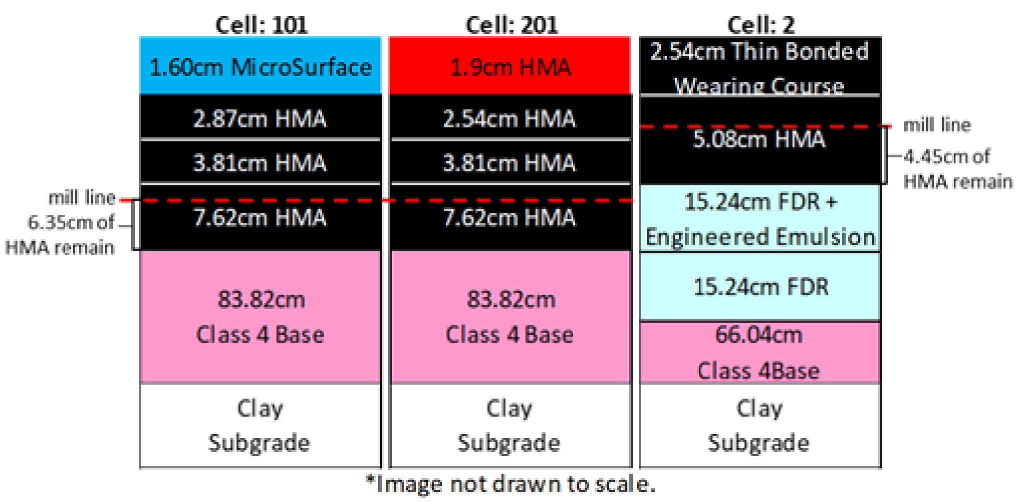


Figure 6-1 Pavement Structure Cross-Sections of MnROAD Cells 101, 201, & 2

Table 6-2 Pavement Structure Variable: Cell 101 Laboratory Testing Results

MnROAD Cell	Pre- or Post-Mill Core & Parameter Evaluated	Core ID	Specific Gravity	Permeability (cm/sec)	Resilient Modulus (MPa)	Indirect Tensile Strength (kPa)
MnROAD Cell 101 Driving Lane	Pre-milling cores	PS1D-B1	2.305	-	3397	1013
		PS1D-B2	2.226	-	5697	1057
		PS1D-B3	-	-	-	-
		PS1D-B4	2.262	6.78E-07	3836	1192
		Average	**2.264**	**6.78E-07**	**4310**	**1087**
	Post-milling cores	PS1D-A1	2.311	1.47E-05	4994	1121
		PS1D-A2	2.304	-	8117	1091
		PS1D-A3	2.286	-	7406	1035
		PS1D-A4	-	-	-	-
		Average	**2.300**	**1.47E-05**	**6839**	**1082**
MnROAD Cell 101 Passing Lane	Pre-milling cores	PS1P-B1	2.296	5.96E-07	-	1160
		PS1P-B2	2.212	-	5487	939
		PS1P-B3	-	-	-	-
		PS1P-B4	-	-	-	-
		Average	**2.254**	**5.96E-07**	**5487**	**1049**
	Post-milling cores	PS1P-A1	2.285	9.08E-06	9384	1028
		PS1P-A2	2.227	5.26E-06	5494	1063
		PS1P-A3	2.278	5.94E-07	6786	1142
		PS1P-A4	2.268	2.64E-04	6907	1061
		Average	**2.265**	**6.97E-05**	**7143**	**1074**

- Indicates that the data was unable to be collected

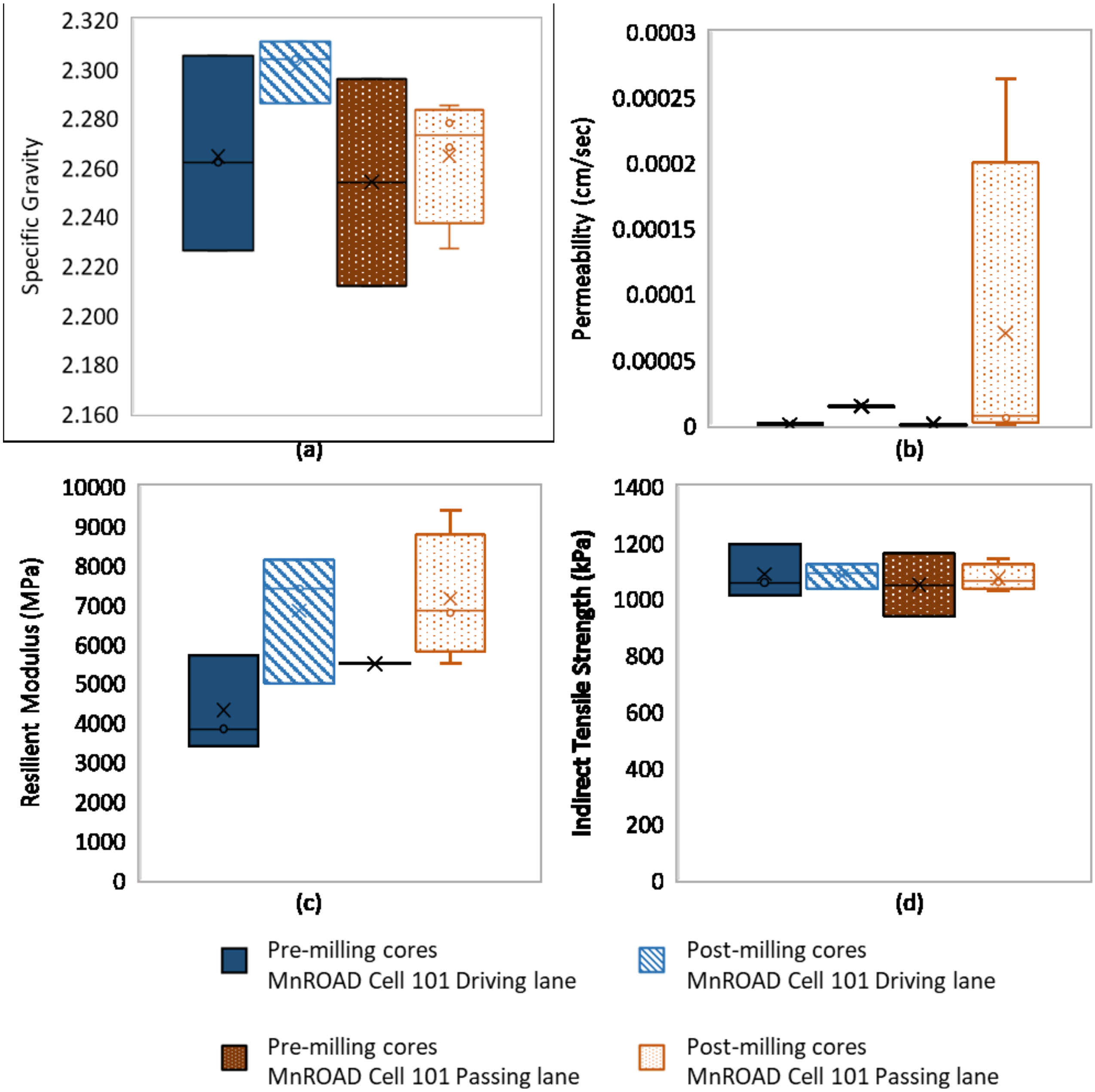


Figure 6-2 Impact of Milling to MnROAD Cell 101 in terms of (a) Specific Gravity, (b) Permeability, (c) MR and (d) ITS of the Pavement Layer Directly Below the Mill Line

Table 6-3 Pavement Structure Variable: Cell 201 Laboratory Testing Results

MnROAD Cell	Pre- or Post-Mill Core & Parameter Evaluated	Core ID	Specific Gravity	Permeability (cm/sec)	Resilient Modulus (MPa)	Indirect Tensile Strength (kPa)
MnROAD Cell 201 Driving Lane	Pre-milling cores	PS2D-B1	2.288	-	5446	1042
		PS2D-B2	2.307	-	6576	1044
		PS2D-B3	2.331	6.15E-07	3448	967
		PS2D-B4	2.307	5.21E-05	5071	1103
		Average	**2.308**	**2.64E-05**	**5135**	**1039**
	Post-milling cores	PS2D-A1	2.261	5.17E-07	7701	1259
		PS2D-A2	2.334	-	5494	1260
		PS2D-A3	2.295	5.41E-07	4631	964
		PS2D-A3-02	2.301	-	6333	1173
		PS2D-A4	2.318	1.85E-06	6618	850
		Average	**2.302**	**9.69E-07**	**6155**	**1101**
MnROAD Cell 201 Passing Lane	Pre-milling cores	PS2P-B1	-	-	-	-
		PS2P-B2	2.301	4.49E-06	6451	1044
		PS2P-B2-03	2.258	-	3196	1007
		PS2P-B3	-	-	-	-
		PS2P-B4	-	-	-	-
		Average	**2.280**	**4.49E-06**	**4824**	**1026**
	Post-milling cores	PS2P-A1	2.327	-	7791	1180
		PS2P-A2	2.319	-	11214	1464
		PS2P-A3	-	-	-	-
		PS2P-A4	-	-	-	-
		Average	**2.323**	**-**	**9502**	**1322**

- Indicates that the data was unable to be collected

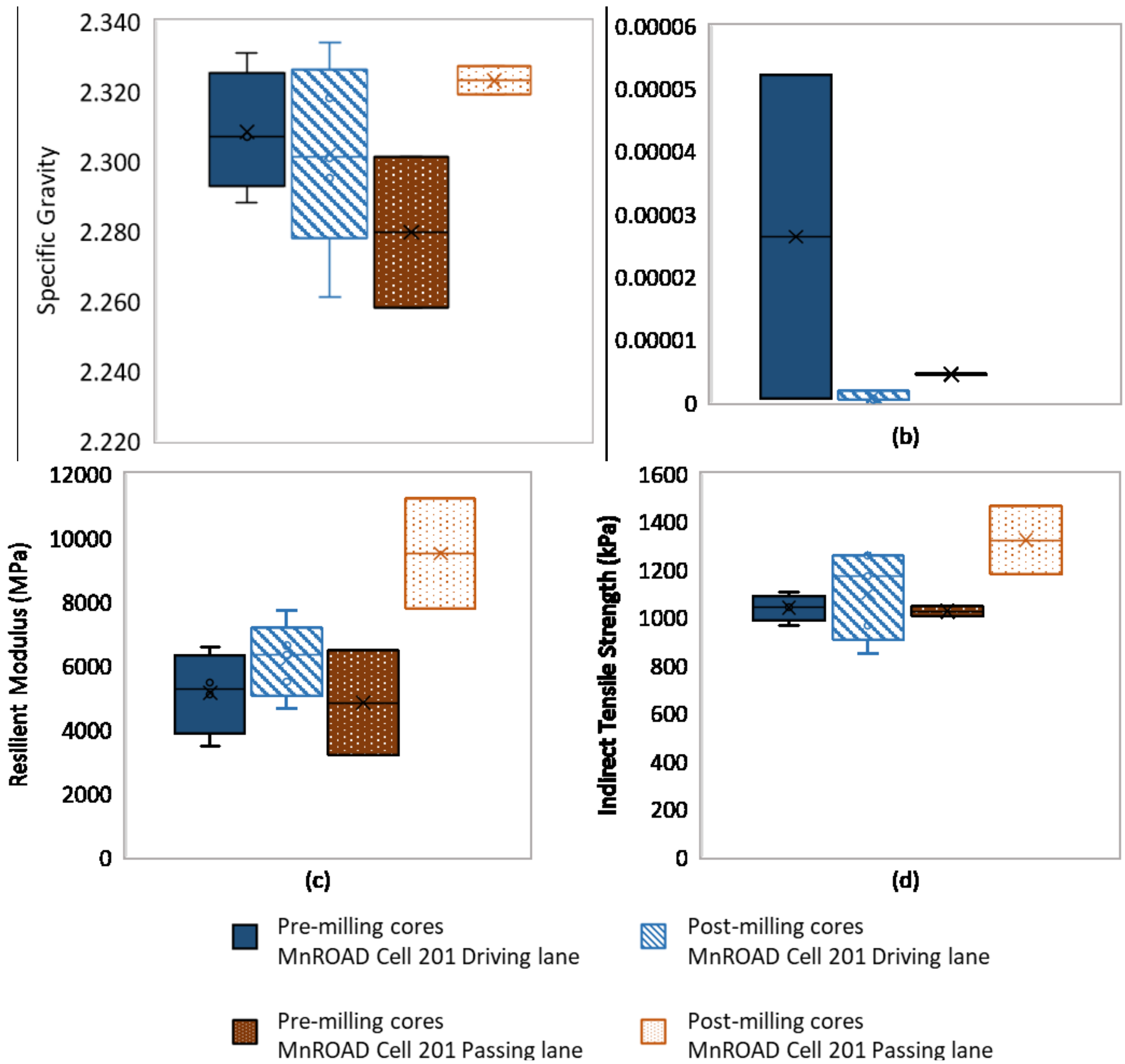


Figure 6-3 Impact of Milling to MnROAD Cell 201 in terms of (a) Specific Gravity, (b) Permeability, (c)MR and (d) ITS of the Pavement Layer Directly Below the Mill Line

Table 6-4 Pavement Structure Variable: Cell 2 Laboratory Testing Results

MnROAD Cell	Pre- or Post-Mill Core & Parameter Evaluated	Core ID	Specific Gravity	Permeability (cm/sec)	Resilient Modulus (MPa)	Indirect Tensile Strength (kPa)
MnROAD Cell 2 Driving Lane	Pre-milling cores	PS3D-B1	2.311	1.19E-06	1474	669
		PS3D-B2	2.296	2.01E-05	1518	515
		PS3D-B3	2.238	5.60E-06	1182	564
		PS3D-B4	2.307	2.22E-06	1452	530
		Average	**2.288**	**7.28E-06**	**1407**	**569**
	Post-milling cores	PS3D-A1	2.196	1.69E-06	1872	570
		PS3D-A2	2.364	-	2097	504
		PS3D-A3	-	-	-	-
		PS3D-A4	2.278	-	2033	516
		Average	**2.279**	**1.69E-06**	**2001**	**530**
MnROAD Cell 2 Passing Lane	Pre-milling cores	PS3P-B1	2.291	5.78E-07	935	452
		PS3P-B2	2.315	0.00E+00	1411	595
		PS3P-B3	2.365	-	1357	555
		PS3P-B4	2.296	4.12E-07	1247	510
		Average	**2.317**	**3.30E-07**	**1237**	**528**
	Post-milling cores	PS3P-A1	2.273	-	1751	500
		PS3P-A2	2.365	0.00E+00	1072	455
		PS3P-A3	2.372	5.88E-07	2088	551
		PS3P-A4	2.335	-	1420	509
		PS3P-A5	2.366	-	1682	478
		Average	**2.342**	**2.94E-07**	**1603**	**498**

- Indicates that the data was unable to be collected

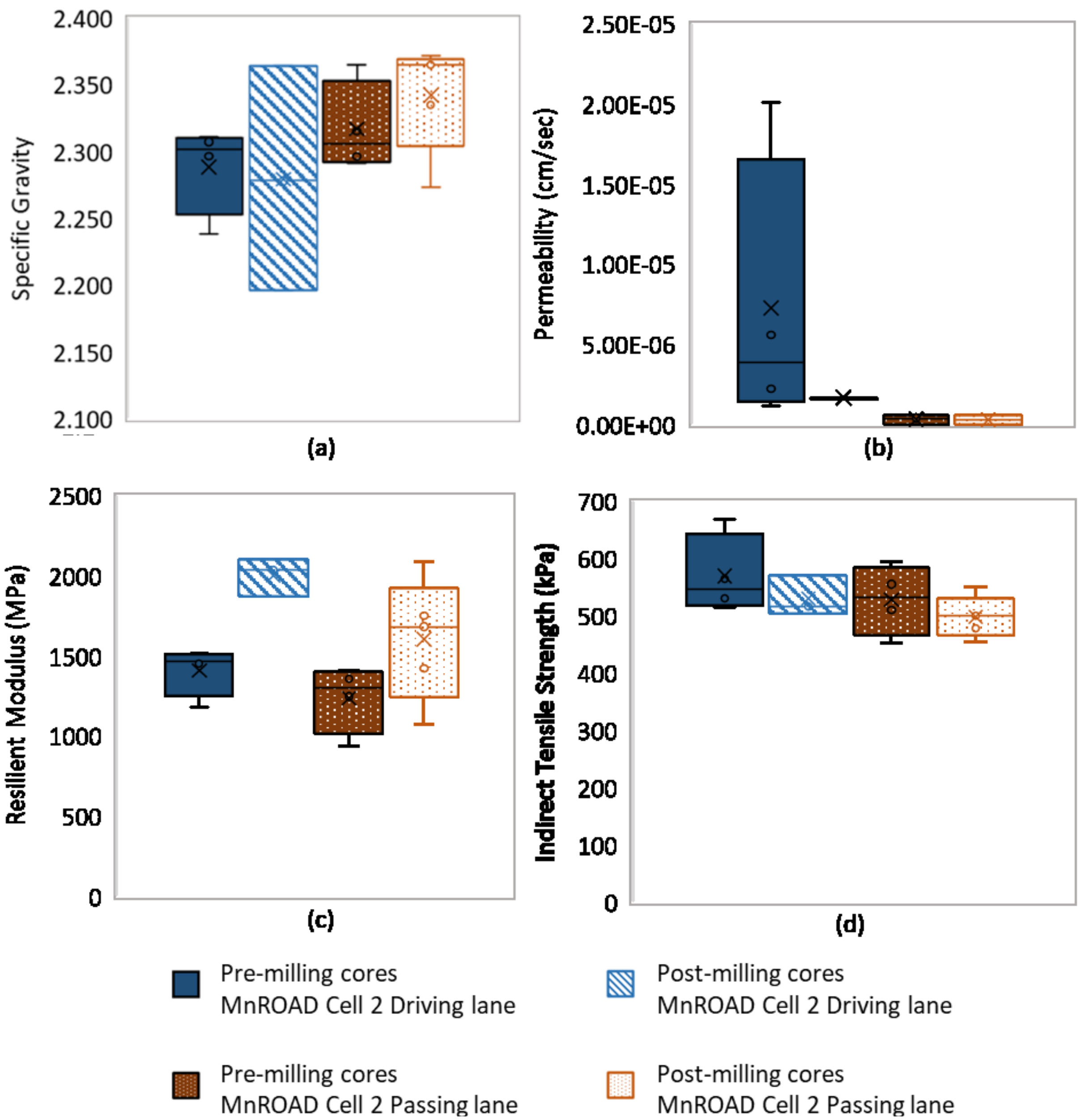


Figure 6-4 Impact of Milling to MnROAD Cell 2 in terms of (a) Specific Gravity, (b) Permeability, (c) MR and (d) ITS of the Pavement Layer Directly Below the Mill Line

The percent difference calculations presented in Table 6-5 below along with the figures above display the results from the laboratory testing for each of the three MnROAD Cells evaluated while Table 6-6 below displays the results from the statistical significance testing for the properties of the cores from these cells. In Cell 101, the results indicate that there was a slight increase in the specific gravity from the pre- to post-milling cores in both the driving and passing lanes. Further, in the driving lane of Cell 101, the results indicate an increase to the resilient modulus of the HMA, post-milling. The ITS values in Cell 101 did not have consistent changes between the two lanes, but the percent differences were minimal in both lanes. In Cell 201, there were small differences between the specific gravity of the pre- and post-milling cores in both lanes, and a large percent decrease in the measured permeability in the driving lane of this cell. The results of Cell 201 also indicated percent increases from the pre- to post-milling resilient modulus and ITS values, where for both properties the percent increase was greater in the passing lane than it was in the driving lane. Lastly, the results from Cell 2 similarly showed small differences between the specific gravity of the pre- and post-milling cores, and further showed that milling caused a decrease to the permeability of the HMA in the passing lane. In this cell, the results also indicated that post-milling, the resilient modulus of the HMA increased in both lanes, while the ITS decreased in both lanes. The percent change to the resilient modulus was greater than that of the ITS.

The conditions evaluated in this study indicate that milling did not have a statistically significant impact on the specific gravity, resilient modulus, or indirect tensile strength of MnROAD Cells 101 or 201. Comparatively, the conditions evaluated in this study do show a significant difference due to milling in the resilient modulus of the HMA directly below the mill line in the driving lane of the MnROAD Cell 2, but not in the passing lane of this cell. Thus, for the conditions evaluated in this study, milling under the same parameters did not consistently have different impacts on each of the three pavement structures evaluated, as it did not impact Cells 101 and 201, but did impact Cell 2.

The expected pavement life analysis was performed for the driving lane of MnROAD Cell 2 due to the statistically significant difference experienced between the pre- and post-milling modulus values. The conditions evaluated in this study found that not accounting for the impact of milling could cause an expected pavement life underestimation of 11% for the thin pavement structure and 18% for the thick pavement structure, resulting in an overdesigned pavement.

Table 6-5 Percent Differences between Pre- and Post-Milling Cores: Pavement Structure

Test Section	Parameter	Percent Difference between Pre- and Post-Milling Cores			
		Specific Gravity	Permeability	Resilient Modulus	Indirect Tensile Strength
PS1D	Cell 101 Driving	1.6%	-	58.7%	-0.5%
PS1P	Cell 101 Passing	0.5%	-	-	2.3%
PS2D	Cell 201 Driving	-0.2%	-96.3%	19.9%	6.0%
PS2P	Cell 201 Passing	1.9%	-	97.0%	28.9%
PS3D	Cell 2 Driving	-0.4%	-	42.2%	-6.9%
PS3P	Cell 2 Passing	1.1%	-10.9%	29.5%	-5.6%

- Indicates that insufficient data was available

Table 6-6 Significance Testing Results: Existing Pavement Structure

Test Section	Parameter	Statistical Difference between the Properties of Pre- and Post-Milling Cores in terms of p-values			
		Specific Gravity	Permeability	Resilient Modulus	Indirect Tensile Strength
PS1D	Cell 101 Driving	0.251	-	0.104	0.936
PS1P	Cell 101 Passing	0.846	-	-	0.864
PS2D	Cell 201 Driving	0.683	0.504	0.264	0.509
PS2P	Cell 201 Passing	0.284	-	0.186	0.280
PS3D	Cell 2 Driving	0.879	-	***0.002****	0.379
PS3P	Cell 2 Passing	0.343	0.927	0.115	0.439

**** Indicates statistical significance***

- Indicates that insufficient data was available

FWD testing was performed on MnROAD Cells 101, 201, and 2. Examples of the deflection bowls measured during the testing are presented in Figure 6-5. The backcalculated pre- and post-milling HMA modulus values from each of the cells is presented in Figure 6-6. The post-milling values for Cell 2 are unrealistically high; it is hypothesized that this is likely due in part to the thin HMA layer that remained after milling, which was only 44.5mm. To display these values in the figure below along with the other values, the red dashed line indicates a break in the y-axis. Further, the results showed an increase in the HMA modulus values from the pre- to post-milling structures in both lanes of Cells 101 and 201. It is notable that there was the smallest percent difference between the pre- and post-milling modulus values in the passing lane of MnROAD Cell 201, which had the greatest percentage difference in resilient modulus for the laboratory measured values. For the other cells and lanes evaluated, there was a greater difference between the pre- and post-milling modulus values from the FWD testing than there was from the laboratory resilient modulus testing results.

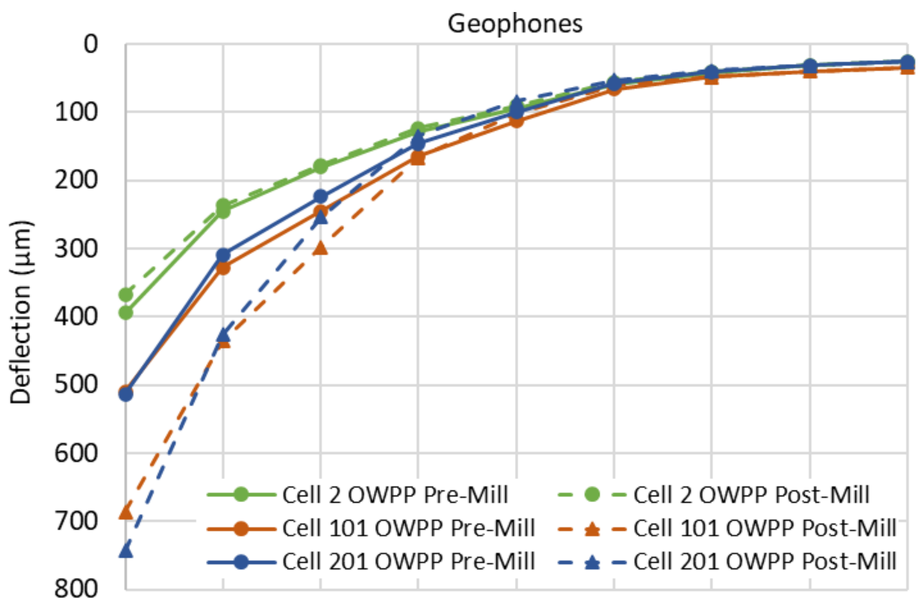


Figure 6-5 FWD Deflection Basins MnROAD Cells 2, 101, & 201

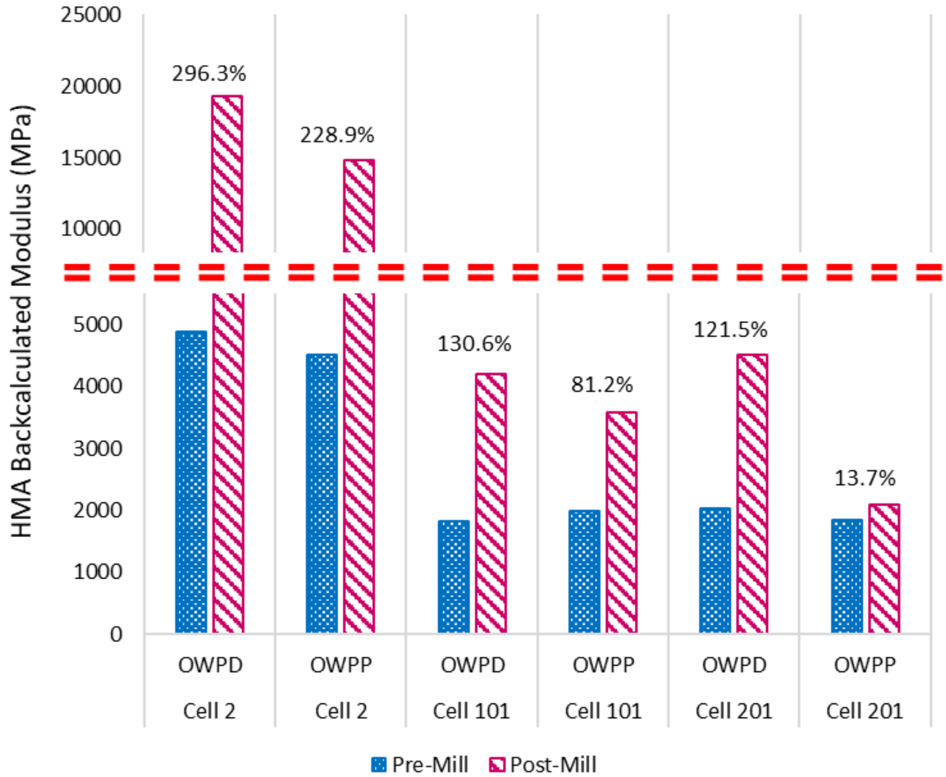


Figure 6-6 FWD Results MnROAD Cells 2, 101, and 201 (values above bars are the % difference)

The surface modulus results are presented in Figure 6-7 below. By examining the figure, the results show that in MnROAD Cells 101 and 201, the surface modulus decreased from the pre-milling to post-milling structures in both the driving and passing lanes, while in MnROAD Cell 2, the surface modulus increased from the pre-milling to post-milling structures in both the driving and passing lanes. Similarly, the surface modulus data from MnROAD Cells 101 and 201 show greater percent differences between the pre- and post-milling values in the passing lane than they do in the driving lane, while the surface modulus data from MnROAD Cell 2 shows a greater percent difference between the pre- and post-milling values in the driving lane than it does in the passing lane. In general, these results show that for Cell 2 the milling activity did not lower overall structural capacity of the cell. For Cell 101 and 201, milling activity did lower the structural capacity, however, the loss of surface modulus may be compound effect of reduction in HMA thickness from milling as well as any damage from milling to the post-milled pavement layers. The combination of this information with the lab resilient modulus measurements for these sections show that the cause for lowering of surface modulus is more likely due to reduced cross-section as opposed to damage to post-milled pavement layers. This is because the laboratory measured resilient modulus values for Cells 101 and 201 increased post-milling, whereas their surface modulus values for these cells decreased post-milling.

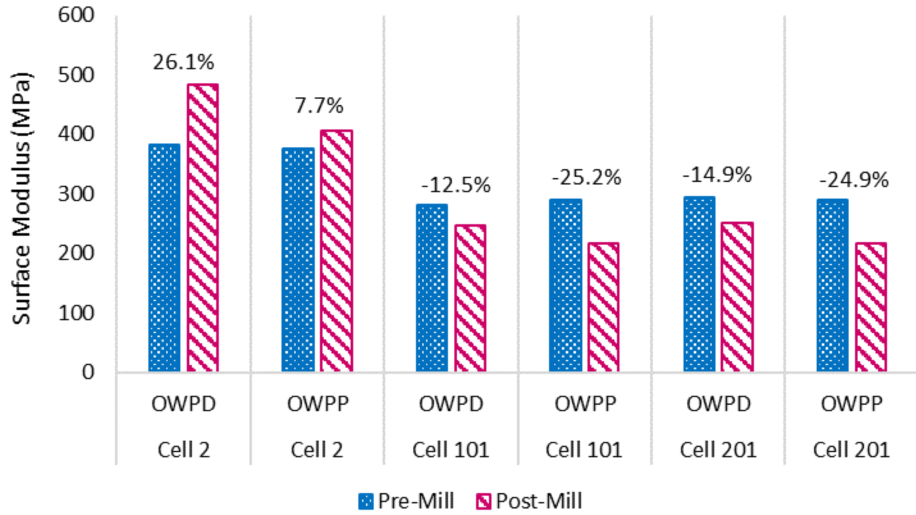


Figure 6-7 Surface Modulus of MnROAD Cells 2, 101, and 201 (values above bars are the % difference)

6.3 Time Between Milling and Post-Mill Overlay Construction

The amount of time between milling and post-mill overlay construction was evaluated was to determine if leaving a milled roadway exposed to construction traffic and weather for extended periods of time impacts the layer just below the mill line. To assess this, pre-milling cores were collected, then milling was performed, after which post-milling cores were collected after varying amounts of time: directly after milling, 1 week after milling, and 2 weeks after milling. These three parameter variations are presented in Table 6-7 below.

Table 6-7 Summary of Time between Milling and Post-Mill Overlay Construction Variable

Test Section	Core ID	MnROAD Cell	Milling Parameter Variations
1	TM1D	3 – Driving Lane	Post-milling cores collected immediately after milling
2	TM2D	4 – Driving Lane	Post-milling cores collected 1 week after milling
3	TM3D	4 – Driving Lane	Post-milling cores collected 2 weeks after milling

To evaluate the three parameter variations presented in the table above, the pre-milling cores for all three variations were collected on May 20, 2022, from the MnROAD facility. The post-milling cores for the TM1D variation were collected on the same day. The TM2D post-milling cores were collected one week later, while the TM3D post-milling cores were collected 2 weeks later. The weather conditions over those two weeks in Otsego, MN, where MnROAD is located is presented in Table 6-8 below. It is evident that over both weeks, there were not freezing temperatures in the area, and relatively low amounts of rain were experienced.

Table 6-8 Weather Conditions Post-Milling (Otsego, MN)

Week	Average High Temperature (^oF)	Average Temperature (^oF)	Average Low Temperature (^oF)	Total Rainfall
(1) May 20, 2022 – May 27, 2022	68.4	59.1	50.4	0.33 inches
(2) May 27, 2022 – June 3, 2022	72.3	63.4	53.7	1.00 inch

The laboratory testing results for each of the variations are presented in Table 6-9 and Figure 6-8 below.

Table 6-9 Time between Milling and Post-Mill Overlay Const. Variable Laboratory Testing Results

MnROAD Cell	Pre- or Post-Mill Core & Parameter Evaluated	Core ID	Specific Gravity	Permeability (cm/sec)	Resilient Modulus (MPa)	Indirect Tensile Strength (kPa)
MnROAD Cell 3 Driving lane	Pre-milling cores	TM1D-B1	2.303	3.42E-06	2447	552
		TM1D-B2	2.291	3.49E-06	1786	581
		TM1D-B3	2.358	5.33E-06	1742	580
		TM1D-B4	2.301	5.81E-07	1538	598
		Average	**2.313**	**3.21E-06**	**1878**	**578**
	Post-milling cores (Collected immediately after milling)	TM1D-A1	2.295	5.89E-06	2067	639
		TM1D-A2	2.311	7.67E-06	1467	561
		TM1D-A3	2.390	8.95E-06	1530	585
		TM1D-A4	2.324	1.62E-06	1319	463
		Average	**2.330**	**6.03E-06**	**1596**	**562**
MnROAD Cell 4 Driving lane	Pre-milling cores	TM2D-B1	2.404	2.48E-05	4715	743
		TM2D-B2	2.319	4.46E-05	3678	633
		TM2D-B3	2.335	4.99E-05	3307	647
		TM2D-B4	-	-	-	-
		TM2D-B5	2.344	1.10E-04	2923	665
		TM3D-B1	2.348	8.64E-06	2656	624
		TM3D-B2	2.245	6.14E-06	198	573
		TM3D-B3	-	-	-	-
		TM3D-B4	2.323	5.25E-07	1329	457
		Average	**2.331**	**3.49E-05**	**2937**	**620**
	Post-milling cores (Collected 1 week after milling)	TM2D-A1	2.417	2.51E-05	4524	687
		TM2D-A2	2.215	-	5812	720
		TM2D-A3	2.245	-	4151	686
		TM2D-A4	2.305	1.79E-05	3410	616
		TM2D-A5	2.289	1.21E-04	3147	632
		Average	**2.294**	**5.47E-05**	**4209**	**668**
	Post-milling cores (Collected 2 weeks after milling)	TM3D-A1	2.295	2.07E-05	3260	474
		TM3D-A2	2.249	1.22E-05	1865	568
		TM3D-A3	2.262	2.06E-05	1434	497
		TM3D-A4	-	-	-	-
		Average	**2.269**	**1.78E-05**	**2186**	**513**

“-“ Indicates that insufficient data was available

The percent difference calculations presented in Table 6-10 below along with the figure above indicate that when the post-milling cores were collected one week after milling, there was an increase to the strength and resilient modulus of the HMA, yet when collected two weeks after milling, there was a decrease to the strength and resilient modulus of the HMA. The cause for this is unknown, but it is hypothesized that the initial exposure to traffic on the freshly milled HMA may provide a slight compaction of the layer, as the temperature during this time was favorable to this potentially occurring, while additionally helping to close some of the microcracks from milling. In comparison, the repetitive traffic loading on the freshly milled HMA may have eventually degraded it and could have reopened those microcracks. In addition, the rain experienced in the second week of exposure may have contributed to potential moisture damage.

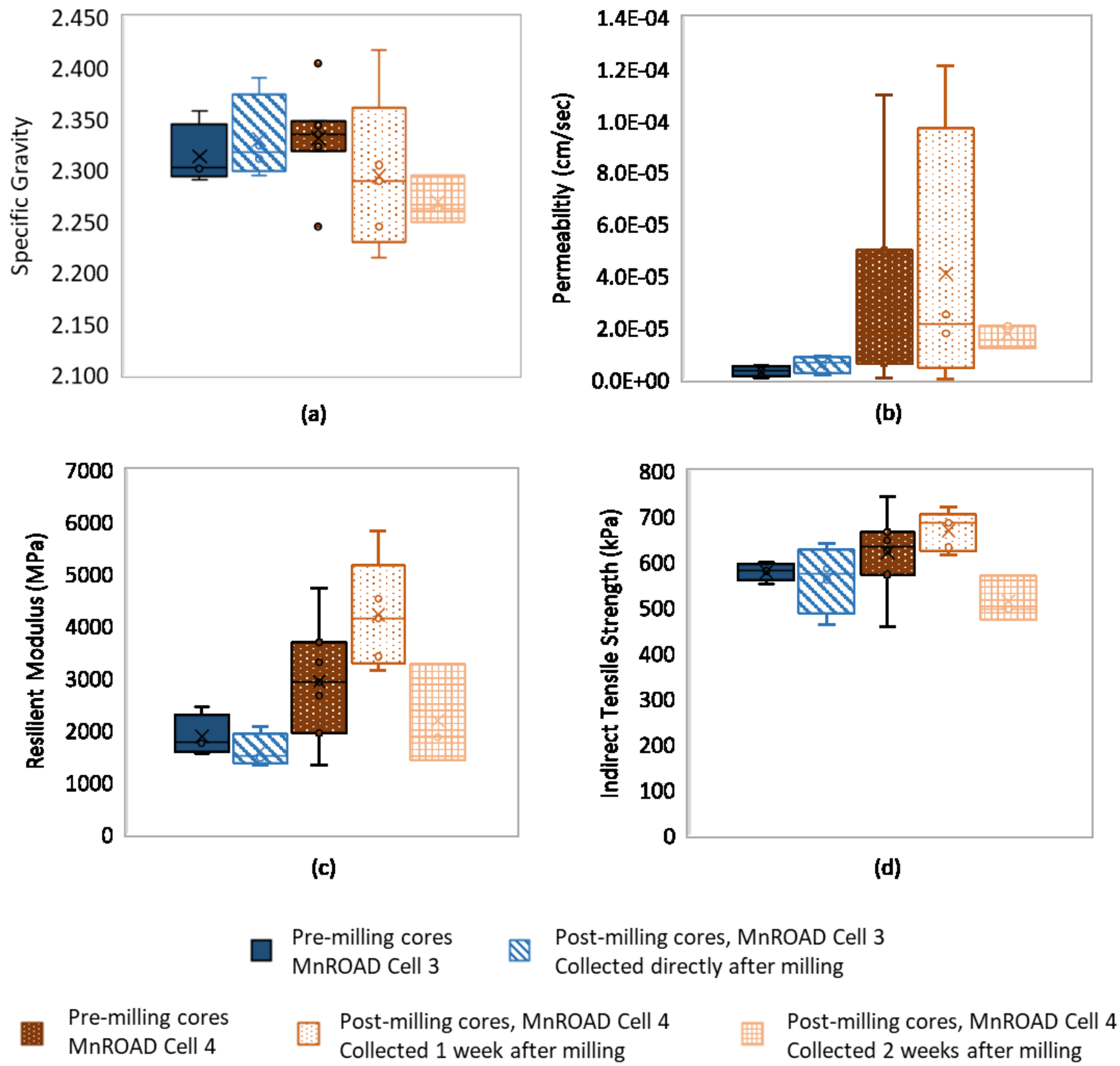


Figure 6-8 Impact of Time between Milling and Post-Mill Overlay Construction on the (a) Specific Gravity, (b) Permeability, (c) MR and (d) ITS of the Pavement Layer Directly Below the Mill Line

The statistical significance testing results are presented in Table 6-11 below. The results indicate that there was a significant decrease to the specific gravity and the indirect tensile strength of the HMA below the mill line when the milled HMA layer was exposed for two weeks after milling. The decrease in specific gravity shows a decrease in density of the material, and therefore the decrease in the indirect tensile strength is likely a result of the decrease of the density of the HMA. Comparatively, the results did not indicate a significant difference when the post-milling cores were collected directly or one week after milling.

Due to the statistically significant decrease in the ITS and specific gravity in the HMA when exposed for 2 weeks, the expected pavement life analysis was conducted. This analysis indicated the impact of leaving a milled pavement exposed for two weeks did not cause a change in the expected pavement life of the thin pavement structure. Comparatively, leaving a milled pavement exposed for 2 weeks showed an overestimation of 13.3% for the expected pavement life of the thick structure, ultimately having the potential to cause the pavement to be under designed.

Table 6-10 Percent Differences between Pre- and Post-Milling Cores: Time between Milling and Post-Mill Construction

Test Section	Parameter	Percent Difference between Pre- and Post-Milling Cores			
		Specific Gravity	Permeability	Resilient Modulus	Indirect Tensile Strength
TM1D	Collected directly after milling	0.7%	87.9%	-15.0%	-2.7%
TM2D	Collected 1 week after milling	-1.6%	56.7%	43.3%	7.7%
TM3D	Collected 2 weeks after milling	-2.7%	-49.0%	-25.5%	-17.3%

Table 6-11 Significance Testing Results: Time between Milling and Post-Mill Construction

Test Section	Parameter	Statistical Difference between the Properties of Pre- and Post-Milling Cores in terms of P-Values			
		Specific Gravity	Permeability	Resilient Modulus	Indirect Tensile Strength
TM1D	Collected directly after milling	0.542	0.192	0.314	0.707
TM2D	Collected 1 week after milling	0.378	0.627	0.075	0.246
TM3D	Collected 2 weeks after milling	***0.026****	0.286	0.334	***0.045****

***** Indicates statistical significance***

FWD testing was performed on MnROAD Cell 3. An example of the deflection bowls measured during the testing are presented in Figure 6-9. The backcalculated pre- and post-milling HMA modulus values from this cell is presented in Figure 6-10. The results show an increase in the HMA modulus values from the pre- to post-milling structures in both the driving and passing lanes of this cell. The post-milling modulus values that were backcalculated from the FWD data from MnROAD Cell 3 (similar to that of MnROAD Cell 2 discussed in Section 3.1 above) are unrealistically high. These values will be disregarded as these are likely to be extremely elevated due in part to the low thickness of the HMA layer that remained after milling which was only 44.5mm thick. Backcalculated results are usually not trustworthy when using such thin pavement layers.

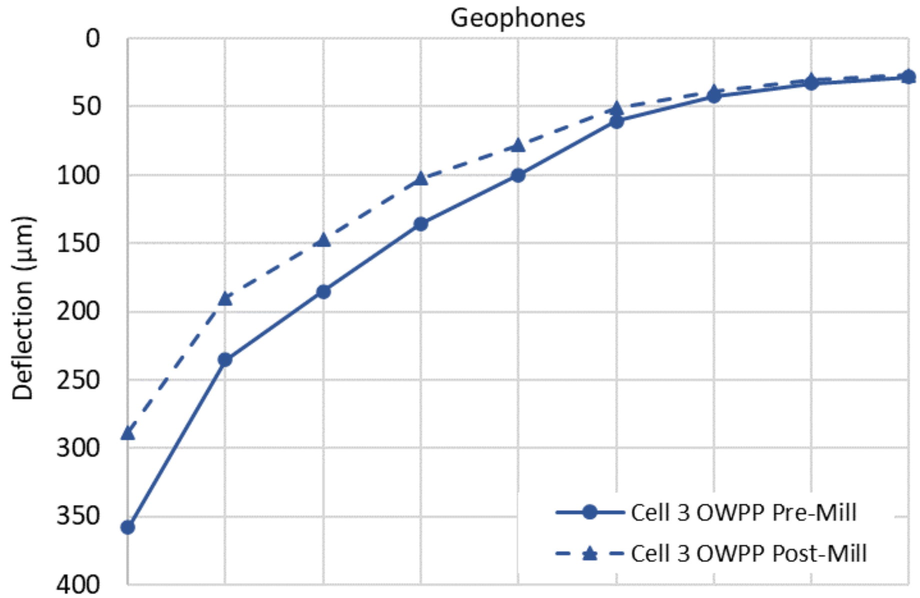


Figure 6-9 FWD Deflection Basin MnROAD Cell 3

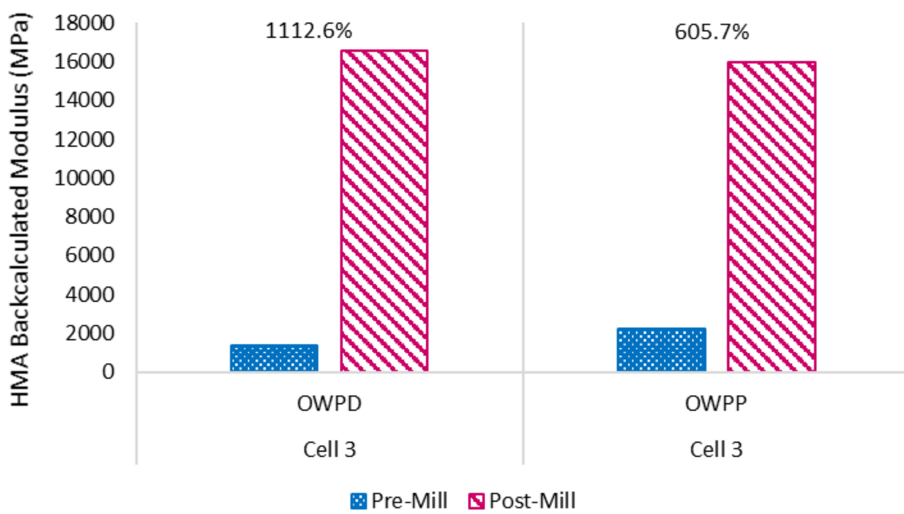


Figure 6-10 FWD Results MnROAD Cell 3 (values above bars are the % difference)

The surface modulus results for MnROAD Cell 3 are displayed in Figure 6-11 below. The results indicate that in both the passing and driving lanes, the calculated surface modulus of the pre-milling structure was less than that of the post-milling structure. Further, the data shows that there was a greater percent increase in the driving lane of this cell than there is in the passing lane in terms of its surface modulus. In general, these results show that for Cell 3 the milling activity did not lower the overall structural capacity of the cell. Therefore, the surface modulus data shows that even with a lower HMA thickness, the overall capacity of the Cell 3 pavement structure did not decrease, and thus it can be assumed that there was no damage to this cell from the milling activity.

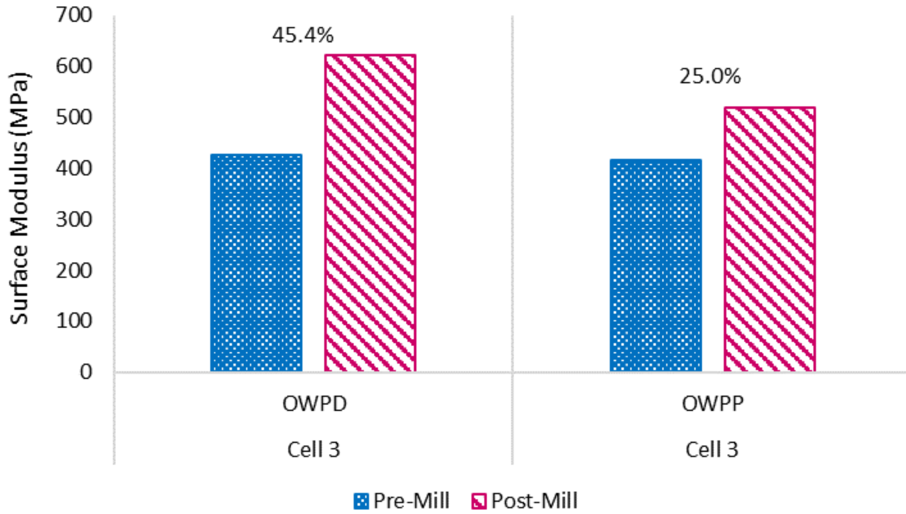


Figure 6-11 Surface Modulus of MnROAD Cell 3 (values above bars are the % difference)

6.4 Depth of Milling Relative to the Layer Interface

To determine if the depth of milling relative to the layer interface influences the impact of milling to the layer of asphalt directly below the mill line, milling was performed at different depths into an existing pavement structure. Pre- and post-milling cores were collected with milling performed to the layer interface, halfway through the lift, and three-quarters of the way through the lift. The summary of these parameters is presented in Table 6-12 below, while the laboratory testing results of the cores used to evaluate this parameter are presented in Table 6-13 and Figure 6-12 below.

Table 6-12 Summary of Depth of Milling Parameter

Test Section	Core ID	MnROAD Cell	Milling Parameter Variations
1	DM1P	115 – Passing Lane	Milling depth: to layer interface
2	DM2P	115 & 215 – Passing Lane	Milling depth: to halfway through lift
3	DM3P	215 – Passing Lane	Milling depth: to three-quarters through lift

Table 6-13 Depth of Milling Variable Laboratory Testing Results

MnROAD Cell	Pre- or Post-Mill Core & Parameter Evaluated	Core ID	Specific Gravity	Resilient Modulus (MPa)	Indirect Tensile Strength (kPa)
MnROAD Cell 115 & 215 Passing Lane	Pre-milling cores	DM1P-B1	2.390	4784	885
		DM1P-B2	2.263	3812	951
		DM1P-B3	-	-	-
		DM1P-B4	2.285	4663	1094
		DM2P-B1	-	-	-
		DM2P-B2	2.291	2206	713
		DM2P-B3	2.287	4393	1029
		DM2P-B4	2.279	4164	985
		DM3P-B1	2.366	3090	670
		DM3P-B2	2.235	3425	814
		DM3P-B3	2.239	3523	857
		DM3P-B4	-	-	-
		Average	**2.293**	**3784**	**889**
MnROAD Cell 115 Passing Lane	Post-milling cores (Milling depth: to layer interface)	DM1P-A1	2.280	4315	875
		DM1P-A2	2.249	4248	891
		DM1P-A3	-	-	-
		DM1P-A4	2.271	5041	1000
		Average	**2.267**	**4535**	**922**
MnROAD Cell 115 & 215 Passing Lane	Post-milling cores (Milling depth: halfway through lift)	DM2P-A1	-	-	-
		DM2P-A2	2.236	2265	619
		DM2P-A3	2.250	2745	683
		DM2P-A4	2.272	4645	916
		Average	**2.253**	**3218**	**739**
MnROAD Cell 215 Passing Lane	Post-milling cores (Milling depth: three-quarters through lift)	DM3P-A1	2.368	3898	850
		DM3P-A2	2.248	3142	859
		DM3P-A3	2.293	4032	8241
		DM3P-A4	2.327	3290	921
		Average	**2.309**	**3590**	**864**
"-" Indicates that insufficient data was available					

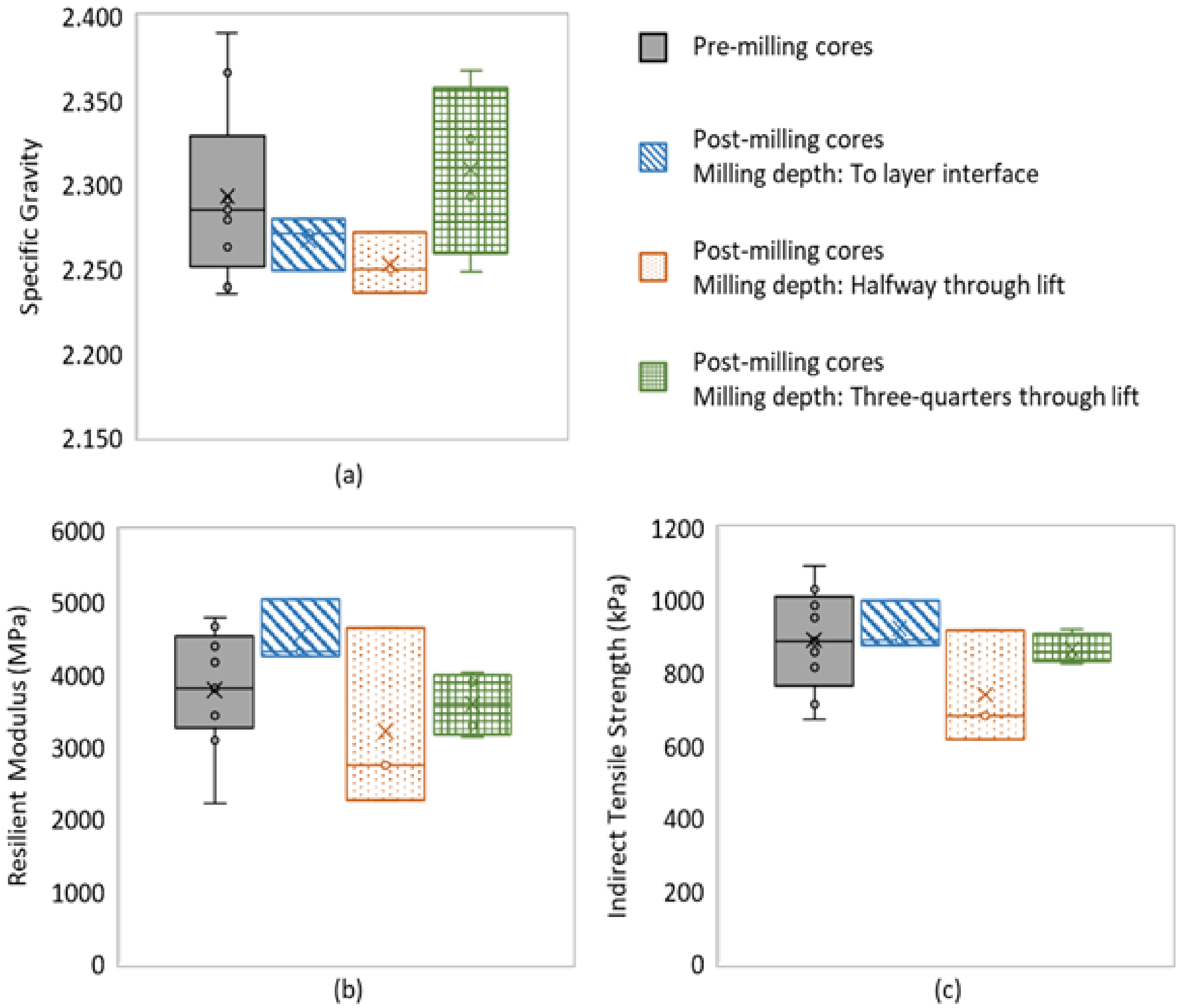


Figure 6-12 Impact of Depth of Milling on the (a) Specific Gravity, (b) Permeability, (c) MR and (d) ITS of the Pavement Layer Directly Below the Mill Line

The percent difference results displayed in Table 6-14 below show that there was an increase from the pre-milling values of resilient modulus and ITS to the post-milling values when milling was performed to the layer interface. This is likely a marginal increase and cannot be conclusive of an actual impact. Comparatively, when milling was performed to halfway or three-quarters of the way through the lift, the percent different results show a decrease from the pre-milling resilient modulus and ITS values to the post-milling values. The reasoning behind this is something that could be studied in future projects but is likely caused by a natural weakness formed in the pavement at the interface between layers, and therefore the breaking-off of the material causes less stress to the remaining HMA than when milling is performed to a depth where a natural weakness is not already occurring.

The results of the statistical significance testing are presented in Table 6-15 below, and do not indicate that there is a statistically significant impact to the specific gravity, resilient modulus, or indirect tensile strength of the HMA below the mill line, regardless of the milling depth relative to the layer interface. This indicates that in future milling projects, the depth of milling may be determined based on project needs and other appropriate criteria, as this study did not find any significant impact of the selected depth of milling.

Table 6-14 Percent Difference between Pre- and Post-Milling Cores: Depth of Milling

Test Section	Parameter	Percent Difference between Pre- and Post-Milling Cores		
		Specific Gravity	Resilient Modulus	Indirect Tensile Strength
DM1P	Milling to layer interface	-1.1%	19.8%	3.7%
DM2P	Milling to halfway through lift	-1.7%	-15.0%	-16.8%
DM3P	Milling to three-quarters through lift	0.7%	-5.1%	-2.8%

Table 6-15 Significance Testing Results: Depth of Milling

Test Section	Parameter	Statistical Difference between the Properties of Pre- and Post-Milling Cores in terms of P-Values		
		Specific Gravity	Resilient Modulus	Indirect Tensile Strength
DM1P	Milling to layer interface	0.217	0.085	0.607
DM2P	Milling to halfway through lift	0.079	0.526	0.234
DM3P	Milling to three-quarters through lift	0.619	0.594	0.635

FWD testing was performed on MnROAD Cells 115 and 215. Examples of the deflection bowls measured during the testing are presented in Figure 6-13. The backcalculated pre- and post-milling HMA modulus values from each of the cells is presented in Figure 6-14. The backcalculated modulus values from Cell 115 indicated a 25.5% percent increase from the pre-milling structure HMA to the post-milling structure HMA, relative to the pre-milling HMA. Comparatively, the backcalculated modulus values from Cell 215 indicated a -11.8% percent decrease from the pre-milling structure HMA to the post-milling structure HMA, relative to the pre-milling HMA.

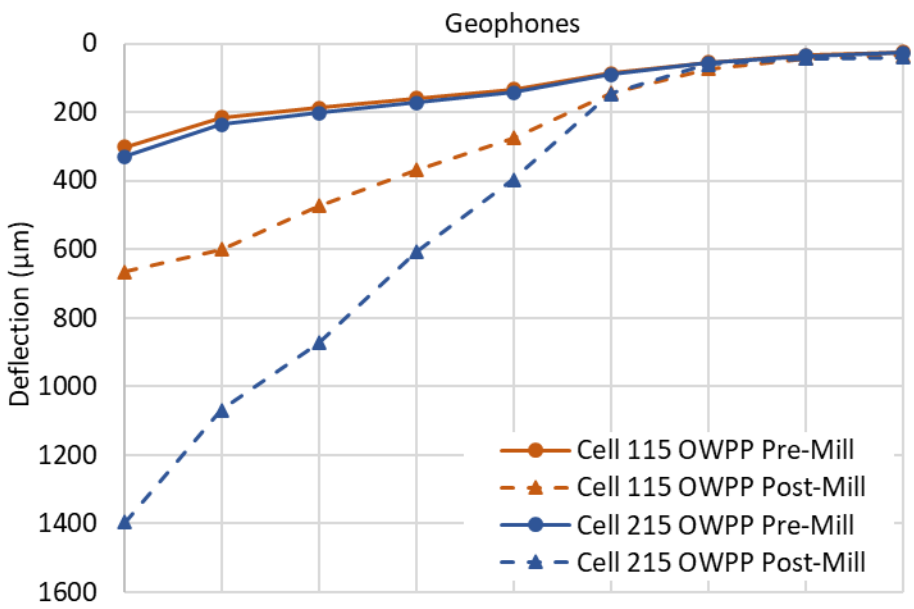


Figure 6-13 FWD Deflection Basins MnROAD Cells 115 & 215

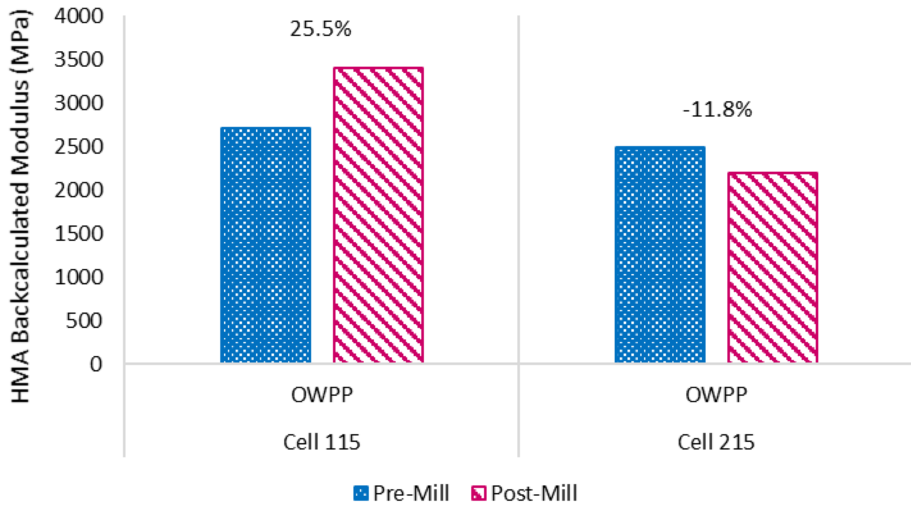


Figure 6-14 FWD Results MnROAD Cells 115 & 215 (values above bars are the % difference)

The surface modulus results for MnROAD Cells 115 and 215 are displayed in Figure 6-15 below. By examining the figure below, the results show that in both MnROAD Cells 115 and 215, the calculated surface modulus of the pre-milling structure was less than that of the post-milling structure. Further, the data shows that there was a greater percent decrease from the pre- to post-milling surface modulus, relative to the pre-milling surface modulus for Cell 115 than there was in Cell 215. In general, for Cell 115 and 215, the surface modulus results demonstrate that the milling activity did lower the structural capacity of the pavement, however, the loss of surface modulus may be a compound effect of damage from milling to the post-milled layers in addition to the overall reduction in the thickness of the HMA from the milling that was performed.

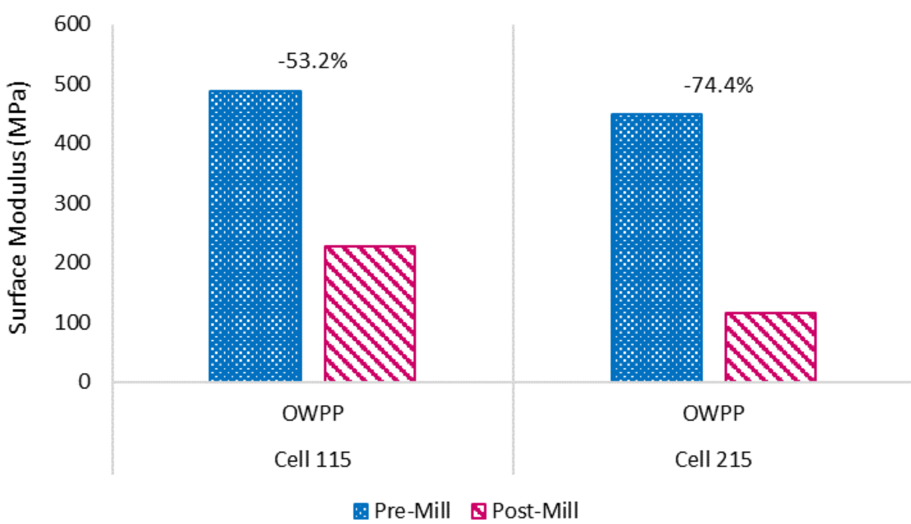


Figure 6-15 Surface Modulus of MnROAD Cells 115 and 215 (values above bars are the % difference)

6.5 Operational and Equipment Parameters

The objective of the operational and equipment parameters variable was to evaluate how changing the rotor speed, spacing between milling teeth, or rotor type while milling influenced the impact of milling on the pavement layer directly below the mill line. Five variations of milling operational and equipment parameters were evaluated and are presented in Table 6-16 below. Due to their thinness, many of the post-milling cores from MnROAD Cell 16 cracked during their transit from MnROAD facility to the laboratory in New Hampshire. Thus, many of them were unusable, and because of that, the research team was unable to collect sufficient results to be able to evaluate the impact of using different rotor types or the impact of changing the spacing between teeth. The cores to evaluate the impact of changing the rotor speed were collected from MnROAD Cells 21, 22, and 23 and were able to be evaluated. The laboratory testing results of cores collected from Cell 16 are presented in Table 6-17 below, the results of the cores collected from Cell 21 are presented in Table 6-18 below, the results of the cores collected from Cell 22 are presented in Table 6-19 below, and finally the results of the cores collected from Cell 23 are presented in Table 6-20 below. The laboratory testing results of the cores collected from Cells 21, 22, and 23 are further presented in Figure 6-16 below.

Table 6-16 Summary of Operational and Equipment Parameters Variable

Test Section	Core ID	MnROAD Cell	Milling Parameter Variations		
			Rotor Speed (RPM)	Teeth Spacing (mm)	Rotor Type*
1	OP1P	16 – Passing Lane	118	8	K
2	OP2P	16 – Passing Lane	118	8	G
3	OP3P	21 – Passing Lane	100	15	K
4	OP4P	22 – Passing Lane	109	15	K
5	OP5P	23 – Passing Lane	118	15	K

*The System G Rotor is Caterpillar's 'Legacy Design' whereas the System K Rotor is a more modern design with a larger shank, a longer wear collar, is configured for higher horsepower machines, all while having more durable components for an extended life.

Table 6-17 Operational and Equipment Parameters: MnROAD Cell 16 Passing Lane Laboratory Testing Results

Pre- or Post-Mill Core & Parameter Evaluated	Core ID	Specific Gravity	Resilient Modulus (MPa)	Indirect Tensile Strength (kPa)
Pre-milling cores	OP1P-B1	2.409	4181	1169
	OP1P-B2	2.379	4200	1068
	OP1P-B3	-	-	-
	OP1P-B4	2.313	4631	1196
	OP1P-B4-02	2.380	3597	859
	OP1P-B5	2.356	5084	1156
	OP2P-B1	2.330	4975	1053
	OP2P-B2	2.271	6008	1420
	OP2P-B3	2.292	4801	1169
	OP2P-B4	2.315	-	1192
	Average	**2.343**	**4685**	**1143**
Post-milling cores (118RPM rotor speed, 8mm teeth spacing, K rotor type)	OP1P-A1	-	-	-
	OP1P-A2	-	-	-
	OP1P-A3	-	-	-
	OP1P-A4	-	-	-
	Average	**-**	-	-
Post-milling cores (118RPM rotor speed, 8mm teeth spacing, G rotor type)	OP2P-A1	-	-	-
	OP2P-A2	2.274	4304	1032
	OP2P-A3	-	-	-
	OP2P-A4	-	-	-
	Average	**2.274**	**4304**	**1032**

"-" Indicates that the data was unable to be collected

Table 6-18 Operational and Equipment Parameters: MnROAD Cell 21 Passing Lane Laboratory Testing Results

Pre- or Post-Mill Core & Parameter Evaluated	Core ID	Specific Gravity	Resilient Modulus (MPa)	Indirect Tensile Strength (kPa)
Pre-milling cores	OP3P-B1	2.376	3559	1125
	OP3P-B1-01	2.389	5548	1194
	OP3P-B2	2.432	4419	1055
	OP3P-B3	2.378	3122	971
	OP3P-B3-01	2.437	5025	1185
	OP3P-B4	2.385	3727	1162
	OP3P-B4-01	-	3761	1140
	OP3P-B5	-	-	-
	OP3P-B6	2.382	5258	1227
	OP3P-B7	2.408	3761	1104
	OP3P-B8	2.400	3675	1069
	Average	**2.399**	**4185**	**1123**
Post-milling cores (100RPM rotor speed, 15mm teeth spacing, K rotor type)	OP3P-A1	2.417	4849	1057
	OP3P-A2	2.477	6101	1182
	OP3P-A3	2.441	3612	-
	OP3P-A4	2.394	5496	1049
	OP3P-A5	-	-	-
	OP3P-A6	2.411	5179	931
	OP3P-A7	2.418	4177	1026
	OP3P-A8	2.408	4798	1074
	Average	**2.424**	**4887**	**1053**

“-“ Indicates that the data was unable to be collected

Table 6-19 Operational and Equipment Parameters: MnROAD Cell 22 Passing Lane Laboratory Testing Results

Pre- or Post-Mill Core & Parameter Evaluated	Core ID	Specific Gravity	Resilient Modulus (MPa)	Indirect Tensile Strength (kPa)
Pre-milling cores	OP4P-B1	2.359	7601	1513
	OP4P-B2	2.340	6954	1393
	OP4P-B3	2.338	6127	1393
	OP4P-B4	2.444	6801	1306
	OP4P-B5	2.345	-	1200
	OP4P-B6	2.387	5794	1173
	OP4P-B7	2.310	7576	1141
	OP4P-B8	2.363	4863	1090
	Average	**2.361**	**6531**	**1276**
Post-milling cores (109RPM rotor speed, 15mm teeth spacing, K rotor type)	OP4P-A1	2.329	7666	1213
	OP4P-A2	-	-	-
	OP4P-A3	2.343	7098	1275
	OP4P-A4	2.343	6701	1039
	OP4P-A5	2.323	8051	1265
	OP4P-A6	2.319	7930	1090
	OP4P-A7	2.395	6694	1091
	OP4P-A8	2.304	6581	1163
	Average	**2.337**	**7246**	**1162**

"-" Indicates that the data was unable to be collected

Table 6-20 Operational and Equipment Parameters: MnROAD Cell 23 Passing Lane Laboratory Testing Results

Pre- or Post-Mill Core & Parameter Evaluated	Core ID	Specific Gravity	Resilient Modulus (MPa)	Indirect Tensile Strength (kPa)
Pre-milling cores	OP5P-B1	2.331	7009	1269
	OP5P-B2	2.300	5689	1047
	OP5P-B3	2.367	5551	934
	OP5P-B4	2.343	5454	1245
	OP5P-B5	2.373	6122	1076
	OP5P-B6	-	-	-
	OP5P-B7	2.382	6626	1158
	OP5P-B8	2.330	6140	1297
	Average	**2.347**	**6084**	**1147**
Post-milling cores (118RPM rotor speed, 15mm teeth spacing, K rotor type)	OP5P-A1	2.337	5849	1017
	OP5P-A2	2.296	5613	1026
	OP5P-A3	2.360	5450	1257
	OP5P-A4	2.353	5247	1153
	OP5P-A5	2.365	5003	1248
	OP5P-A6	2.370	6247	1204
	OP5P-A7	2.385	5264	1267
	OP5P-A8	2.307	6053	1158
	Average	**2.347**	**5591**	**1166**

"-" Indicates that the data was unable to be collected

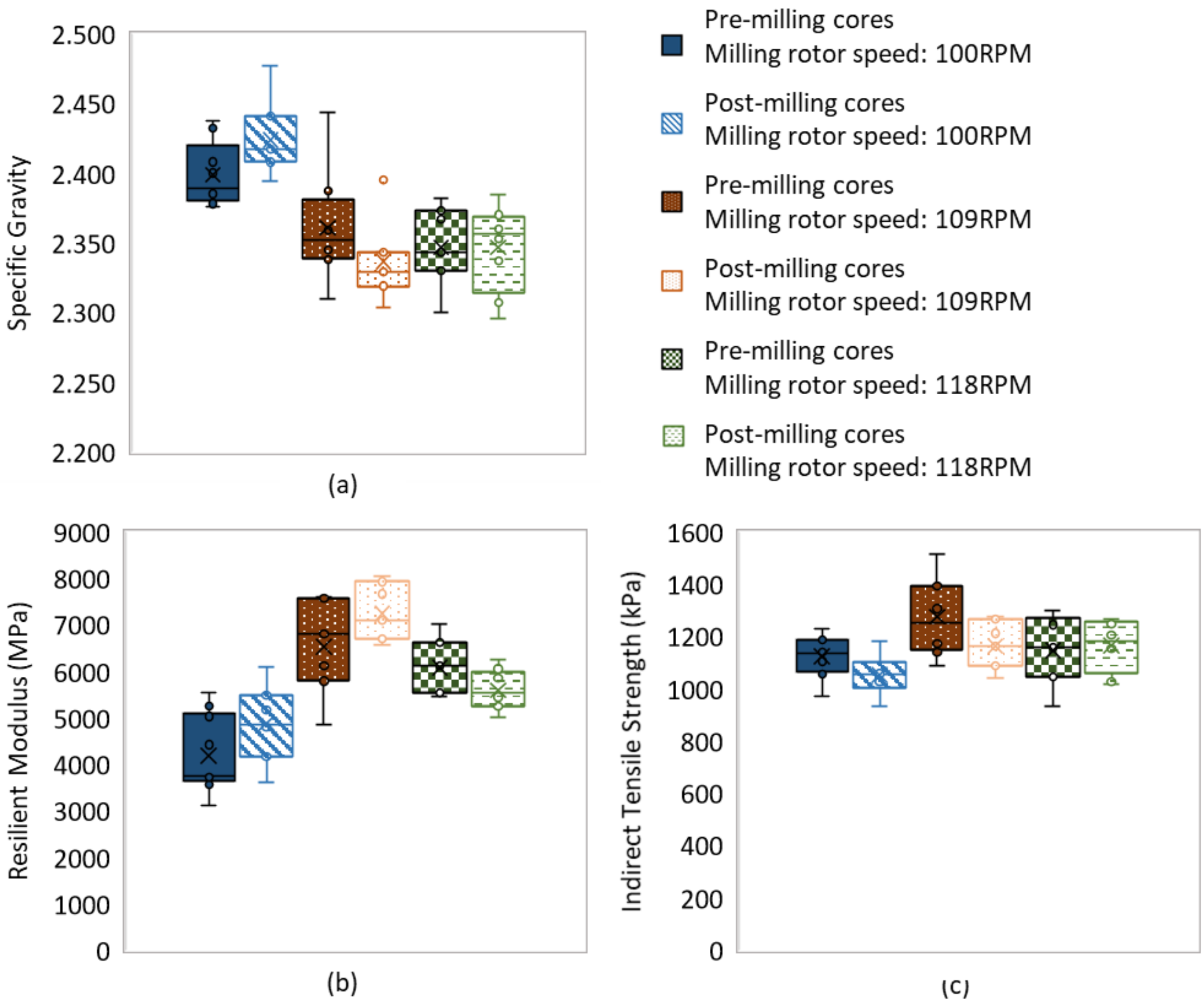


Figure 6-16 Impact of Rotor Speed when Milling on the (a) Specific Gravity, (b) MR, and (c) ITS of the Pavement Layer Directly Below the Mill Line

Table 6-21 below presents the percent differences between the average value of the pre- and post-milling cores for each of the laboratory tests, under each of the three milling parameter variations evaluated. When the rotor was rotating at the slowest speed, there was the greatest percent increase in the resilient modulus. Comparatively, when the rotor was rotating at the highest speed, there was a decrease in the resilient modulus from the pre-milling to the post-milling cores. These percent difference results indicate that as the rotor speed increases, the resilient modulus of the post-milling cores decreased, relative to resilient modulus of the pre-milling cores. The percent differences between the specific gravity and indirect tensile strength of the pre- and post-milling cores did not display consistent changes as the rotor speed was changed. Further, Table 6-22 presents the results of the statistical significance testing between the pre- and post-milling cores properties under these milling parameter variations. Assuming a confidence interval of 95%, the results in this study did not indicate that there was a statistically significant difference to the properties evaluated of the HMA below the mill line, regardless of the rotor speed while milling. This indicates that in future milling projects, the milling rotor speed may be determined based on project needs, since this study did not find any significant impact of the rotor speed between 100 and 118 RPM.

Table 6-21 Percent Differences between Pre- and Post-Milling Cores: Operational & Equipment Parameters

Test Section	Parameter	Percent Difference between Pre- and Post-Milling Cores		
		Specific Gravity	Resilient Modulus (MPa)	Indirect Tensile Strength (kPa)
OP1P	118RPM, 8mm, K type	-	-	-
OP2P	118RPM, 8mm, G type	-	-	-
OP3P	100RPM, 15mm, K type	1.0%	16.78%	-6.23%
OP4P	109RPM, 15mm, K type	-1.0%	10.9%	-8.9%
OP5P	118RPM, 15mm, K type	0%	-8.1%	1.7%
"-" Indicates that insufficient data was available				

Table 6-22 Significance Testing Results: Operational & Equipment Parameters

Test Section	Parameter	Statistical Difference between the Properties of Pre- and Post-Milling Cores in terms of P-Values		
		Specific Gravity	Resilient Modulus	Indirect Tensile Strength
OP1P	118RPM, 8mm, K type	-	-	-
OP2P	118RPM, 8mm, G type	-	-	-
OP3P	100RPM, 15mm, K type	0.075	0.107	0.116
OP4P	109RPM, 15mm, K type	0.204	0.139	0.954
OP5P	118RPM, 15mm, K type	0.997	0.090	0.755
"-" Indicates that insufficient data was available				

6.6 Pavement Temperature at the Time of Milling

To determine how the pavement temperature at the time of milling influences the impact of milling to the layer of asphalt directly below the mill line, milling was performed at two temperature ranges. The summary of the parameters of this variable are presented in Table 6-23 below. There were 6 pre-milling cores and 6 adjacent post-milling cores collected from Cells 21 and 22 to evaluate milling at a cooler temperature, while there was similarly 6 pre-milling cores and 6 adjacent post-milling cores collected from Cells 22 and 23 to evaluate milling at a warmer temperature. MnROAD Cells 21 and 22 had identical structures, and thus were able to be evaluated together, whereas MnROAD Cells 22 and 23 had different performance grade (PG) binder in their HMA layers, and thus were evaluated separately. The laboratory testing results of all these cores are presented in Table 6-24 and Figure 6-17 below.

Table 6-23 Summary of Pavement Temperature at Time of Milling Variable

Test Section	Core ID	MnROAD Cell	Milling Variable Parameters
1	TP1S	21-22 – Driving Shoulder	Pavement temp: 12.2°C – 15.6°C, Air temp: 8.3°C
2	TP2S	22-23 – Driving Shoulder	Pavement temp: 33.3°C – 47.2°C, Air temp: 18.3°C

Table 6-24 Temperature Variable Laboratory Testing Results

MnROAD Cell	Pre- or Post-Mill Core & Parameter Evaluated	Core ID	Specific Gravity	Resilient Modulus (MPa)	Indirect Tensile Strength (kPa)
MnROAD Cell 21 Driving Shoulder	Pre-milling cores	TP1S-B1	-	-	-
		TP1S-B2	2.390	6006	1280
MnROAD Cell 22 Driving Shoulder		TP1S-B3	-	-	-
		TP1S-B4	2.359	6006	1488
		TP1S-B5	2.344	7253	1560
		TP1S-B6	2.348	5703	2119
		TP2S-B1	2.343	7032	1821
		TP2S-B2	2.337	6438	1539
		TP2S-B3	2.364	5612	1462
		TP2S-B4	2.335	6254	1402
Both		**Average**	**2.353**	**6288**	**1584**
MnROAD Cell 21 Driving Shoulder	Post-milling cores Cooler pavement temperature at time of milling (12.2°C – 15.6°C)	TP1S-A1	2.270	4871	1031
		TP1S-A2	2.395	3857	1042
MnROAD Cell 22 Driving Shoulder		TP1S-A3	2.333	5916	1150
		TP1S-A4	2.325	5710	1208
		TP1S-A5	2.289	6732	1133
		TP1S-A6	2.295	5892	1002
Both		**Average**	**2.318**	**5496**	**1094**
MnROAD Cell 22 Driving Shoulder	Post-milling cores Warmer pavement temperature at time of milling (33.3°C – 47.2°C)	TP2S-A1	2.339	6576	1332
		TP2S-A2	2.322	6534	1333
		TP2S-A3	2.364	6961	1604
		TP2S-A4	2.336	6706	1206
		Average	**2.340**	**6694**	**1369**
MnROAD Cell 23 Driving Shoulder	Pre-milling cores	TP2S-B5	2.335	8557	1483
		TP2S-B6	2.302	6704	1650
		Average	**2.319**	**7631**	**1567**
	Post-milling cores Warmer pavement temperature at time of milling (33.3°C – 47.2°C)	TP2S-A5	2.351	6036	1207
		TP2S-A6	2.305	6210	1219
		Average	**2.328**	**6123**	**1213**

- Indicates that the data was unable to be collected

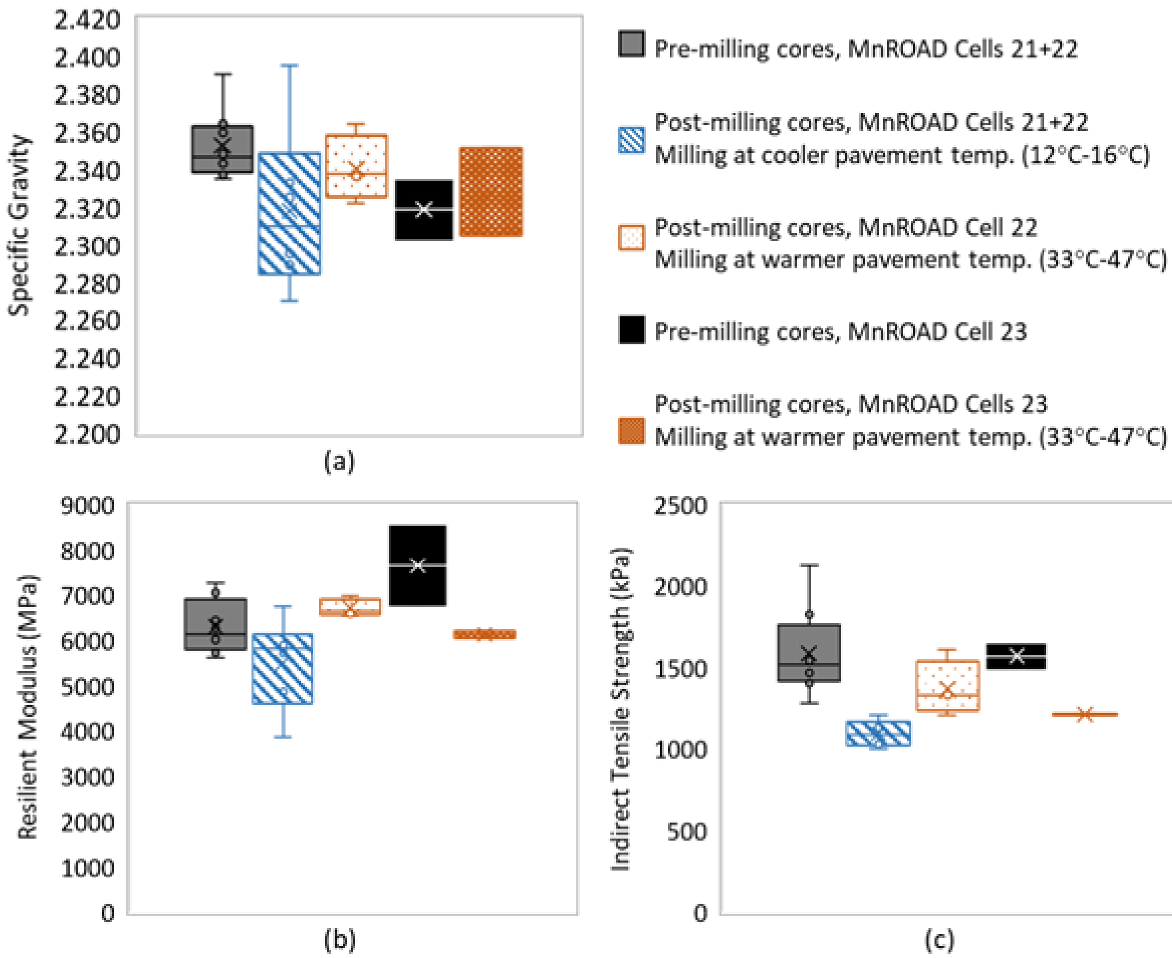


Figure 6-17 Impact of Temperature at Time of Milling on the (a) Specific Gravity, (b) MR, and (c) ITS of the Pavement Layer Directly Below the Mill Line

The percent difference between the pre- and post-milling cores are presented in Table 6-25, while the statistical significance testing results are presented in Table 6-26. The percent difference calculations show that there was a greater percent decrease to the HMA below the mill line when milling was performed at a cooler temperature than there was when milling was performed at a warmer temperature. With that, the conditions evaluated in this study showed there was a statistically significant decrease to the ITS of the HMA directly below the mill line when milling was performed at a cooler temperature but did not indicate that there was a statistically significant difference between the ITS of the pre- and post-milling cores when milling was performed at a warmer temperature. This study did not show significant differences between the pre- and post-milling cores of the specific gravity or resilient modulus when milling was performed at either temperature, and similarly did not show consistent changes to these properties by the percent difference calculations. That said, there was a decrease in the specific gravity post-milling when milling was performed at a cooler temperature, although not a statistically significant decrease. This decrease in specific gravity could have contributed to the statistically significant decrease to the indirect tensile strength of the HMA that remained below the mill line when milling at a cooler temperature.

Due to the significant decrease to the strength of the layer below the mill line when milling at a cooler temperature, the expected pavement life analysis was conducted to evaluate this parameter. Not considering the impact of milling at a cooler temperature caused for an overestimation in pavement life by 8.33% and 5% for the thin and thick structures, respectively. This means that both structures would likely be under designed. In comparison, it was also determined that not taking milling into account when milling at a warmer temperature did not have an impact to the expected pavement life with either the thin or thick pavement structure. This is an important finding from this study. It highlights a need to further study the potential impact that the pavement temperature while milling has on the indirect tensile strength of the HMA that remains below the mill line.

Table 6-25 Percent Differences between Pre- and Post-Milling Cores: Pavement Temperature

Test Section	Parameter	Percent Difference between Pre- and Post-Milling Cores		
		Specific Gravity	Resilient Modulus	Indirect Tensile Strength
TP1S	Cooler pavement temperature	-1.5%	-12.6%	-30.9%
TP2S - MnROAD Cell 22	Warmer pavement temperature	-0.5%	6.5%	-13.6%
TP2S - MnROAD Cell 23	Warmer pavement temperature	0.4%	-19.8%	-22.6%

Table 6-26 Significance Testing Results: Pavement Temperature

Test Section	Parameter	Statistical Difference between the Properties of Pre- and Post-Milling Cores in terms of P-Values		
		Specific Gravity	Resilient Modulus	Indirect Tensile Strength
TP1S	Cooler pavement temperature	0.120	0.124	***0.00094****
TP2S - MnROAD Cell 22	Warmer pavement temperature	0.300	0.111	0.122
TP2S - MnROAD Cell 23	Warmer pavement temperature	0.772	0.349	0.147

Indicates statistical significance

6.7 Summary

This section of the report presented all results from the laboratory testing performed on the pre- and post-milling cores, to field measurements collected on the pre- and post-milling pavement structures, to lastly data analysis results from the methods carried out to compare the pre- and post-milled pavements. The following section of this report will present the major findings found through conducting this study.

Chapter 7: Summary and Findings

This report documents the study *Understanding and Improving Pavement Milling Operations*. The initial literature review and survey that were conducted were used to assist in determining the most critical milling parameters that should be evaluated. The parameters that were selected to be evaluated in this study were the structure of the existing pavement, the time between milling and post-mill overlay construction, the depth of milling relative to the layer interface, milling operational and equipment parameters such as rotor speed, and lastly the pavement temperature at the time of milling. Once these parameters had been determined, pre- and post-milling cores were collected from the MnROAD research facility while milling was performed under the different parameter variations. The cores were then trimmed to represent the equivalent layer directly below the mill line and were then evaluated in the laboratory for bulk specific gravity, permeability, resilient modulus, and indirect tensile strength. Statistical testing was then performed to determine whether there were statistically significant differences between the laboratory measured properties of the pre- versus post-milling cores to determine if milling or specific milling parameters impacted the physical or mechanical properties of the asphalt layer that remained directly below the mill line. The major findings from the conditions evaluated in this study are summarized below:

- There are not consistent significant differences between pre- and post-milled pavement layers' structural and volumetric properties due to the differences in the pavement structures (which also considers different pavement ages and conditions) evaluated.
- Leaving a milled pavement exposed for two weeks can cause a significant decrease in the specific gravity and indirect tensile strength of the HMA remaining below the mill line. This is likely due to the exposure of the milled layer to traffic and weather conditions.
- Milling was performed to the layer interface, halfway through the lift, and three-quarters of the way through the lift. The depth of milling relative to the layer interface, at these three depths, were found to have no significant impacts to the properties of the HMA that remains below the mill line.
- Milling was performed at rotor speeds of 100, 109, and 118 RPM. The rotor speed, at these three speeds, were found to have no significant impacts to the properties of the HMA that remains below the mill line.
- Based on the limited amount of testing conducted in this study, milling at cooler pavement temperatures can cause a significant decrease in the indirect tensile strength of the HMA that remains below the mill line. There is a likely interaction effect of the pavement temperature while milling and the strength of the remaining layers, therefore causing a resultant effect on the post-milled pavement. Further research efforts that include evaluation of milling under various pavement temperatures are needed to confirm these preliminary outcomes and determine if there is a need to develop guidelines for minimum allowable milling temperatures.

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Appendix A: Copy of Survey

The agency survey questionnaire is presented in this appendix.

This is the state of practice survey on pavement milling. This survey is being administered as part of the National Road Research Alliance (NRRA) innovation project titled: Understanding and Improving Pavement Milling Operations.

Block-1: Contact Information and Affiliation

Question 1: Please provide identification and contact information.

Name (first, last) (1) ____
Affiliation (2) ____
Job title (3) ____
Email address (4) ____
Phone number (5) ____

Question 2: Which category best describes your organization?

- ☐ State Transportation Agency (1)
- ☐ Other Transportation Agency (City, County etc.) (2)
- ☐ Pavement (Construction) Equipment Manufacturer (3)
- ☐ Pavement (Construction) Contractor (4)
- ☐ Other (please specify) (5) ____

Display This Question:
If Which category best describes your organization? = State Transportation Agency
Or Which category best describes your organization? = Other Transportation Agency (City, County etc.)
Or Which category best describes your organization? = Other (please specify)

Question 3: Does your agency have a construction specification on milling of asphalt pavements (including specifications for specialized milling, such as, micromilling)?

- ○ Yes (1)
- ○ No (2)

Display This Question:
If Which category best describes your organization? = State Transportation Agency
Or Which category best describes your organization? = Other Transportation Agency (City, County etc.)
Or Which category best describes your organization? = Other (please specify)

Question 4: Does your agency specify milling equipment and operational parameters (either through standard specifications or provisional standards or through some other mechanisms)?

- ○ Yes (1)
- ○ No (2)

Display This Question:
If Does your agency have a construction specification on milling of asphalt pavements (including spe... = Yes

Question 5: Please share asphalt pavement milling specification(s) for your agency: (you can either upload specification file(s) or email specifications to eshan.dave@unh.edu)

Display This Question:
If Does your agency have a construction specification on milling of asphalt pavements (including spe... = No

Question 6: In absence of standard/provisional specifications or other mechanisms for asphalt pavement milling, what are guidance documents/contractual requirements that are used by your agency for pavement milling contracts? (select all that apply)

- ▢ Project specific provisional specifications (1)
- ▢ Construction contractor identified procedures (2)
- ▢ Consultant identified procedures (3)
- ▢ Equipment manufacturer recommendations (4)
- ▢ Other (please describe) (5) ____
- ▢ None (6)

Display This Question:
If Does your agency specify milling equipment and operational parameters (either through standard sp... = Yes

Question 7: Select equipment parameters that are specified for your entity's milling projects through standard or provisional specifications or through some other means: (select all that apply)

- ▢ Drum size (1)
- ▢ Teeth configuration/pattern and spacing (2)
- ▢ Teeth dimensions (3)
- ▢ Teeth Type (e.g. with or without extractor grooves) (9)
- ▢ Drum speed (RPM) (4)
- ▢ Machine speed (ft. per minute) (5)
- ▢ Cutting mode (up-cutting or down-cutting) (10)
- ▢ Water/spray application rate (6)
- ▢ None (8)
- ▢ Other (please specify) (7) ____

Display This Question:

If Does your agency specify milling equipment and operational parameters (either through standard sp... = Yes

Question 8: Select milling operational parameters that are specified for your entity's asphalt pavement milling projects through standard or provisional specifications or through some other means: (select all that apply)

- ☐ Pavement surface temperature (1)
- ☐ Ambient temperature (2)
- ☐ Time since last precipitation event (3)
- ☐ Precipitation during milling operation (4)
- ☐ Pavement subsurface moisture state (5)
- ☐ Other (please specify) (6) ____

Display This Question:

If Does your agency specify milling equipment and operational parameters (either through standard sp... = Yes

Question 9: Select pavement condition parameters that may impact specification of milling operational/equipment parameters for your entity's asphalt pavement milling projects through standard or provisional specifications or through some other means: (select all that apply)

- ☐ Amount of structural distress (cracking, rutting etc.) (1)
- ☐ Amount of surface distresses (potholes, raveling etc.) (2)
- ☐ Pavement structural condition (3)
- ☐ Base and subbase conditions (4)
- ☐ Pavement foundation stiffness/strength (5)
- ☐ Other (please specify) (6) ____

Block-2: Criteria for Milling

Question 10: For your entity, please indicate prevalence of the purpose for asphalt pavement milling work? (0 = never; 10 = always)

_______ Removal of asphalt layer for application of overlay (1)
_______ Removal of asphalt layer for reconstruction of pavement (2)
_______ Friction/skid resistance improvement (3)
_______ Removal of surface distresses without overlay application (4)
_______ Profile correction (6)
_______ Other (please specify) (5)

Display This Question:

If Which category best describes your organization? = State Transportation Agency

Or Which category best describes your organization? = Other Transportation Agency (City, County etc.)

Question 11: Please rank most common triggers that are used by your agency to reach decision of milling asphalt pavements (select all that apply)

_______ Roughness threshold reached (1)
_______ Pavement rehabilitation (such as, mill and overlay) (2)
_______ Pavement reconstruction (3)
_______ Milling of temporary pavements (commonly due to phased construction/construction traffic bypass) (4)
_______ Skid resistance improvements (6)
_______ Other (please specify) (5)

Question 12: Please select appropriate milling depths (inch) on the basis of project conducted by your entity in last two years (please leave blank if this question does not apply):

	0 1 1 2 2 3 3 4 4 5 5 6
Most common depth (inch) ()	
Minimum depth (inch) ()	
Maximum depth (inch) ()	

Display This Question:

If Which category best describes your organization? = State Transportation Agency

Or Which category best describes your organization? = Other Transportation Agency (City, County etc.)

Or Which category best describes your organization? = Other (please specify)

Question 13: In last two years, please indicate overlay thicknesses (inch) of mill-and-overlay (M&O) projects done by your entity?

	0 1 1 2 2 3 3 4 4 5 5 6
Most common overlay thickness (inch) ()	
Lowest overlay thickness (inch) ()	
Highest overlay thickness (inch) ()	

Question 14: For projects conducted in last two years in your entity, which of the following represent most common overlay thickness to milling depth ratio for mill-and-overlay (M&O) project:

- ☐ less than 1 (milling depth > overlay thickness) (please specify an average value) (1) ____
- ☐ 1 (milling depth = overlay thickness) (2)
- ☐ greater than 1 (milling depth < overlay thickness) (please specify an average value) (3) ____
- ☐ Unknown (4)

Block-3: Milling Specifications

Question 15: Are there specific pavement attributes due to which your entity may consider to not conduct milling on a specific asphalt pavement? (for example, certain roadway functional classes, minimum asphalt layer thicknesses, specific asphalt mixture types etc.)

- ☐ No, milling may be considered on any asphalt pavement. (1)
- ☐ Yes (please elaborate on attributes that result in decision to not mill the pavement) (2)

Question 16: How does your entity define different types of asphalt milling activities? (select all that apply)

- ☐ Pavement rehabilitation, preservation, and reconstruction related distinctions (milling for mill-and-overlay, milling for CIR, preventive maintenance related milling etc.) (1)
- ☐ Depth related distinctions (micro-milling, deep milling etc.) (2)
- ☐ Milling equipment and operational factor related distinctions (cutting speeds, time of year, pavement temperature etc.) (3)
- ☐ Other(s) (please specify) (4) ____

Question 17: How is depth of milling (if multiple passes are conducted, please provide response for each milling pass) determined by your entity? (select all that apply)

- ☐ Based solely on final pavement structure after construction (as specified by pavement design) (1)
- ☐ Based on thicknesses of individual asphalt lifts in the milled pavement (2)
- ☐ Based on total asphalt thickness of milled pavement (3)
- ☐ Proximity of mill line to interface between two asphalt lifts (4)
- ☐ Bond between asphalt lifts of existing pavement (5)
- ☐ Other (please specify) (6) ____

Question 18: How does your entity specify quality of milled surface? (select all that apply)

- ☐ Roughness of milled pavement (1)
- ☐ Maximum vertical deviations in milled surface (2)
- ☐ Amount of loose material in milled surface (3)
- ☐ Other (please specify) (4) ____

Appendix B: Agency Survey Responses

Block-1: Contact Information and Affiliation

Question 2: Which category best describes your organization?

Options	Option count
State Transportation Agency	10
Other Transportation Agency (City, County etc.)	2
Pavement (Construction) Equipment Manufacturer	
Pavement (Construction) Contractor	
Other	

Display This Question:

If Which category best describes your organization? = State Transportation Agency

Or Which category best describes your organization? = Other Transportation Agency (City, County etc.)

Or Which category best describes your organization? = Other (please specify)

Question 3: Does your agency have a construction specification on milling of asphalt pavements (including specifications for specialized milling, such as, micromilling)?

Options	Option count
Yes	12
No	

Display This Question:

If Which category best describes your organization? = State Transportation Agency

Or Which category best describes your organization? = Other Transportation Agency (City, County etc.)

Or Which category best describes your organization? = Other (please specify)

Question 4: Does your agency specify milling equipment and operational parameters (either through standard specifications or provisional standards or through some other mechanisms)?

Options	Option count
Yes	11
No	1

Display This Question:

If Does your agency specify milling equipment and operational parameters (either through standard sp... = Yes

Question 7: Select equipment parameters that are specified for your entity's milling projects through standard or provisional specifications or through some other means: (select all that apply)

Options	Option count
Drum size	3
Teeth configuration/pattern and spacing	3
Teeth dimensions	1
Teeth type (e.g. with or without extractor grooves)	2
Drum speed (RPM)	1
Machine speed (ft. per minute)	2
Cutting mode (up-cutting or down-cutting)	1
Water/spray application rate	1
None	4
Other	5

Other

- Longitudinal profile and transverse slope controls
- All other parameters can be adjusted to provide desired milled surface characteristics
- Elevation and slope control
- 30 minimum skid length or rolling straightedge
- Transfer conveyors
- Capable of removing the pavement surface to the necessary depth
- Use cold planing equipment
- Capable of milling the surface of one traffic lane in no more than two passes
- Milling drum with a minimum of 60 cutting teeth per foot of width with a transverse spacing of approximately 1/4 inch
- Cutting teeth with a cutting head face which is pointed to an angle of not more than 75 degrees
- Milling drum that produces a uniformly cut surface free of ridges or valleys

Display This Question:

If Does your agency specify milling equipment and operational parameters (either through standard sp... = Yes

Question 8: Select milling operational parameters that are specified for your entity's asphalt pavement milling projects through standard or provisional specifications or through some other means: (select all that apply)

Options	Option count
Pavement surface temperature	
Ambient temperature	1
Time since last precipitation event	
Precipitation during milling operation	
Pavement subsurface moisture state	
Other	7

Other

- None of the above
- Contractor to prevent ponding of water on milled surface
- Traffic of more than 5 days, the contractor is responsible for damage
- Not specific
- Not in Section 2531 but CIR specification in 2318 does have weather limitations

Display This Question:

If Does your agency specify milling equipment and operational parameters (either through standard sp... = Yes

Question 9: Select pavement condition parameters that may impact specification of milling operational/equipment parameters for your entity's asphalt pavement milling projects through standard or provisional specifications or through some other means: (select all that apply)

Options	Option count
Amount of structural distress (cracking, rutting etc.)	5
Amount of surface distresses (potholes, raveling etc.)	3
Pavement structural condition	6
Base and subbase conditions	3
Pavement foundation stiffness/strength	1
Other	1 (None of the above)

Block-2: Criteria for Milling

Question 10: For your entity, please indicate prevalence of the purpose for asphalt pavement milling work? (0 = never; 10 = always)

	Ranking										
Options	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Removal of asphalt layer for application of overlay								1	4	4	3
Removal of asphalt layer for reconstruction of pavement	1	1	1	2		1	1	1	2		2
Friction/skid resistance improvement	7	2	3								
Removal of surface distresses without overlay application	8	1	3								
Profile correction	3	1	1	1		1	1	2		1	1

Display This Question:

If Which category best describes your organization? = State Transportation Agency

Or Which category best describes your organization? = Other Transportation Agency (City, County etc.)

Question 11: Please rank most common triggers that are used by your agency to reach decision of milling asphalt pavements (select all that apply)

	Ranking				
Options	**1**	**2**	**3**	**4**	**5**
Roughness threshold reached	1	3	2	4	1
Pavement rehabilitation (such as, mill and overlay)	10	1			
Pavement reconstruction		6	4		1
Milling of temporary pavements (commonly due to phased construction/ construction traffic bypass)			5	6	
Skid resistance improvements		1		1	9

Question 12: Please select appropriate milling depths (inch) on the basis of project conducted by your entity in last two years (please leave blank if this question does not apply):

	Thickness (inch)											
Options	**0.5**	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**	**5.5**	**6**
Most common depth (inch)			1	9	1			1				
Minimum depth (inch)	4	1	3	1								
Maximum depth (inch)							1	6				3

Display This Question:

If Which category best describes your organization? = State Transportation Agency

Or Which category best describes your organization? = Other Transportation Agency (City, County etc.)

Or Which category best describes your organization? = Other (please specify)

Question 13: In last two years, please indicate overlay thicknesses (inch) of mill-and-overlay (M&O) projects done by your entity?

	Thickness (inch)											
Options	**0.5**	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**	**5.5**	**6**
Most common overlay thickness (inch)			2	6	2	2						
Lowest overlay thickness (inch)	1	2	7	1								
Highest overlay thickness (inch)				1	1	2	1	4				1

Question 14: For projects conducted in last two years in your entity, which of the following represent most common overlay thickness to milling depth ratio for mill-and-overlay (M&O) project:

Options	Option count
Less than 1 (milling depth > overlay thickness) (please specify an average value)	
1 (milling depth = overlay thickness)	7
Greater than 1 (milling depth < overlay thickness) (please specify an average value)	5
Unknown	

Other (for greater than 1) 2

- Widely vary
- 1.26 is the average for the past 2 years

Block-3: Milling Specifications

Question 15: Are there specific pavement attributes due to which your entity may consider to not conduct milling on a specific asphalt pavement? (for example, certain roadway functional classes, minimum asphalt layer thicknesses, specific asphalt mixture types etc.)

Options	Option count
No, milling may be considered on any asphalt pavement	6
Yes (please elaborate on attributes that result in decision to not mill the pavement)	6

Other

- Existing thickness
- Condition/age of existing pavement
- Existing pavement is distorted
- Existing pavement is too thin
- In most of those cases, we would do a reclaim & overlay project
- Some pavements require additional structure; therefore, we proceeded with an overlay with no milling
- If there is room width wise for the overlay, there may be no milling to retain the structural strength

- Thin asphalt layer over PCC, areas with PCC patching
- Additional structure is needed

Question 16: How does your entity define different types of asphalt milling activities? (select all that apply)

Options	Option count
Pavement rehabilitation, preservation, and reconstruction related distinctions (milling for mill-and-overlay, milling for CIR, preventive maintenance related milling etc.)	11
Depth related distinctions (micro-milling, deep milling etc.)	3
Milling equipment and operational factor related distinctions (cutting speeds, time of year, pavement temperature etc.)	1
Other(s) (please specify)	1 (None of the above)

Question 17: How is depth of milling (if multiple passes are conducted, please provide response for each milling pass) determined by your entity? (select all that apply)

Options	Option count
Based solely on final pavement structure after construction (as specified by pavement design)	4
Based on thickness of individual asphalt lifts in the milled pavement	5
Based on total asphalt thickness of milled pavement	6
Proximity of mill line to interface between two asphalt lifts	6
Bond between asphalt lifts of existing pavement	2
Other (please specify)	3

Other

- Stripping is an issue for us. We perform coring operations to determine if stripping is an issue and where that stripping may be taking place. Sometimes those results guide our decisions on how deep to mill.
- Typically, cores are cut to determine the necessary milling depth to remove deficient material. Additionally, mill depth would always go slightly beyond the bond interface.
- No specific rules

Question 18: How does your entity specify quality of milled surface? (select all that apply)

Options	Option count
Roughness of milled pavement	4
Maximum vertical deviations in milled surface	8
Amount of loose material in milled surface	3
Other (please specify)	2

Other

- Remove the existing asphaltic pavement or surfacing without incorporating or damaging underlying material that will remain in place
- Provide a uniform milled surface that is reasonably plane, free of large scarification marks, and has the grade and transverse slope the plans show or the engineer directs
- Smoothness specification

Appendix C: Non-Agency Survey Responses

Block-1: Contact Information and Affiliation

Question 2: Which category best describes your organization?

Options	Option count
State Transportation Agency	
Other Transportation Agency (City, County etc.)	
Pavement (Construction) Equipment Manufacturer	4
Pavement (Construction) Contractor	1
Other	1 (Engineering consultant)

Display This Question:

If Does your agency specify milling equipment and operational parameters (either through standard sp... = Yes

Question 7: Select equipment parameters that are specified for your entity's milling projects through standard or provisional specifications or through some other means: (select all that apply)

Options	Option count
Drum size	1
Teeth configuration/pattern and spacing	1
Teeth dimensions	
Teeth type (e.g. with or without extractor grooves)	
Drum speed (RPM)	
Machine speed (ft. per minute)	
Cutting mode (up-cutting or down-cutting)	
Water/spray application rate	
None	
Other	1 (Pavement removal accuracy)

Display This Question:

If Does your agency specify milling equipment and operational parameters (either through standard sp... = Yes

Question 9: Select pavement condition parameters that may impact specification of milling operational/equipment parameters for your entity's asphalt pavement milling projects through standard or provisional specifications or through some other means: (select all that apply)

Options	Option count
Amount of structural distress (cracking, rutting etc.)	1
Amount of surface distresses (potholes, raveling etc.)	1
Pavement structural condition	1
Base and subbase conditions	1
Pavement foundation stiffness/strength	1
Other	

Block-2: Criteria for Milling

Question 10: For your entity, please indicate prevalence of the purpose for asphalt pavement milling work? (0 = never; 10 = always)

	Ranking										
Options	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Removal of asphalt layer for application of overlay							1		3	1	1
Removal of asphalt layer for reconstruction of pavement		1	1				2	1			1
Friction/skid resistance improvement	1	3			1		1				
Removal of surface distresses without overlay application	1	2	2					1			
Profile correction		2	1	1	1			1			

Other

- Curb Reveal (Ranked 2)
- Bridge decks (Ranked 1)

Question 12: Please select appropriate milling depths (inch) on the basis of project conducted by your entity in last two years (please leave blank if this question does not apply):

	Thickness (inch)											
Options	**0.5**	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**	**5.5**	**6**
Most common depth (inch)				5			1					
Minimum depth (inch)	3	2	1									
Maximum depth (inch)						1		1				4

Display This Question:

If Which category best describes your organization? = State Transportation Agency

Or Which category best describes your organization? = Other Transportation Agency (City, County etc.)

Or Which category best describes your organization? = Other (please specify)

Question 13: In last two years, please indicate overlay thicknesses (inch) of mill-and-overlay (M&O) projects done by your entity?

	Thickness (inch)						
Options	**0.5**	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**
Most common overlay thickness (inch)				1			
Lowest overlay thickness (inch)		1				1	
Highest overlay thickness (inch)							

Question 14: For projects conducted in last two years in your entity, which of the following represent most common overlay thickness to milling depth ratio for mill-and-overlay (M&O) project:

Options	Option count
Less than 1 (milling depth > overlay thickness) (please specify an average value)	
1 (milling depth = overlay thickness)	5
Greater than 1 (milling depth < overlay thickness) (please specify an average value)	1 (1.5-2.5 inch)
Unknown	

Block-3: Milling Specifications

Question 15: Are there specific pavement attributes due to which your entity may consider to not conduct milling on a specific asphalt pavement? (for example, certain roadway functional classes, minimum asphalt layer thicknesses, specific asphalt mixture types etc.)

Options	Option count
No, milling may be considered on any asphalt pavement	3
Yes (please elaborate on attributes that result in decision to not mill the pavement)	3

Attributes

- Alternative recycling techniques (CIR, FDR, SFDR, etc.)
- Structural improvements of sound pavements (no structural distress)
- If milling is expected to mitigate reflective cracking after milling and overlaying, where the specified milling depth is not great enough to remove cracks in the existing layer

Question 16: How does your entity define different types of asphalt milling activities? (select all that apply)

Options	Option count
Pavement rehabilitation, preservation, and reconstruction related distinctions (milling for mill-and-overlay, milling for CIR, preventive maintenance related milling etc.)	5
Depth related distinctions (micro-milling, deep milling etc.)	6
Milling equipment and operational factor related distinctions (cutting speeds, time of year, pavement temperature etc.)	2
Other(s) (please specify)	

Question 17: How is depth of milling (if multiple passes are conducted, please provide response for each milling pass) determined by your entity? (select all that apply)

Options	Option count
Based solely on final pavement structure after construction (as specified by pavement design)	3
Based on thickness of individual asphalt lifts in the milled pavement	3
Based on total asphalt thickness of milled pavement	4
Proximity of mill line to interface between two asphalt lifts	4
Bond between asphalt lifts of existing pavement	2
Other (please specify)	4

Other

- Depth selected by owner
- All factors are considered during evaluation stage prior to final pavement design recommendations
- Based on smoothness requirement of the finished surface (to be paved back) after milling
- Based on capabilities of available equipment

Question 18: How does your entity specify quality of milled surface? (select all that apply)

Options	Option count
Roughness of milled pavement	6
Maximum vertical deviations in milled surface	3
Amount of loose material in milled surface	1
Other (please specify)	1

Other: Pattern design, whether it needs to be straight line or v form. this may fall under roughness, but I wanted to state that pattern smoothness can also dictate interlocking capability of the new asphalt to the milled surface.

Appendix D:
Agency Equipment Specification

Equipment specifications of Illinois DOT with respect to milling specification of asphalt pavement

- Self-propelled cold milling machine capable of cutting existing HMA surface and depositing the cuttings into a windrow or directly into a truck
- Equipment should be capable of cutting a minimum of 6 ft in width and 1 ½ in in depth within one pass
- The use of a milling machine having a width less than 6 ft is permitted except that the area milled shall not be wider than the width of the work specified on the plan
- The milling machine shall be capable of accurately and automatically establishing profile grades to provide a milled surface within a tolerance of 3/16 in in 16 ft when tested with a 16 ft straightedge by reference from
    - either the existing pavement
    - or from an independent grade control
- An effective means shall be equipped for removing any dust from escaping into the air

Equipment specifications of Texas DOT with respect to milling specification of asphalt pavement

- Planing machine should have a minimum cutting head of 6 ft for areas less than 6 ft wide
- Milling machine must be self-propelled to maintain an accurate depth of cut and slope with enough power, traction, and stability
- Equipment must be able to cut up to 4 in of asphalt concrete pavement
- Machine should be capable of operating automatically
    - on both sides from any longitudinal grade reference using dual longitudinal controls, which includes string line, ski, mobile string line, or matching shoe
    - to control cross slope at a given rate using transverse controls
- Device must use integral loading to allow cutting, removal, and discharge of the material into a truck in one operation and include devices to control dust created by the cutting action

Equipment specifications of Caltrans with respect to milling specification of asphalt pavement

- Cold planing machine must be equipped with a cutter head having a head width that matches the planing width
- The milling machine must be equipped with automatic controls for longitudinal grade and transverse slope of the cutter head and:
    - If a ski device is used, it must be at least 30 ft long, rigid, and 1 piece unit. The entire length must be used in activating the sensor
    - If referencing from existing pavement, the cold planing machine must be controlled by a self-contained grade reference system. The system must be used at or near the centerline of the roadway. On the adjacent pass with the cold planing machine, a joint-matching shoe may be used.

- Dust must be effectively controlled by the planing equipment
- Milling machine must be operated such that no smoke or fumes is produced

Equipment specifications of Iowa DOT with respect to milling specification of asphalt pavement

- Cold planing equipment must be capable of removing the necessary depth out of the pavement surface
- Planing machine must be capable of milling the surface of one traffic within a maximum of two passes
- Milling drum must have a minimum of 60 cutting teeth per foot of width with a transverse spacing of approximately ¼ inch
- Cutting teeth must be pointed to an angle of not more than 75 degrees with a cutting head face
- Milling drum must yields a uniformly cut surface free of ridges or valleys
- Milling equipment must be able to be automatically controlled on one or both sides and also has cross slope control

Equipment specifications of Michigan DOT with respect to milling specification of asphalt pavement

- Cold milling equipment must consistently remove the HMA surface, in one or more passes, to the required grade and cross section, and produces a uniformly textured surface.
- Machines should be equipped with the following:
    - Automatically controlled and activated cutting drums
- Grade reference and transverse slope control capabilities

Equipment specifications of Minnesota DOT with respect to milling specification of asphalt pavement

- Milling machine must be power operated, self-propelled capable of removing asphalt concrete materials, as indicated on the plans, to the profile, cross-slope, grade, and elevation uniformly across the pavement surface
- Equipment must have automatic controls to control grade, elevation, cross-slope, and profile
- Machine needs ski, matching shoe, or an independent grade control to reference the existing pavement and automatically establish profile grades along each edge of the machine with ±¼ inch

Equipment specifications of North Dakota DOT with respect to milling specification of asphalt pavement

- Use a self-propelled milling machine that automatically adjusts the elevation and transverse slope of the milling head using a control system.
- Milling machine shall provide a 30 ft minimum length skid, rolling traveling straightedge, or other approved device to establish the grade reference for control of the milling head

- Equipment must use a system that permits the grade reference device to operate on either side of the milling machine and maintains the desired transverse slope regardless of changes in the elevation of the milling head
- Milling machine must be capable of providing necessary equipment to transfer the milled material from the roadway to a truck by means of conveyors capable of side, rear, or front loading

Equipment specifications of Missouri DOT with respect to milling specification of asphalt pavement

- The equipment for milling and removing the pavement surface shall be capable of removing a thickness of bituminous or concrete material to the specified depth and providing a uniform profile and cross slope
- The equipment shall be capable of accurately and automatically establishing profile grades within 1/8 in. of each edge of the machine
- The milling equipment shall be regulated by an automatically controlled grade leveling and slope control device. The device shall provide control for producing a uniform surface to the established grade and a cross slope in accordance with the typical section
- The device shall also be equipped with the necessary controls to permit the operator to adjust or vary the slope as directed by the engineer
- The equipment shall have dust control systems and other particulate matter created by the cutting action by means of provisions
- As the pavement is milled, the equipment shall also have an effective means of removing cuttings from the pavement and discharging them into a hauling unit, all in one operation

Equipment specifications of Wisconsin DOT with respect to milling specification of asphalt pavement

- Use of a self-propelled milling machine with depth, grade, and slope controls
- The drum must be shrouded to prevent discharging loosened material into adjacent work areas or live traffic lanes
- Machine must provide an engineer-approved dust control system

Equipment specifications of Mississippi DOT with respect to milling specification of asphalt pavement

- The equipment to be used for this work shall be a self-propelled milling machine capable of removing a minimum width of four feet
- The equipment shall have sufficient power, traction, and stability to remove material and maintain an accurate grade and slope
- The equipment shall accurately and automatically establishing profile grade along each edge of the machine by referencing from the existing pavement with means of an approved profile averaging device with extreme contact points with surface at least 30 ft apart, or from an independent grade line and shall have an automatic system for controlling cross slope.
- The machine shall be equipped with an automatic system for controlling cross slope. The machine shall be equipped with an integral loading and reclaiming means to immediately remove material being cut from the surface and discharge the cuttings into a truck or windrow, all in one operation

- Adequate back up equipment, such as mechanical sweepers, loaders, water truck, etc., and personnel shall be provided to ensure that all cuttings are removed immediately behind the milling machine

Appendix E: Agency Construction Specification

Construction specifications of Illinois DOT with respect to milling of asphalt pavement.

- When portions are to remain of existing pavement and trimmings are to remain in place, suitable transitions shall be made between replacements and the portions remaining in place by means of provisions
- At the ends of all edges of portions to be removed, a full depth, perpendicular, straight joint shall be sawn
- The engineer shall repair or remove and replace any damage done to the existing pavement or appurtenance to be remained in place
- The plans shall show the thickness of the existing pavement to be removed (depth of milling), including overlays and other appurtenances
- The milled surface shall not be torn, gouged, shoved or otherwise damaged by the milling operation including the temperature at which the work is performed, the nature and condition of the equipment, and the manner of performing the work
- All irregularities or high spots are eliminated by sufficient cutting passes and must satisfy the Engineer. The milled surface shall have no surface variations in excess of 5 mm (3/16 in.) when tested with a 5m (16 ft) straightedge
- Milling to the required depth adjacent to structures in the pavement surface such as drain castings and utility covers, shall be accomplished either machine or hand methods in a manner that satisfies the Engineer
- Milled pavement shall be resurfaced within ten calendar days.

Construction specifications of Texas DOT with respect to milling of asphalt pavement.

- Grade reference:
    - Place grade reference points at maximum intervals of 50 ft. use the control points to set the grade reference.
    - Support the grade reference so that the maximum deflection does not exceed 1/16 in between supports
- Planing and Texturing:
    - Vary the speed of the machine to leave a grid or other pattern type with discontinuous longitudinal reach.
    - Remove the pavement surface for the length, depth, width, and establish line and grade shown on plans
    - Remove pavement to vertical lines adjacent to curbs, gutters, inlets, manholes, or other obstructions. Do not damage appurtenances or underlying pavement. Provide a planed surface that has a uniform textured appearance and riding surface, free of gouges, continuous longitudinal grooves, ridges, oil film, and other imperfections of workmanship.
    - In case of asphalt concrete overlay over concrete pavement, leave a uniform surface of concrete pavement free of asphalt materials
    - Provide a minimum texture depth of not less than 0.05 in when an overlay on the planed pavement is not required. Stop planning operations when surface texture depth is not sufficient.
    - Provide a smooth riding quality pavement surface after planing to the established line, grade, and cross-section. Provide a pavement surface that does not vary more than 1/8 in. in 10 ft. when evaluated with a 10-ft. straightedge placed parallel to the centerline of the roadway.

Deviations will be measured from the top of the texture. Correct any point in the surface not meeting this requirement.
    - Leave pavement and curb clean by sweeping pavement and gutter

Construction specifications of Caltrans with respect to milling of asphalt pavement.

- Do not use a heating device to soften the pavement
- Replace broken, missing, or worn machine teeth
- If you do not complete placing the HMA surfacing before opening the area to traffic, you must:
    - Construct a temporary HMA taper to the level of the existing pavement
    - Place HMA during the next work shift
    - Submit a corrective action plan that shows you will complete cold planing and placement of HMA in the same work shift. Restart cold planing activities when corrective action plan is authorized
- Grade control and surface smoothness:
    - Install and maintain grade and transverse slope references. You may adjust the planed depth up to ± 0.03 foot from the depth shown to achieve uniform pavement profile, cross slope, and surface smoothness. The average cold planed depth must be equal to or greater than the depth shown
    - The final cut must result in a neat and uniform surface
    - Using a 12-foot straightedge parallel with the centerline, the milled surface must not vary more than 0.02 foot. The transverse slope of the planed surface must not vary more than 0.03 foot with the straightedge at right angles to the centerline
- The engineer must be notified if you encounter delaminations (scabbing) during planing operations. Adjust the planed depth up to ± 0.05 foot to remove delaminations, once authorized. A change order work needs to be authorized beyond the ± 0.05 foot range or other authorized mitigation work
- The drop-off between adjacent lanes must not be more than 0.15 foot when lanes are open to traffic
- Planed material:
    - Remove cold planed material concurrently from behind the planer such that the removal does not lag more than 50 ft
- Temporary HMA tapers:
    - Construct a temporary HMA taper before opening to traffic, if a drop-off between the existing pavement and the planed area at transverse joints cannot be avoided

Construction specifications of Iowa DOT with respect to milling of asphalt pavement.

- Pavement surface repair:
    - Mill substantially the entire surface of the pavement in a longitudinal direction, until:
        - The pavement surface on both sides of the transverse joints and all cracks are in the same plane and have the same surface texture
        - The pavement meets the smoothness requirement
    - In every 100 ft in each lane, 95% or more of the area must have a newly textured surface. Except at or near joints and cracks, limit milling to no more than ½ inch in depth. At joints and cracks, limit milling to no more than ¾ inch in depth

- Meet the following requirements for milling:
    - Progress in the lane being milled should be in the direction against normal traffic milled unless specified otherwise by the Engineer
    - Ensure all construction traffic entering or leaving the work area moves in the direction of traffic of the open lane
    - Begin and end at lines normal to the pavement center line within any one milled area and at the project limits except for end of each shift
    - Control the depth of adjacent cuts to produce a smooth, uniform cross section, free from irregularities between adjacent passes of the milling equipment
    - When the machine has stopped, make sure there are no transverse troughs due to lowering the drum below the cutting plane
    - Limit milling in each traffic lane to no more than two passes, but additional passes in the cutting path may be necessary to secure a smooth profile
    - Ensure each single pass does not extend beyond the center line to both sides or a lane line between traffic lanes. However, ensure the first pass at the center line or lane line overlaps the joint line approximately 2 inches to minimize spalling
    - Ensure the joint match, if any, between two passes in a traffic lane is within 1 foot of the center of the lane, to avoid joints directly in the wheel path, and is straight or parallel to the center line or lane line
    - Ensure each pass is designed to maintain the existing crown and a taper from center line to pavement edge
    - Ensure the transverse slope of the milled pavement is uniform to a degree that there is no depression or misalignment greater than ¼ inch in 12 feet when tested by stringline or straightedge placed perpendicular to the center line. Ensure the joint match between two adjacent passes matches within 1/8 inch
    - To match the outside edge of the pavement, mill adjacent paved areas (for example, shoulders, curb and gutter, turn lanes, tapers, paved crossovers, and so forth) to minimize vertical projections
    - Ensure the finished surface has a uniform, coarse texture, and approved by the Engineer
    - Prevent the formation of visible corrugations on the milled surface by controlling the forward speed of the milling machine
- Smoothness:
  - Provide a control profilograph trace prior to performing any grinding work. This control trace will be used to identify the required smoothness for the project. Each segment of the finished ground surface is to:
    - Have a final profile index of 35% of the control profilograph trace or 10 inch per mile, whichever is greater
    - Not include any bumps exceeding 0.5 inches in 25 ft
  - When the engineer approves, the following areas will be excluded from profilograph testing:
    - Depressed pavement areas due to subsidence or other localized cause, and
    - Areas where the maximum
  - End profilograph testing 15 ft (5m) prior to excluded areas (depressed pavement areas or areas where the maximum cut at mid panel or fault restricts further milling) and resume 15 ft following excluded areas

- Pavement markings:
    - After the lane is opened to traffic, pavement marking of edge lines on interstate pavement may be delayed up to 24 hours, except for Sundays and holidays unless the engineer approves it

Construction specifications of Michigan DOT with respect to milling of asphalt pavement.

- Obtain approved mix design and ensure the HMA mix quantities are enough to cover milled surfaces, before milling existing pavement
- Following the plans, remove the HMA surface to the depth, width, grade, and cross section. In case of depressions caused by the removal of material below the required grade, backfill and compact depressions.
- The department will pay for all associated costs, as extra work, for all buried structures within the specified grade, such as valve boxes, manholes, or railroad tracks that are not identified on the plans while milling.
- Clean and dispose removed material immediately after milling.

Construction specifications of Minnesota DOT with respect to milling of asphalt pavement.

- Mill the pavement surface to the depth, width, grade, and cross slope as shown on the plans without damaging the underlying material. Ensure surface irregularities is under ½ inch using a 10-foot straightedge laid transversely and longitudinally after milling is complete. The Engineer directs the areas considered as reference for the milling operation from an independent grade control and establish and maintain grade control.
- When the pavement is open to traffic, mill the entire pavement width to a flush surface at the end of each work period. If the operation is uncompleted, reslope the longitudinal face to provide a taper before opening to traffic. Construct temporary bituminous tapers at intersecting streets, around utility appurtenances, and appropriated entrances during the milling operations, as directed by the Engineer.
- Mill by hand or using other equipment or methods as approved by the Engineer areas inaccessible to the milling machine.
- The milled material may be recycled and reused on the project or disposed of properly.
- Sweep or vacuum clean the milled area with equipment approved by the Engineer after milling to the required depth shown on the plans.
- Mill previously patched areas to the specified depth below the pavement surface that existed before placement of the previous patch, and not from the surface of the patch.
- Avoid disturbing or damaging existing drainage or utility structures on the project. Repair damage resulting from the milling operations at no additional cost to the Department.
- The milled pavement surface must be kept free of all loose materials and dust.

Construction specifications of North Dakota DOT with respect to milling of asphalt pavement

- Remove deleterious material from the pavement before milling.
- Mill the surface parallel to the centerline, beginning at the centerline and progressing outward to the edge of pavement. Do not leave a longitudinal drop off in place for greater than one day, if using

the adjacent lane for traffic. When the milling machine is stopped, provide a smooth transition to the original pavement surface.

- Mill the surface to prevent water from ponding on surface.
- Milled surface must be free of irregularities and not exceeding ¼ inches when measured with a 10 ft straightedge.
- Remove loose material from the milled surface prior opening lane to traffic.
- Coordinate milling and paving operations so that no section of milled roadway has public or construction traffic operating on it for more than 5 days, otherwise the roadway is repaired as directed by the engineer at no additional cost to the department.

Construction specifications of Missouri DOT with respect to milling of asphalt pavement.

- Resurfacing of all pavement that is cold milled for the purpose of mill and overlay shall be done during the same day or night work shift as the cold milling operation
- The milling operations, except in depth transition areas, shall be regulated by an automatically controlled grade leveling and slope control device.
- The roadway pavement surface shall be removed and planed around and over manholes, utility valves and drainage appurtenances, while placing a temporary wedge around it, without any damages or else shall be repaired by the contractor at the contractor's expense.
- The final milled surface of each layer shall be substantially uniform, free from waves or irregularities where it shall not vary more than 1/4 inch from a 10-foot straightedge, applied parallel to the centerline. The texture of the final milled surface shall be a grid surface with discontinuous longitudinal striations.
- Existing shoulder material shall be removed as necessary to ensure no ponding of water on the driving surface occurs after the milling operation.
- Loose material let behind the milling machine must be picked up or swept to the shoulders as approved by the engineer.
- The contractor shall provide pavement marking as shown on the plans through the limits of the milled surfaces.

Construction specifications of Wisconsin DOT with respect to milling of asphalt pavement.

- Removing or surfacing asphalt pavement must be done to the depth the plans show. Recycled material may be disposed or reused in the project.
- Remove the existing asphaltic pavement or surfacing without incorporating or damaging underlying material that will remain in place.
- Provide a uniform milled surface that is reasonably plane, free of large scarification marks, and has the grade and transverse slope the plans show, or the engineer directs.
- Maintain one lane of traffic open during working hours, unless continuous removal and pick-up operation is used without windrowing or storing material on the roadway.
- Roadway should be cleared of materials and equipment during non-working hours.
- Grade shoulders adjacent to milled areas by the end of each workday to provide positive drainage of the pavement. Do not allow abrupt longitudinal differences of 2 inches or more between lanes during non-working hours unless the highway is closed to traffic.

Construction specifications of Mississippi DOT with respect to milling of asphalt pavement.

- The contractor shall have an approved job mix formula and is prepared to begin paving operations, prior to beginning milling operations.
- The pavement and shoulder material shall be removed to the depth, width, and grade and cross section shown on the plans, or as directed by the engineer. The number of passes necessary to accomplish the required work shall be determined by the contractor.
- After milling, the milled surface of the pavement and shoulders shall be reasonably smooth and true to the established line, grade, and cross section. Areas damaged by the contractor's operations shall be corrected and/or repaired as directed by the engineer at no additional costs to the state. The contractor shall take necessary action to prevent or minimize the ponding of water on the milled roadway and shoulder.
- No more than 2 ¼ inch differential in grade between the milled area and the adjacent surface will be allowed where traffic is required to be maintained adjacent to the milled area, unless the two areas are separated.
- A longitudinal pavement edge that traffic is expected to move across should have an elevation difference of not more than 2 ¼ inch. Uneven pavement signs, as shown in the plans or contact documents, will be required if the pavement edge is more than 1 ½ inch and less than or equal to 2 ¼ inches. Transverse pavement joints shall be sufficiently tapered to allow for the safe movement of traffic.
- When traffic is required to be maintained adjacent to milled shoulders, traffic control devices shall be placed
- It is understood that the milled shoulder shall be covered with the next required course as soon as possible but in no case later than 30 calendar days after milling.

Appendix F: MnPAVE Inputs

This appendix details the inputs used in the MnPAVE software along with the correction process used to adjust the modulus values for seasonal temperature differences in the pavement life analysis. The constant inputs used in the MnPAVE software for this analysis are shown in Table F-1 and Table F-2 below.

Table F-1 MnPAVE Traffic Inputs

Traffic Inputs	
Thin Structure	1 million ESALs over its 20-year design life
Thick Structure	3.5 million ESALs over its 20-year design life

Table F- 2 MnPAVE Modulus of Structure Inputs

Layer ↓	Constant Structural Inputs of Pavement Layers: Modulus (ksi)				
Season →	Fall	Winter	Early Spring	Late Spring	Summer
HMA PG58-34	503.7	1349	743.4	334.3	134.1
Old HMA					
Aggregate Base	27	50	9.72	22.68	27.54
Engineered Soil	9.566	50	50	6.697	8.132
Undisturbed Soil	5.551	50	50	3.886	4.719

The average laboratory measured HMA modulus value was used as the old HMA modulus value but was adjusted for the seasonal temperature impacts. The average seasonal air temperatures were outputted in the MnPAVE software for the selected climatic zone of Wright County, Minnesota, as shown in Table F-3 below. Wright County, Minnesota was selected as the MnROAD facility is in this county.

Table F-3 Average Seasonal Air Temperatures in Wright County, Minnesota

Season →	Fall	Winter	Early Spring	Late Spring	Summer
Average seasonal air temperature (^{o}F)	41	19	33	50	70

The average seasonal air temperatures were used in the following equation (which is stated in the MnPAVE software) to determine the average seasonal pavement temperatures for the region.

$$T_P = T_A\left(1+\frac{1}{z+4}\right)-\frac{34}{z+4}+6 \qquad \text{(eq. A.1)}$$

Where,

T_P = Average seasonal pavement temperature (^{o}F)
T_A = Average seasonal air temperature (^{o}F)
z = Depth to 1/3 of Old HMA layer
$z = 2.67in$ for the thin pavement structure, $z = 5.33in$ for the thick pavement structure

The average seasonal pavement temperatures for each season were then converted from ^{o}F to ^{o}C. The average seasonal pavement temperatures in ^{o}C were then used to calculate the temperature correction coefficients by the following equation (FHWA-RD-98-085):

$$Temp.\,Correction\ Coeff. = 10^{slope(average\ seasonal\ pavement\ temp. - measured\ temp.)} \quad \text{(eq. A.2)}$$

In the above equation, the slope was assumed to be -0.021, while the measured temperature used was 25^{o}C, as this was the temperature that the laboratory measured modulus values were measured at. The laboratory measured modulus values were then multiplied by the temperature correction coefficient found above for each season, and the resulting, adjusted modulus value of the pavement in each season was inputted into the MnPAVE software as each of the seasonal old HMA modulus values.