Understanding and Improving Pavement Milling Operations

Task -2: State of the Practice Survey and Review

Prepared by:

Rajib Mallick
Department of Civil and Environmental Engineering
Worcester Polytechnic Institute

Stephanos H. Khalil
Eshan V. Dave
Jo E. Sias
Department of Civil and Environmental Engineering
University of New Hampshire

September 2021

Published by:

Minnesota Department of Transportation
Office of Research & Innovation
395 John Ireland Boulevard, MS 330
St. Paul, Minnesota 55155-1899

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

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 report is to present a state-of-the-art review of milling in asphalt pavements. This report presents the necessity of milling, procedures and equipment, different types of milling, and currently available research on milling in the following sections.

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 1.1).

Figure 1.1 Dozer with ripper-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 no extra step needed 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 is 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. Micromilling, 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 1.2. Micromilling 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 micromilling. The latter generates finer materials close to the required project gradation which diminish the need for crushing before reclaiming the RAP into HMA.

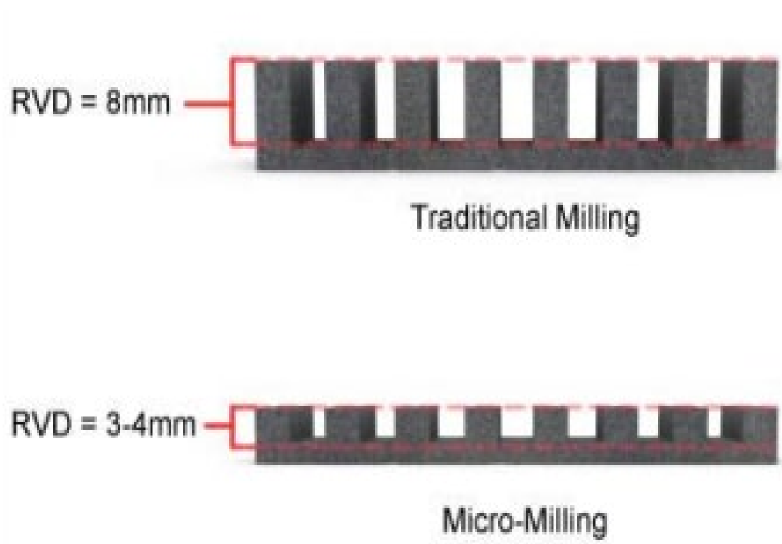


Figure 1.2 Comparison of ridge to valley depth (ARRA, n.d.).

Micromilling 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 micromilling 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 micromilling 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

This document contains five chapters. This chapter introduced background information related to pavement milling, its necessity and advantages. The upcoming chapters will present literature review related to milling and will focus on asphalt pavements and overlays. Chapter 2 covers the milling procedure and equipment. Chapter 3 includes the development and productivity of milling machines. Chapter 4 gathers information from published technical papers and reports with some limitations on milling. Chapter 5 sums up the literature review and provides key findings. Appendix to this report includes a survey that has been administered to gather information on milling practices of NRRA member agencies as well as associate members.

CHAPTER 2: 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 2.1. 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 2.1 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 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 2.5 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 comes 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 2.6. 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 2.7. 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. Baker (2014) defined the tooth wear mechanism into four stages as illustrated in Figure 2.2, 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.

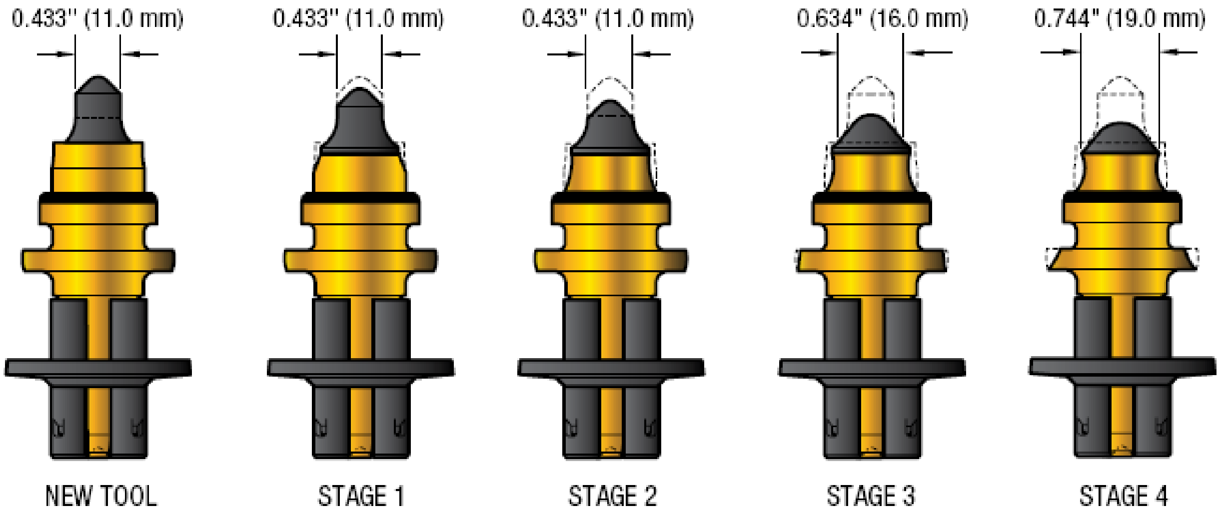


Figure 2.2 Tooth wear stages (Baker, 2014)

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 2.3. Another aspect that is influenced by the worn tools is the production of the machine in a certain project. Figure 2.4 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 (Baker, 2014).

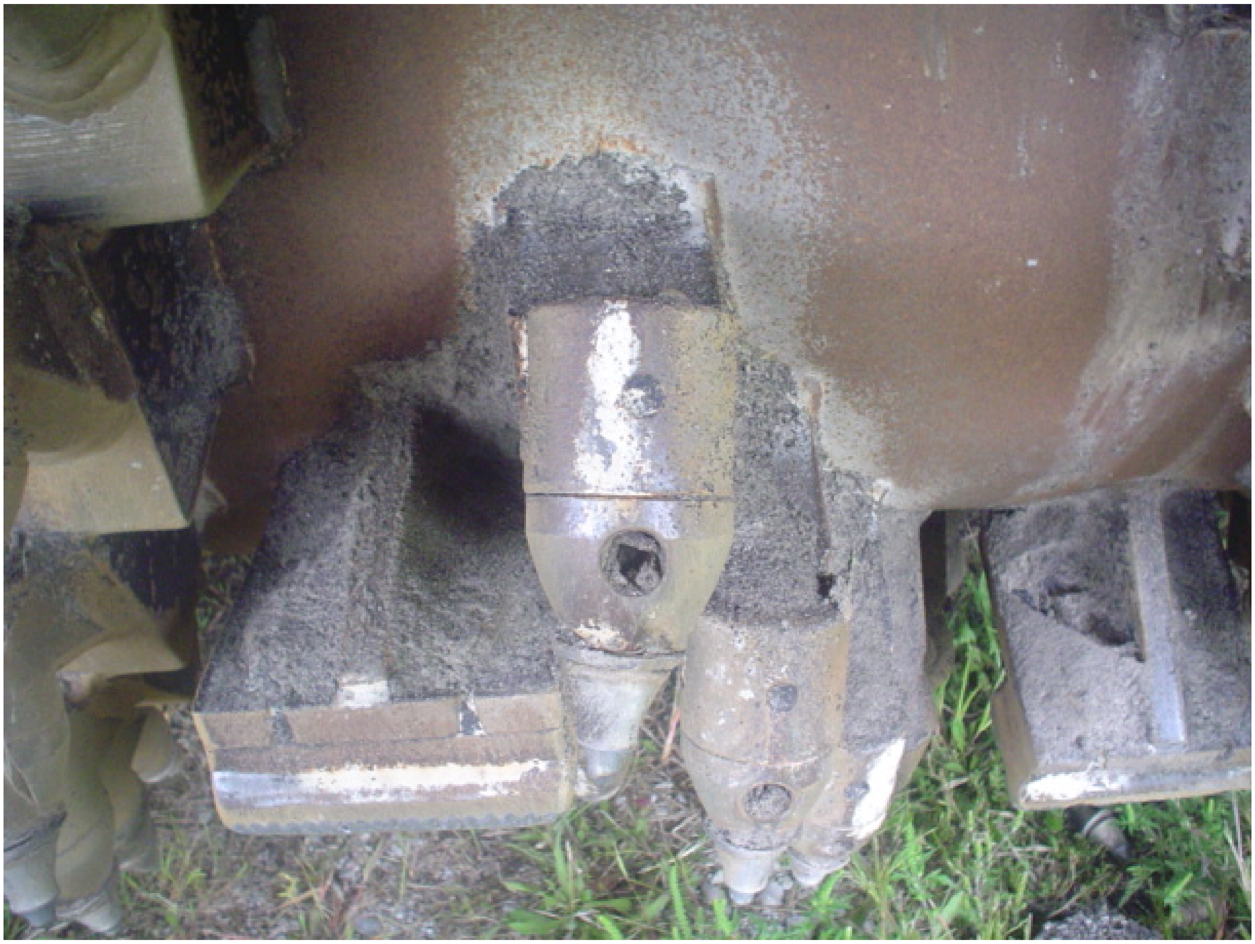


Figure 2.3 Misaligned tool on tooth holder (Baker, 2014)

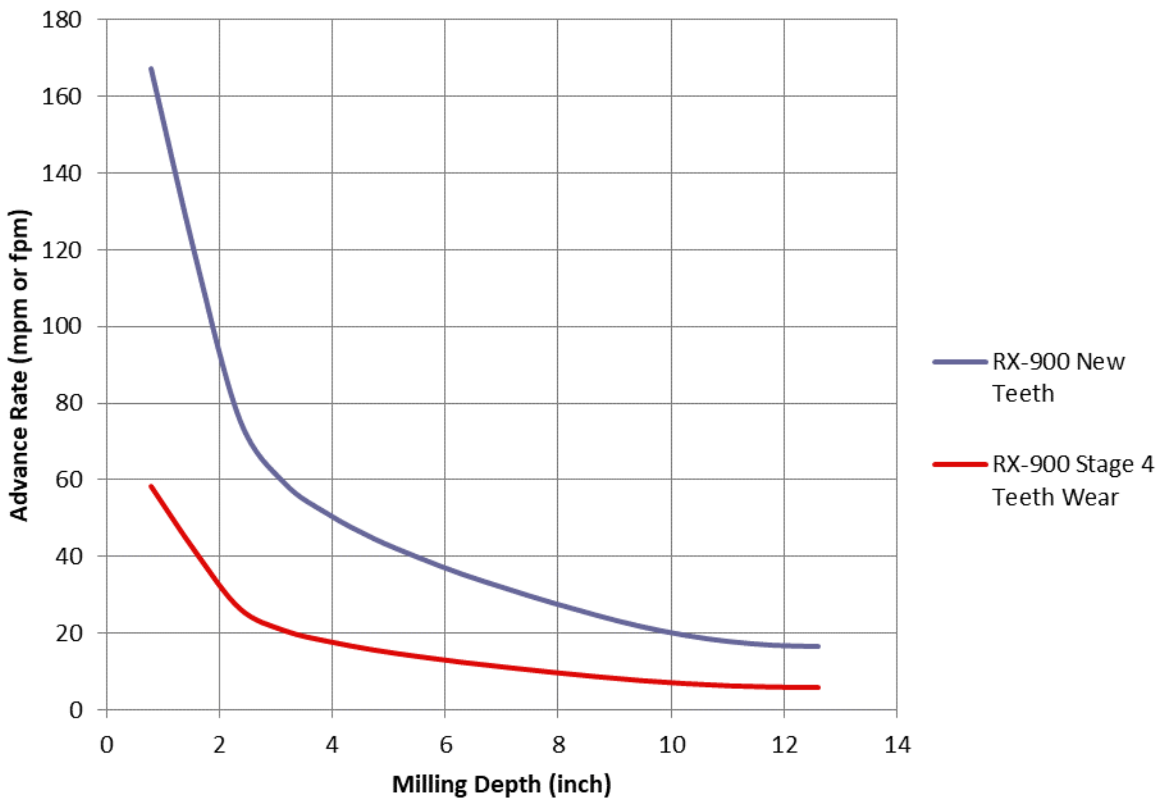


Figure 2.4 Milling machine teeth production tradeoff (Baker, 2014).

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 on 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.

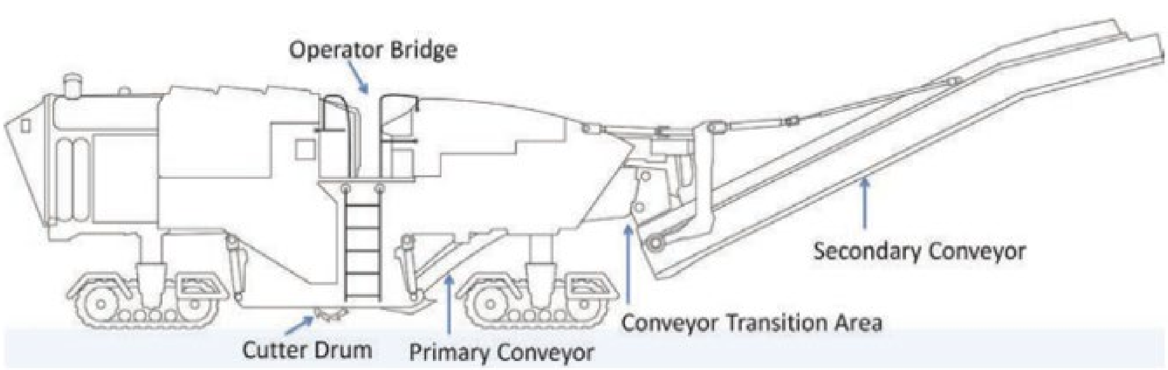


Figure 2.5 Schematic of a typical milling machine (NIOSH, 2015).

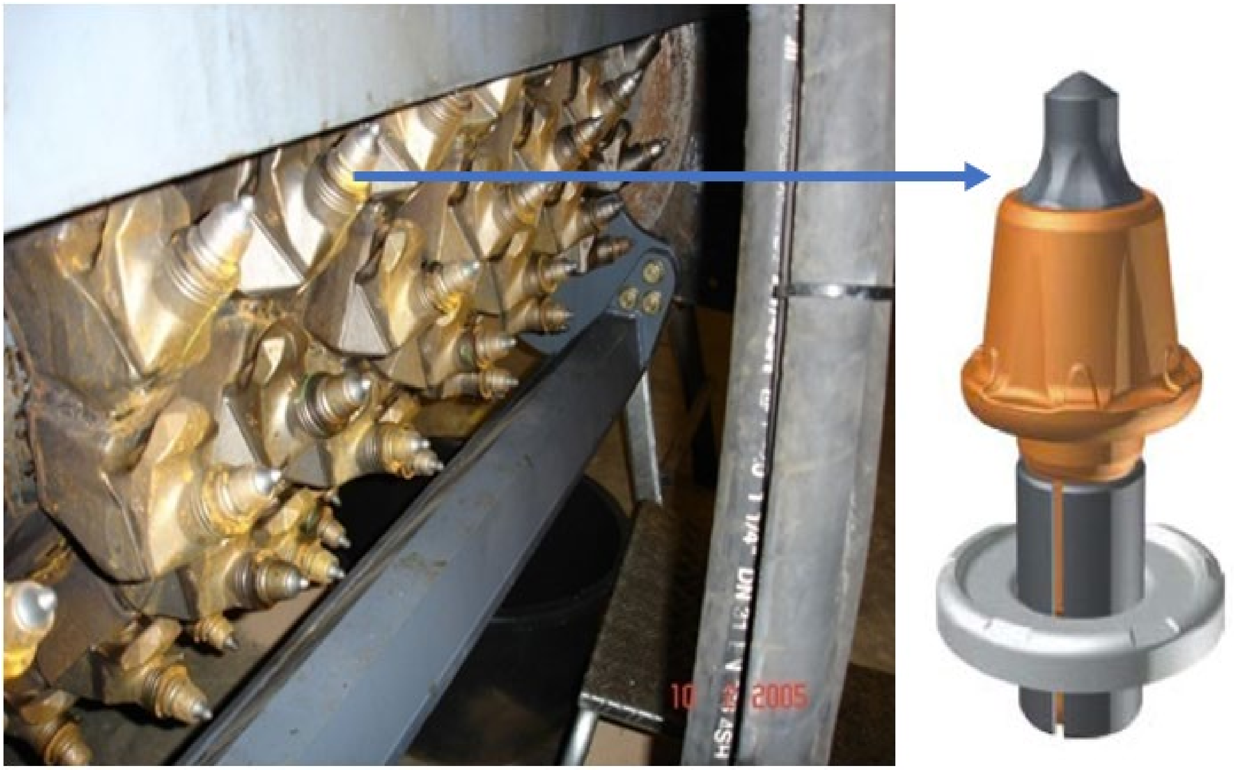


Figure 2.6 Milling teeth or picks (Wirtgen, 2018).

Figure 2.7 Staggered teeth on the milling (Wirtgen, 2018).

2.2 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 2.8). 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 2.8 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 2.9 and Figure 2.10 present the different types of drums and milling patterns, respectively. Some examples of different sizes and capacities of milling machines are displayed in Figure 2.11.

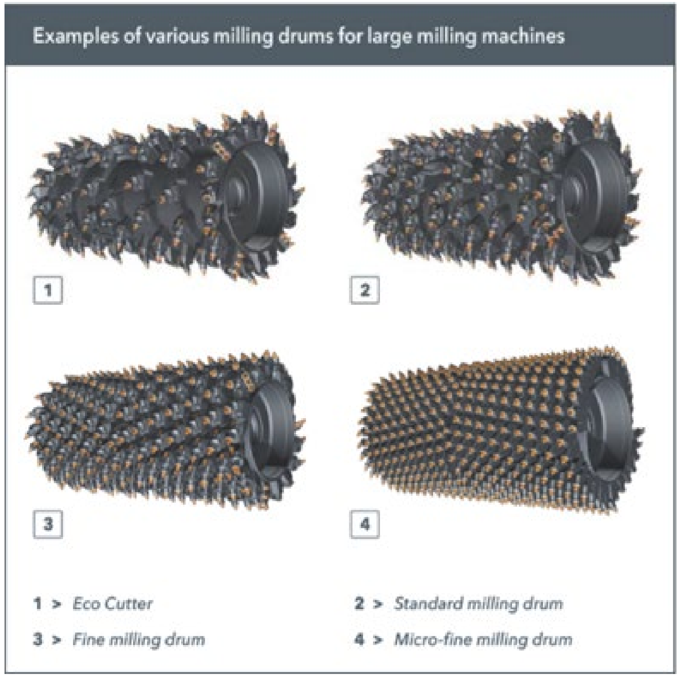
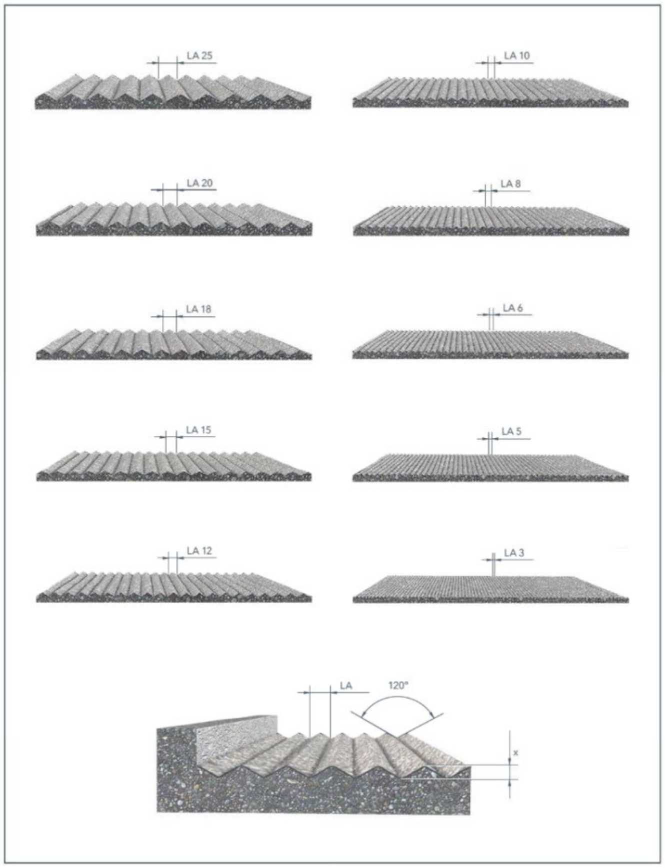


Figure 2.9 Different types of drums (Wirtgen, 2018).



Type of milling drum	LA = Line spacing	x = Theo-retical 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 2.10 Different milling patterns (Wirtgen, 2018).

Figure 2.11 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).

2.3 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 from $9-15 per ton to $0.63-2.26 per ton (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.

CHAPTER 3: 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 3.1). 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 3.2. 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.

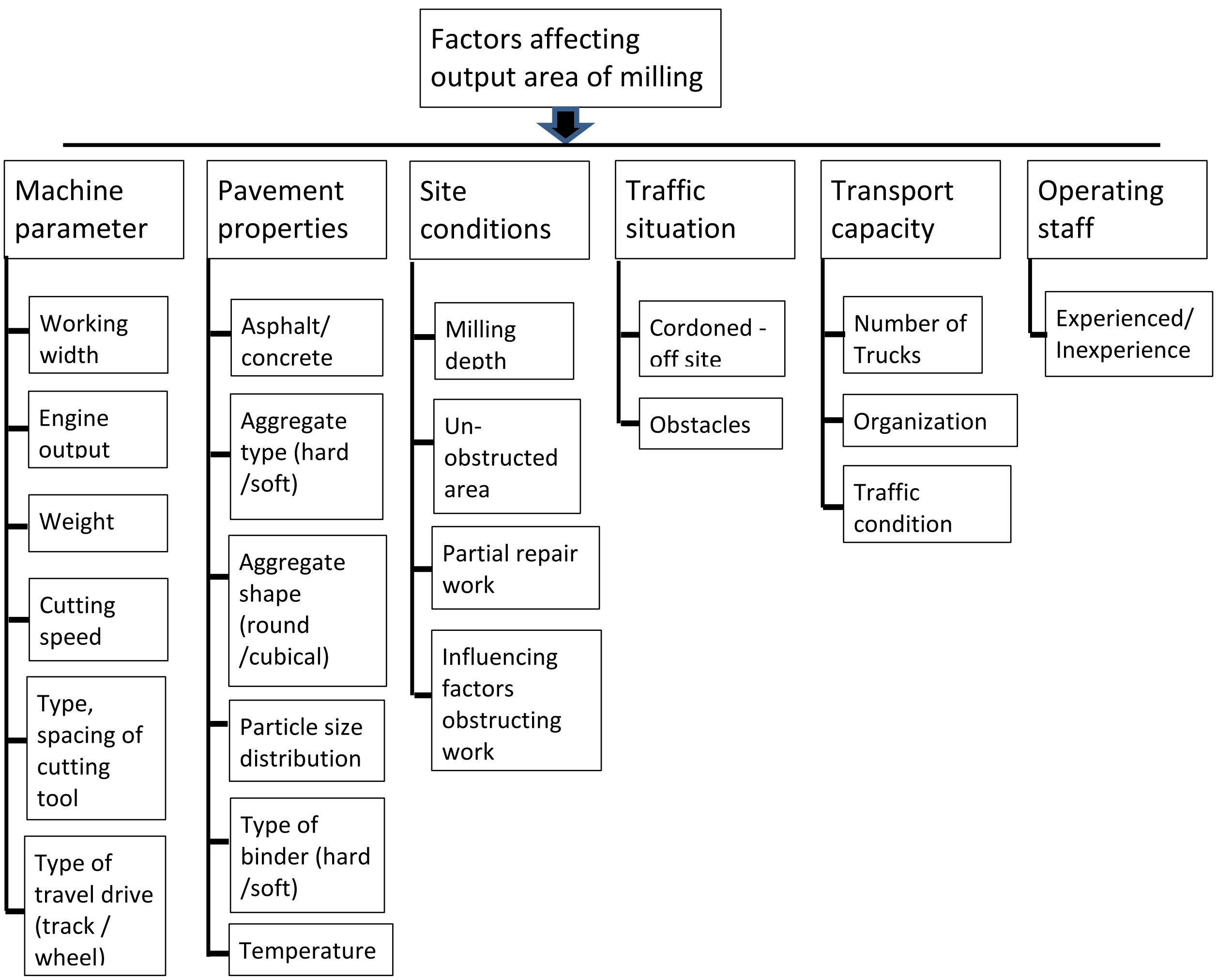


Figure 3.1 Factors affecting milling area output (Adapted from Wirtgen, n.d.).

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

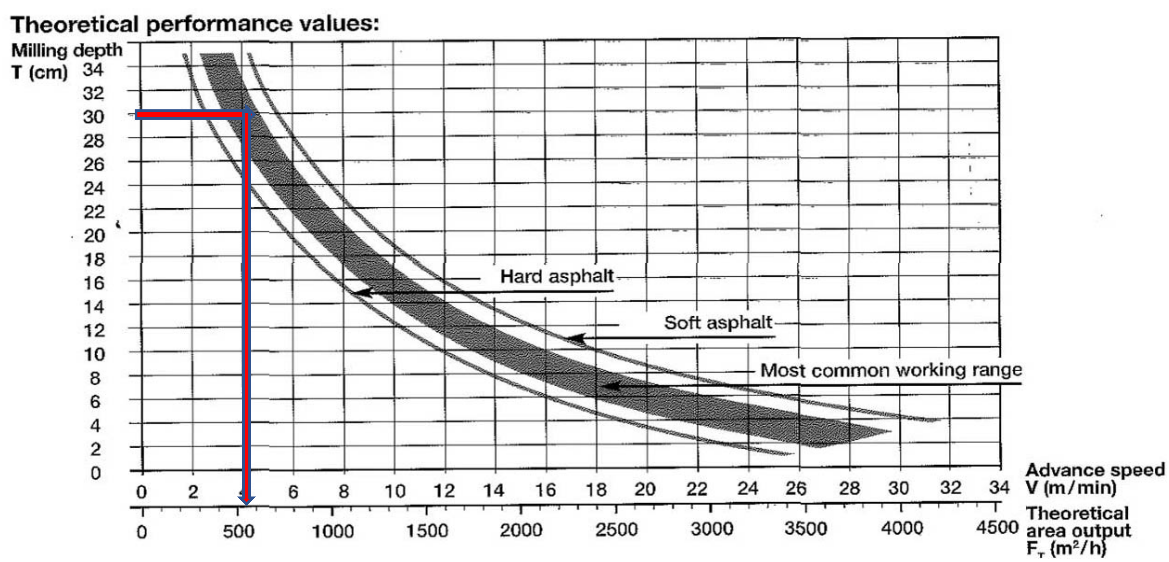


Figure 3.2 Formula and example calculation of milling output area (Adapted from Wirtgen, n.d.).

CHAPTER 4: 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. Tables 4.2, 4.4, 4.5, and 4.6 present the key findings for each study included in the following four subsections respectively.

4.1 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 4.1) 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 4.1) 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 4.1 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	-

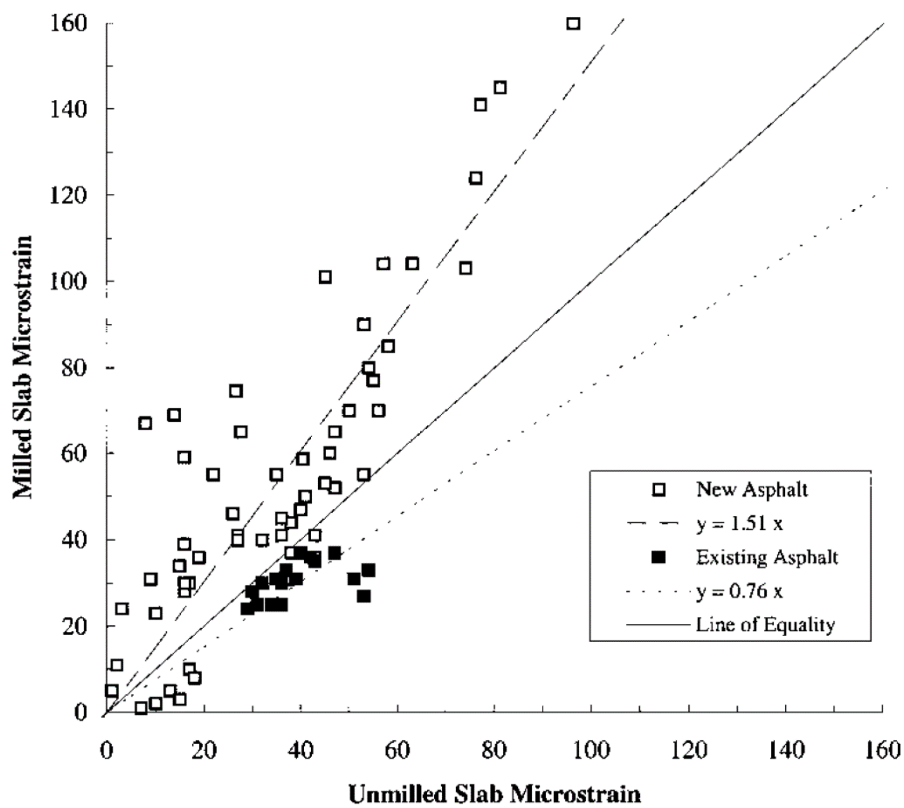


Figure 4.1 Effect of interface milling on load induced strain (Tarr et al., 2000).

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 4.2 Summary of literature review on available studies for evaluation of pavement condition on 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.

4.2 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 ameliorated 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 (≤ 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 (≥ 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 Eqs. (4-1).

$$MTR = \frac{\pi \times \left(\frac{D}{2}\right)^2}{VGB \times 100} \tag{4-1}$$

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 Eqs. (4-2) with the following equation.

$$D = \sqrt{MTR \times VGB \times 100 \times \frac{4}{\pi}} \tag{4-2}$$

Table 4.3 presents the different values and the INDOT requirements. Figure 4.2 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 4.3 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

Note (*)- INDOT requirement for milled surfaces for a single course overlay
Note (**)- INDOT requirement for milled surfaces for a single course overlay

Figure 4.2 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 4.3). 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 4.4) and slowing down for micromilling. 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=ωr: V(velocity, ft/sec), ω(angular velocity, radians/sec), r(radius, ft)).

Figure 4.3 Example of scabbing (Ensell, 2012).

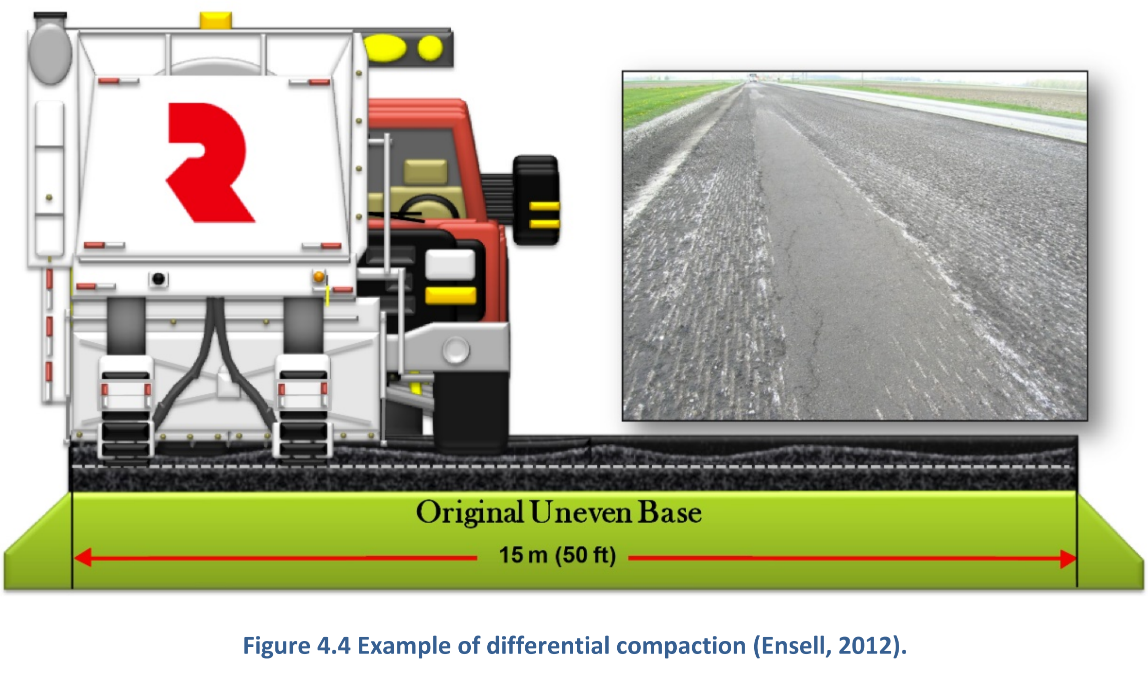


Figure 4.4 Example of differential compaction (Ensell, 2012).

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, wheelpath 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 4.4 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).

4.3 ENVIRONMENTAL AND HEALTH CONCERNS OF MILLING

According to Gadsby and Tsai (2021), conventional milling is expensive and pose a threat to the environment in regard of all the milling and resurfacing. Micro-milling and thin overlay is a new 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 4.5 represent the pavement design in terms of what layer is removed in both processes.

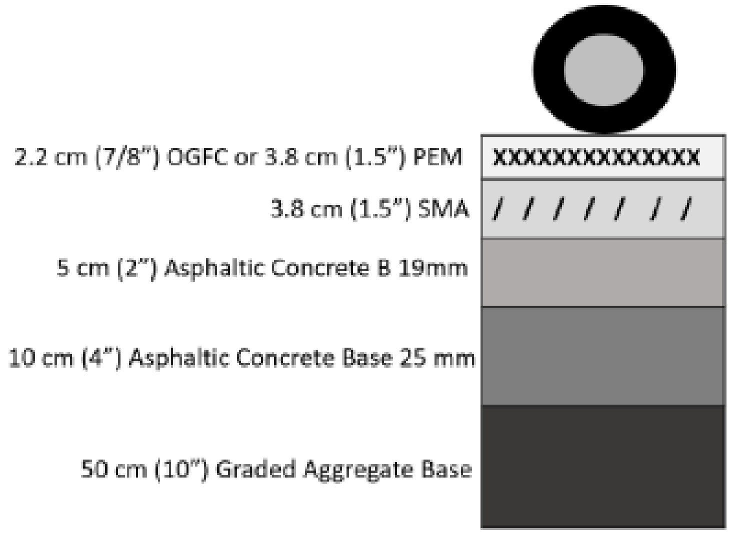


Figure 4.5 Layers removed by micro-milling ("X" marking) vs layers removed by conventional milling ("X" and "/" markings)

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 4.5 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.

4.4 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^o, 45^o, and 50^o. 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^o 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 micromilling); 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. (2020a, b) conducted a study of stresses induced at different depths during milling using FEM analysis. Their study was initiated by an observation of crushed, cracked, and missing materials in HMA samples from milled layers (Figure 4.6). The simulation results indicate that significantly high stresses, which are greater than the tensile strength of most HMA, are expected well below the milling depths (Figure 4.7). These analyses have shown that asphalt mixture below the mill line could be significantly overstressed, leading to a very high potential for damage and cracking for depths ranging from 25 to 100 mm (1 to 4 inch) below the mill line. The stress distribution is affected by the type of mix, milling speed, milling depth, and type of bond between pavement layers. The results indicate that higher stresses will occur in the case of stiffer mixtures, higher milling speeds, and when there is a good bond between layers. Milling at shallow depth generates high stresses proportionally further below the milling depth than deeper mill depths. The time of milling of an asphalt pavement varies from 5 to 10 years, and a significant aging-related increase in stiffness can be expected for most HMA during this time. This aging-related increase in mix stiffness is likely to cause a consequent increase in milling-induced stresses.

Figure 4.6 Crushed, missing, and cracked materials in HMA from layer below milling depth.

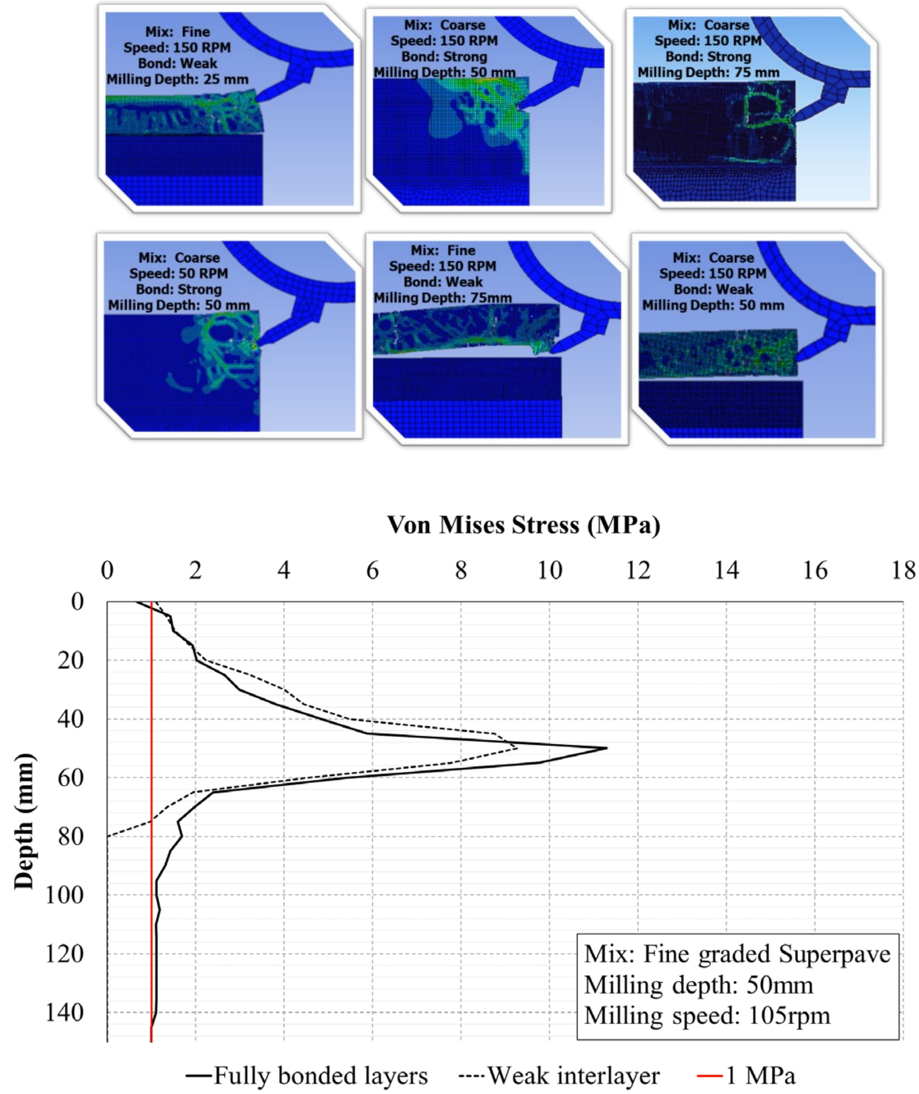


Figure 4.7 Results of finite element simulation (top) and plots of milling induced stresses at different depths (bottom) of HMA (Diouri et al., 2020b).

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 4.8). 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.

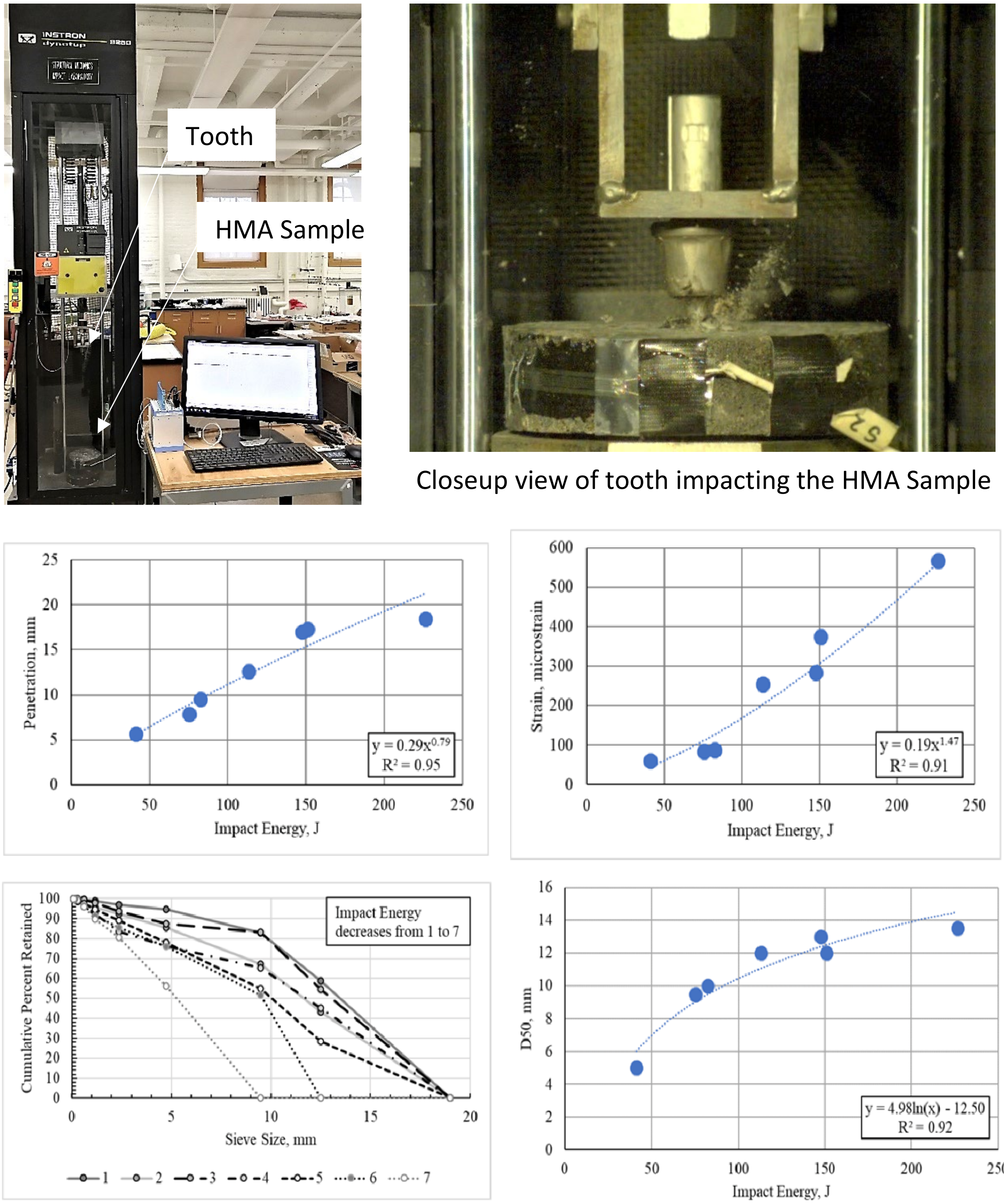


Figure 4.8 Test set-up and plots from resulting data (Diouri et al., 2020c).

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.

Table 4.6 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., 2020a	Stresses higher than the tensile strength of the HMA are generated underneath the milling depths. Type of mix, milling speed, and type of bond affect the stress distribution under the milling depths. A good bond between the milled layer and the underlying layer, a stiffer mix, milling at a shallow depth, and milling at high speed provoke the development of high stresses below the milling line.
Diouri et al., 2020b	Milling induces high stresses at the milling line and at the interface with the next layer. The stiffness of the mix and the milling drum speed affect the maximum stresses and stress distributions.
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.

CHAPTER 5: 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
- High stresses are generated in layers below milling line, and the stress is dependent on mix stiffness, type of bond between two layers, and milling depth; mixes with a higher aging-related stiffness are likely to experience higher milling-induced stresses

REFERENCES

ARRA, 1992. Guideline Specifications for Cold Planing. Asphalt Recycling and Reclaiming Association, Annapolis, MD.

ARRA, 2001. Basic Asphalt Recycling Manual (BARM). Asphalt Recycling and Reclaiming Association, Glen Ellyn, IL.

ARRA, 2016. Recommended Construction Guidelines For Standard Cold Planing (CP) CP101. Asphalt Recycling and Reclaiming Association, Glen Ellyn, IL.

ARRA, n.d. Applications of Micro Milling. Asphalt Recycling and Reclaiming Association, White paper. Glen Ellyn, IL.

ASTEC, 2021. https://www.astecindustries.com/products/infrastructure-solutions/cold-planers.

ASTM E 965-96, *Standard Test Method for Measuring Pavement Macrotexture Depth using a Volumetric Technique*, W. Conshohocken, Pa., Re-approved 2001.

Brock, J. D. and Richmond, J. L. Sr., 2007. Milling and Recycling. Technical Paper T-127. ASTEC INC., Chattanooga, TN, USA, 2007.

Diouri, K., Bousselham, R., De, A., El-Korchi, T. and Mallick, R. B., 2020. Milling Induced Stresses in Asphalt Pavements. Paper presented at the 99th Annual Meeting of the Transportation Research Board, Washington DC.

Diouri, K., Bousselham, R., De, A., Hera, A., El-Korchi, T., and Mallick, R. B., 2020. Some Practical Inferences from Modeling of Asphalt Pavement Milling. Proceedings of the Ninth International Conference on the Maintenance and Rehabilitation of Pavements (MAIRPAV 9), Zurich.

Diouri, K., Wang, S., Bousselham, R., Costa, S., El-Korchi, T. and Mallick, R. B., 2020. Empirical Study of High Strain Rate Loading and Fragmentation of Hot Mix Asphalt. Journal of Materials in Civil Engineering. J. Mater. Civ. Eng. DOI: 10.1061/(ASCE)MT.1943-5533.0003387.

Dunn, L. and Cross, S. 2001. Basic Asphalt Recycling Manual. Asphalt Recycling and Reclaiming Association (ARRA), Lanham, Maryland.

Ensell, J., 2012. AAPT Symposium: Milling and Paving Operations for Smoothness and Uniformity. Journal of American Association of Asphalt Paving Technologists, Volume 81.

Gadsby, A., & Tsai, J. (2021). Environmental impact comparison of new micro-milling and thin overlay and conventional milling for sustainable pavement preservation. International Journal of Pavement Research and Technology, 14(1), 23-29.

Gallivan V. L. and Gundersen J. F., 2005. Development of a Test Method to Measure the Quality of Milling Operations in Asphalt Pavements. Transportation Research Record: Journal of the Transportation Research Board Volume: 1907.

Gallivan V. L., 2005. Test Method for Measuring for Quality in Milling Operations. NCAUPG HMA Conference Lafayette, Indiana.

Gao, L., de Fortier Smit, A., Prozzi, J. A., Buddhavarapu, P., Murphy, M., & Song, L. (2015). Milled pavement texturing to optimize skid improvements. Construction and Building Materials, 101, 602-610.

Guada, I. M., and Harvey, John T., 2018. Effects of Milling and Other Repairs on Smoothness of Overlays: Additional Testing on Construction Under Profiler-Based Smoothness Specifications. Institute of Transportation Studies ◦ University of California, Davis.

Hall, K.T., Correa, C.E., Carpenter, S.H., Elliott, R.P., 2001. Rehabilitation strategies for highway pavements, Final Report, National Cooperative Highway Research Program Transportation Research Board National Research Council.

Hossain, M. and Wu, Z., 2002. Final Report: Estimation of Asphalt Pavement Life Report No. K-TRAN: KSU-97-6, Kansas State University.

Hung, S., Rezaei, A. and Harvey, John T., 2014. Effects of Milling and Other Repairs on Smoothness of Overlays on Asphalt Pavements. Transportation Research Record: Journal of the Transportation Research Board. Volume: 2408.

Kandhal, P.S., Mallick, R.B., 1997. Pavement Recycling Guidelines for State and Local Governments. Fed. Highw. Adm. Publ. No. FHWA-SA-98- 042, Washingt. D.C., USA.

NIOSH, 2015. Best Practice Engineering Control Guidelines to Control Worker Exposure to Respirable Crystalline Silica During Asphalt Pavement Milling. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2015–105.

Baker, E., 2014. Milling for Smoothness, Milling for Profit. Executive Seminar, Roadtec.

Tarr, S., Sheehan, M. J., Ardani, A., 2000. Mechanistic Design of Thin Whitetopping Pavments in Colorado. Transportation Research Record: Journal of the Transportation Research Board Volume: 1730.

Volk, H.J., 2016. Wirtgen Drives the Development of Surface Mining. Procedia Eng. 138, 30–39. https://doi.org/10.1016/j.proeng.2016.02.049.

Wen H., Titi., and Singh, J., 2005. Guidelines for The Surface Preparation/Rehabilitation of Existing Concrete and Asphaltic Pavements Prior To An Asphaltic Concrete Overlay. Final report to the Wisconsin Department of Transportation, WHRP 05-10, Milwaukee, WI.

West, R., 2015. Quality Improvement Series 129. Best Practices for RAP and RAS Management National Asphalt Pavement Association, Lanham, MD.

West, R., Michael, J., Turochy, R. and Maghsoodloo, S., 2011. Use of Data from Specific Pavement Studies Experiment 5 in the Long-Term Pavement Performance Program to Compare Virgin and Recycled Asphalt Pavements. Transportation Research Record: Journal of the Transportation Research Board Volume: 2208.

Williams, Brett A, Willis, J Richard, Ross, T Carter., 2019. Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage:. National Asphalt Pavement Association (NAPA), Greenbelt, MD.

Wirtgen, 2021. https://www.wirtgen-group.com/ocs/en-us/wirtgen/cold-milling-machines-61-c/

Wirtgen GmbH, 2016. The World of Wirtgen Cold Milling Machines. Windhagen, Germany.

Wirtgen GmbH, 2018. Parts and More Catalogue, Windhagen, Germany.

Wirtgen GmbH, n.d. Cold Milling Machines. Calculating the Working Performance. Windhagen, Germany.

Wu, J., Li D., Zhu B., Wu C., 2018. Milling process simulation of old asphalt mixture by discrete element, Construction and Building Materials, Volume 186, https://doi.org/10.1016/j.conbuildmat.2018.08.015.

APPENDIX A

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, ravelling 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) ____
