How to Reduce Tire-Pavement Noise: Better Practices for Constructing and Texturing Concrete Pavement Surfaces

National Concrete Pavement Technology Center

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16. Abstract

Concrete pavements can be designed and constructed to be as quiet as any other conventional pavement type in use today. This report provides an overview of how this can be done—and done consistently.

In order to construct a quieter concrete pavement, the texture must have certain fundamental characteristics. While innovative equipment and techniques have shown promise for constructing quieter pavements in the future, quieter concrete pavements are routinely built today all across the United States using the following standard nominal concrete pavement textures: drag, longitudinal tining, diamond grinding, and even, to limited extent, transverse tining.

This document is intended to serve as a guide that describes better practices for designing, constructing, and texturing quieter concrete pavements.

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Background

Concrete pavements can be designed and constructed to be as quiet as any other conventional pavement type in use today. This report provides an overview of how this can be done—and done consistently.

In order to construct a quieter concrete pavement, the texture must have certain fundamental characteristics. While innovative equipment and techniques have shown promise for constructing quieter pavements in the future, quieter concrete pavements are routinely built today all across the United States using the following standard nominal concrete pavement textures: drag, longitudinal tining, diamond grinding, and even, to limited extent, transverse tining.

Quieter concrete pavements can be durable and cost-effective to build. Furthermore, data have proven that quieter concrete pavements do not sacrifice safety because there is not a direct relationship between friction and noise. As illustrated in Figure 1, quieter surfaces vary in friction in the same way that louder surfaces do. Tire-pavement noise is shown in Figure 1 as measured on-board sound intensity (OBSI) (AASHTO 2011), a technique that takes measurements mere inches from a rolling tire. These measurements are compared to friction values, which in this case are skid numbers—a metric commonly used by state highway agencies (ASTM 2006).

One reason why not all concrete pavements are quiet is the lack of a collective understanding about what makes them quiet. To address this problem, the National Concrete Pavement Technology Center (National CP Tech Center) has managed a Concrete Pavement Surface Characteristics Program (CPSCP), amassing the largest database to date of concrete pavement surface characteristics. The database includes noise, texture, and friction measurements.

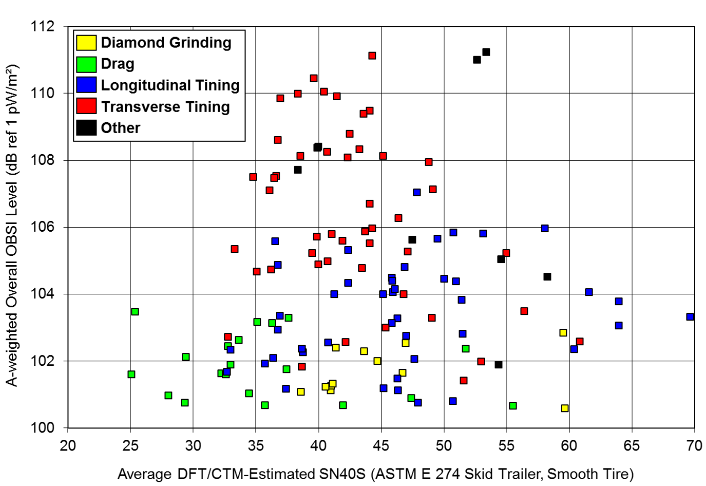

Figure 1. Comparison of noise and friction for various concrete pavement textures

Over 1,500 test sections in North America and Europe have been evaluated. From this effort, an understanding of the fundamental surface properties that affect noise has emerged, and better practices have been developed that serve to enhance surface properties that lead to quieter surfaces. These better practices include the following :

- Better practices for constructing and texturing quieter concrete pavements
- Better practices that answer the question of how we can reduce tire-pavement noise
- Better practices that don't compromise the other things about the pavement that are of equal or greater importance, including safety, cost, and durability

Both the best and the worst of virtually every nominal concrete pavement texture in use today have been catalogued. With so many measurements, the distributions in Figure 2 were developed to show what noise characteristics are possible for each nominal texture type. The pavements are categorized by nominal texture type and illustrate overall noise levels evaluated using OBSI (AASHTO 2011). The variability within these distributions is due to differences in design, construction, age, climate, traffic, and many other factors.

It should be noted that while a large number of pavements have been tested, the distributions tend to be biased toward younger pavements. This bias results from the fact that during the study these measurements were linked to construction factors, which are generally only available for younger sections. Additional sources of the variability in these distributions include the differences between equipment, and also between operators who measure OBSI. This effect has been recently evaluated and reported independently of this study as part of NCHRP 1-44 (Donavan and Lodico 2009; Donavan and Lodico 2011).

Based on the work conducted to date, an A-weighted overall sound intensity level between 101 and 102 dB (ref 1 pW/m²), measured using OBSI at 60 mph, appears to be a reasonable target threshold for quieter concrete pavements (Cackler 2006; Ferragut 2007).

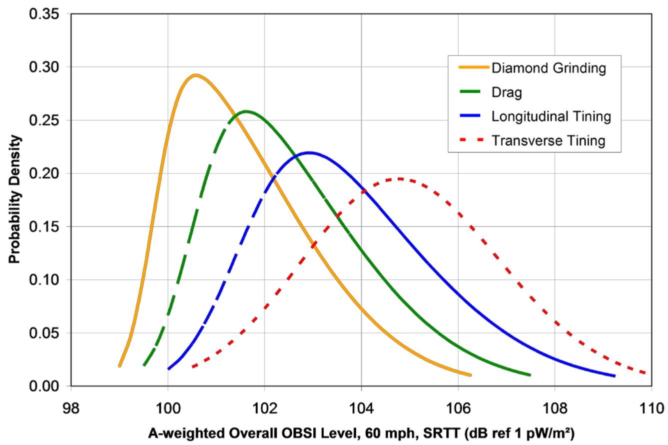

Figure 2. Normalized distributions of OBSI noise levels for conventional concrete pavement textures

Figure 2 illustrates the following:

- A majority of the conventional diamond ground surfaces that were measured met the target threshold.
- About a third of the drag textures measured also met the target threshold.
- About a quarter of the longitudinally tined surfaces measured met the target threshold.
- A small but important fraction of transversely tined surfaces that were measured met the target threshold. For those that met the target, the nominal tine spacings were at or below 0.5 in. (12.5 mm).

The data show that all conventional nominal textures have the potential to be constructed as quieter concrete surfaces, though some are more likely to be quieter than others.

It should also be noted that these results do not include important innovations, such as pervious concrete or the next-generation concrete surface, developed by the American Concrete Pavement Association (ACPA) and the International Grooving and Grinding Association (IGGA). There were not enough measurements to include these in Figure 2; however, many of these levels are among the very quietest of all concrete pavement surfaces measured (Scofield 2011).

While selection of the nominal texture might be the first logical step toward achieving the goal of a quieter pavement, this was not the sole intent of this study. Instead, better practices are needed to help owner-agencies and contractors achieve the quietest surface within any given nominal texture. Developing better practices requires tapping into the combined experience of both concrete paving contractors and paving equipment manufacturers.

In developing this document, the National CP Tech Center drew from decades of experience working for and alongside concrete paving contractors. This document embodies the collective experience of various contractors and equipment manufacturers with a reputation for quality. These guidelines further address the challenges that are faced in consistently producing a high-quality product in a low-bid environment.

This document is intended to serve as a guide that describes better practices for designing, constructing, and texturing quieter concrete pavements.

Summary of Better Practices

To build a quieter concrete pavement, the contractor must do the following:

1. Recognize which properties of a pavement surface make it quiet (and which make it loud).
2. Design the pavement surface in such a way as to avoid those adverse properties.
3. Construct the pavement surface in a manner that is both consistent and cost-effective while avoiding adverse properties.

The first item has been addressed in large part under the CPSCP and through the results of numerous other studies (Ferragut 2007; FEHRL 2006; Sandberg 2002). Figure 3 summarizes some of the key relationships and can serve as a reference for those seeking to better understand the link from the design and construction to the most relevant as-constructed properties affecting tire-pavement noise.

Better practices to improve surface properties (and thus tire-pavement noise) are really about establishing a higher order of control over the texture and other surface properties. Innovation can be helpful in achieving this goal, particularly with feedback systems that are relevant to how the texture is imparted (either in fresh concrete or through diamond grinding). This feedback could instill a renewed awareness of the impact that some of the subtle operational characteristics can have on the texture as constructed.

Predictable tire-pavement noise levels are not about how the texture is imparted as much as they are about the recognition and management of the sources of variability. Regarding the concrete, noise levels have to do with the

Surface texture (bumps and dips)

- Avoid (flatten) texture that repeats itself at intervals of 1 in. or larger.
- Avoid extremely smooth (e.g., floated or polished) surfaces; instead, some fine texture (that is on the scale of 1/8 to 1/4 in.) should be provided.
- Texture should be “negatively oriented", meaning that any “deep” texture should point down (e.g., grooves) rather than up (e.g., fins).
- Striations or “grooves” should, if possible, be oriented in the longitudinal direction, as opposed to the transverse direction.
- If grooves are oriented in the transverse direction, they should be closely spaced and randomized whenever possible. The depth of the grooves can be important in some cases, particularly if material that is displaced is re-deposited on the lands (areas between the grooves).

Concrete properties

- The mortar (at least, near the surface) should be consistently strong, durable, and wear-resistant. Mix design is a key factor, but so are proper placement techniques, including finishing and especially curing.
- Siliceous sands should be used whenever possible in order to improve texture durability and friction.
- For diamond ground pavements, the makeup of the concrete is exposed at the surface. Because the majority of the concrete used in paving consists of coarse aggregate (rock), the nature of this constituent will significantly affect the ability of the surface to retain the texture necessary for both a quiet and safe surface. As with any pavement related decision, careful consideration should be given to friction. With respect to diamond grinding, selection of projects and grinding patterns should be based on experience and/or a careful evaluation of the concrete material, and more specifically, the coarse aggregate type.
- For tined textures, there should be an adequate and consistent depth of mortar near the surface to hold the intended geometry.

Joints

- If joints are present, they can contribute to not only overall noise level, but also annoyance.
- Narrow, single-cut joints are preferred over widened (reservoir) cuts.
- Faulted joints should be avoided by providing adequate load transfer.
- Excess joint sealant should be avoided, especially if it protrudes above pavement surface.
- Spalled joints should be prevented through proper design, materials selection, and construction.

Figure 3. Concrete pavement surface properties that affect tire-pavement noise

fact that the contractors are imparting texture into a material with inherent variability in both stiffness and plasticity. Concrete changes from batch to batch, and it changes within a single batch. The wind and the sun play a major role, as does the timing of the concrete mixing, transport, placement, and the texturing and curing (the latter being important for acoustical durability). Because of these ever-changing parameters, equipment innovations such as vibration and motion monitoring and continuous texture measurements are being developed.

Figure 4 summarizes better practices to reduce tire-pavement noise on concrete pavements. Like Figure 3, this figure can serve as a helpful reference for understanding the numerous issues that affect tire-pavement noise.

These are just a few of the better practices that could be adopted if reducing tire-pavement noise is of concern. Many of these better practices, along with those listed in more detail throughout this document, will also improve smoothness and durability and, in some cases, reduce costs.

For today, we can promote better practices that focus attention on what we should be doing better during concrete paving. For tomorrow, the solution will likely be automation of the texturing operation. Over the years, slipform concrete paving operations have become increasingly automated. Automatic grade control, for example, is now a standard feature for most slipform pavers. Monitoring vibrator functionality and frequency is also common. Because of its importance, monitoring of the texture operation in plastic concrete will likely become a reality in the near future as part of an Intelligent Construction System and Technology (Torres et al. 2012).

To meet the demands for predictable low-noise surfaces, automation will allow the paver, texture cart, and grinding operators to monitor the texture being produced and to make adjustments on the fly. Ultimately, this approach may be the best way to achieve a specified target texture on concrete pavements. For now, we can make significant improvements by simply adopting better practices.

Concrete Materials Selection and Proportioning

- Aggregate gradation—for tining and drag surfaces, having adequate mortar concentration near the surface is a critical variable. Ideally, this could be achieved with a consistent, dense mixture. While it is important to have a nominally ideal mixture, consistency of the mixture as batched and placed is paramount.
- Aggregate selection—selection of fine aggregate should be made with friction in mind; thus siliceous sands are preferred over calcareous sands. Coarse aggregate type is of consequence if the aggregates are expected to become exposed, through either surface wear or diamond grinding. The selection of a hard and durable aggregate is therefore preferred.
- Mortar quality—a high-strength, low-permeability, wear-resistant mortar fraction will help maintain the intended texture over time. Measures to lower the w/cm through the use of SCM and/or chemical admixtures should be used when possible. Although they may promote bond for concrete overlays, sticky mortars should be avoided, as they may not hold the texture as intended, and instead deform under action of tining. Mortars that are too fluid could lead to grooves that slump or close up. Both extremes in mix consistency may lead to unintended or undesirable texture.

Paving Equipment

- Minimize vibrations—to minimize texture in the pavement surface that repeats itself on the order of 1 in. or longer, vibrations in the paver should be avoided—at least, vibrations that could potentially be imparted into the slab surface at the profile pan.
- Uniform paver motion—ideally, the paver should move as smoothly and consistently as possible. In addition to "obvious" problems with sudden starts and stops, even the impact of poorly maintained paving tracks can potentially impart undesirable texture features, as can small but rapid adjustments of the paver resulting from improper elevation and lateral control systems (e.g., stringline).
- Uniform extraction—heavy paving equipment would be preferred as a means to control variations in the pavement surface. Maintaining a constant head of uniform concrete at the proper level is also important.
- Equipment maintenance—equipment maintenance activities may be overlooked as a potential source of jerk or vibration that can manifest itself as texture variations in the pavement surface.

Texture/Cure Equipment

- Minimize vibrations—especially important for tined surfaces where vibrations of the tining rake can potentially impart undesirable texture.
- Cleanliness—for drag and tined surfaces, the texturing medium will always be contaminated to some degree with latent mortar. Care should be taken that the buildup of latency is not so significant as to depart from the intended texture.
- Consistent tracking—texture equipment should have a stable and consistent footing and minimize lateral wander. Track-driven equipment may inadvertently introduce small, repeating texture irregularities, as can wheeled devices due to wheel hop or imperfections. Wheeled devices have a disadvantage in their ability to maintain constant traction.
- Heavy duty curing—curing is paramount to the durability of the pavement surface. While often done immediately after texturing on the same cart, this process cannot be compromised in terms of the timing or application rate. Multiple pass (or higher concentration) curing application is recommended whenever possible.
- Equipment maintenance—like with the paver, proper and routine maintenance could improve the working condition of the texture/cure equipment, potentially preventing unwanted jerk or vibrations.

Grinding Equipment

- Grinding head—there does not appear to be an optimum size and spacing of blades and spacers to reduce tire-pavement noise as there is for improving friction (as a function of aggregate type). In conventional practice, these components are selected based on the specific concrete being ground in order to optimize production rate and the durability of the surface from subsequent wear under traffic and maintenance. This practice is still recommended to better ensure that safety, cost, and durability are not compromised for the sake of decreased noise.
- Size—larger, heavier grinding equipment is more likely to have the control necessary to consistently impart the texture at the intended depth and lateral coverage.
- Holidays and overlap—care should be taken that the match line between passes of the grinder does not coincide with the wheel path, as this can be a source of irregular grinding patterns. Wider grinding heads (e.g., 4 ft) will minimize the number of match lines, keep them out of the wheel path, and potentially impart better control.
- Bogie wheels—any imperfections in the bogie wheels that support the grinding head can manifest as texture variations in the as-ground surface. Care should be taken to ensure that the wheels are true (round).
- Fins—measures should be taken to minimize the variability in the height of the remaining fins of concrete. While some fin wear can be expected under traffic and from winter maintenance activities, excess fin height should be avoided by configuring the grinding head with the appropriate spacers (primarily a function of coarse aggregate type).
- Vibrations—while inevitable due to the nature of grinding, excess vibration should be avoided. If unchecked, these vibrations can impart themselves as undesirable texture in the pavement that can increase noise levels, especially in texture that repeats itself on the order of 1 in. or longer.

Figure 4. Summary of better practices to reduce tire-pavement noise

2 Overview of Concrete Pavement Texturing

2.1 Texture Classifications

The most common conventional surface textures for concrete pavements can be categorized as follows:

1. Tined textures
   a. Transverse
      i. Uniformly spaced
      ii. Randomly spaced
   b. Longitudinal (uniformly spaced)
2. Drag textures
   a. Artificial turf
   b. Burlap
   c. Broom
3. Diamond grinding (for both new concrete pavement surfaces and for surface restoration)

Figures 5 and 6 illustrate typical results of these various techniques. Figure 7 shows how one of the more commonly used techniques—longitudinal tining—is imparted into a fresh concrete surface. While other concrete pavement textures exist (e.g., exposed aggregate), this document will focus only on those found in conventional practice in the United States.

Figure 5. Longitudinal and transverse tined concrete pavements

Figure 6. Drag textured and diamond ground concrete pavements

2.2 Variables Affecting Texture

The methods and practices used today for imparting and controlling surface textures are often ineffective in meeting a nominal texture pattern, much less meeting it in a consistent manner. Even if tining, drag, and diamond grinding are all done with the best equipment, other variables, such as those illustrated in Figure 8, will affect the final texture. To construct a pavement's texture, it is necessary to recognize and control these variables to the greatest extent practical. The "Optimum Texturing Conditions" in Figure 8 are illustrated as overlapping areas of all three major variables—materials, climate, and construction—reinforcing how optimizing concrete pavement surface texture requires the control of these variables.

Figure 7. Longitudinal tining of a newly placed concrete surface

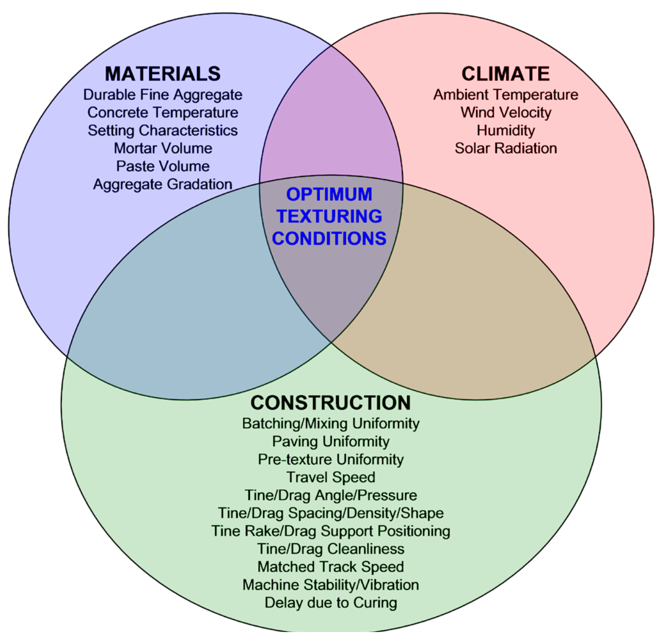

Figure 8. Variables affecting texture and the concept of an optimum texture window

Variables such as climatic conditions are often beyond the control of the contractor; therefore, it is necessary to concentrate on those variables that are more readily changed: materials and construction. Changing materials and construction parameters to respond to climatic changes is desirable. However, to achieve ultimate control, sources of variability in each of the inputs must be both understood and controlled to the greatest extent reasonable. This concept is central to the development of these guidelines, and Figure 8 will be referred to at various points in this text.

2.3 Nominal Surface Texture

Designers and specifiers often describe nominal texture for a concrete surface in terms of dimensions such as spacing, depth, and width. However, there is an interaction with the concrete materials, construction techniques, and climate that will ultimately define the texture as constructed on the concrete surface. The as-constructed texture often deviates from the nominal dimensions, and furthermore, the texture will vary from point to point along the pavement. While these deviations are to be expected, it should be recognized that they will lead to variability in friction, tire-pavement noise, and durability.

Nominal dimensions of spacing, depth, and width are obvious for tined textures—transverse or longitudinal. The rakes and individual tines that are used for texturing are manufactured according to these dimensions. For drag surfaces, however, the inherent nominal texture dimensions are more a function of the specified type, condition, weight, and cleanliness of the material used in the drag.

For diamond grinding, the blades and spacers as stacked on the grinding head are often used to define the nominal dimensions of the as-constructed (as-ground) texture.

2.4 Texture Measurement

The most common method of characterizing texture is depth using the volumetric or "sand" patch test (ASTM 2001). This test is simple to perform, but has many drawbacks as a process control procedure. For example, it can only be performed on a hardened pavement surface. In addition, only a very small area of the pavement is measured by each test, and the test relies on the technician's judgment to determine if the volume of material (typically, glass beads) is properly spread.

As an alternative, some practitioners employ quick measurements to check the texture depth during construction. These are often done with a coin, tire tread gauge, or other graduated device that fits inside of the groove left by the tine. These techniques prove difficult or impossible on drag or diamond ground surfaces. They are also—like the volumetric patch—small samples that may or may not be representative of the entire pavement surface. And, again, these techniques are difficult to perform on fresh concrete surfaces.

Overcoming some of these limitations are laser-based texture profilers. Figure 9 illustrates two such devices: the Circular Track Meter (CTM) and RoboTex (based on the LMI Technologies RoLine sensor). Devices like these can more accurately measure texture and can more fundamentally define texture in terms of spacing, width, and depth. RoboTex actually measures the surface in three dimensions to provide even more clarity of the subtleties of the pavement surface, since most concrete pavement textures are anisotropic (different in the longitudinal and transverse directions). The drawback of any laser-based device is the relatively high cost. In addition, they don't serve as quick checks for texture during construction unless they happen to be integrated as a real-time monitoring system on the paving/texturing equipment.

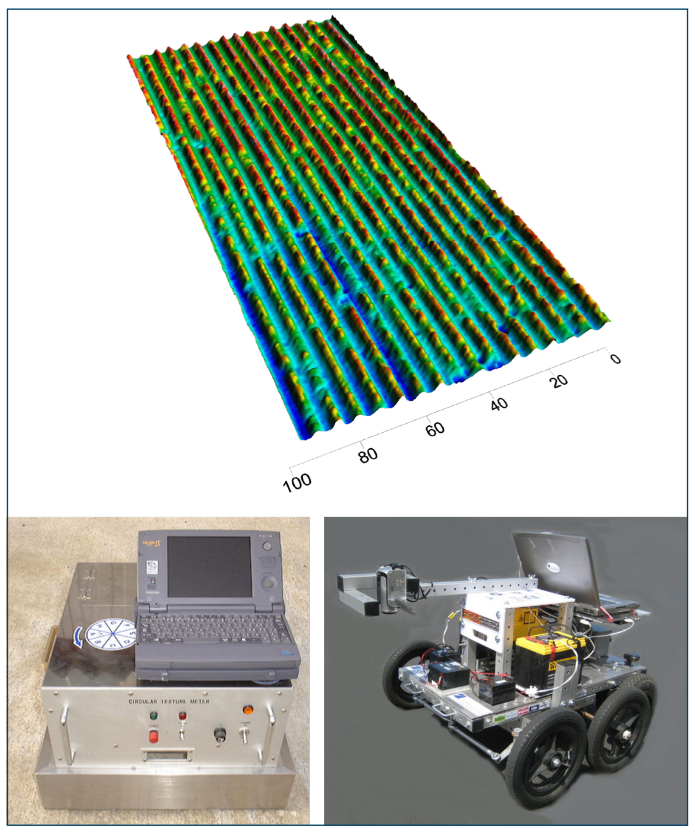

Figure 9. CTM and RoboTex test equipment

3 Controlling Concrete Pavement Surface Texture

Obtaining a consistent texture that adheres to the nominal pattern is critical to tire-pavement noise and is currently a significant problem using today's construction methods and practices. Even if tining, drag, and diamond grinding are all done with the best equipment, the other variables illustrated in Figure 8 will ultimately affect the final texture.

Figures 10 through 12 illustrate this lack of consistency. These photographs show how variability in the as-constructed texture can lead to very different tire-pavement noise levels (measured using OBSI). These photographs were taken on one of the CPSCP test sites on US Highway 30 in Iowa (Ferragut 2007). In each figure, the different appearance of the texture between the louder and quieter areas can be seen. For those sections that are louder, one or more of the texture characteristics noted in Figure 3 can be observed.

Figure 10. Variability of drag texture surface and its effect on overall OBSI level

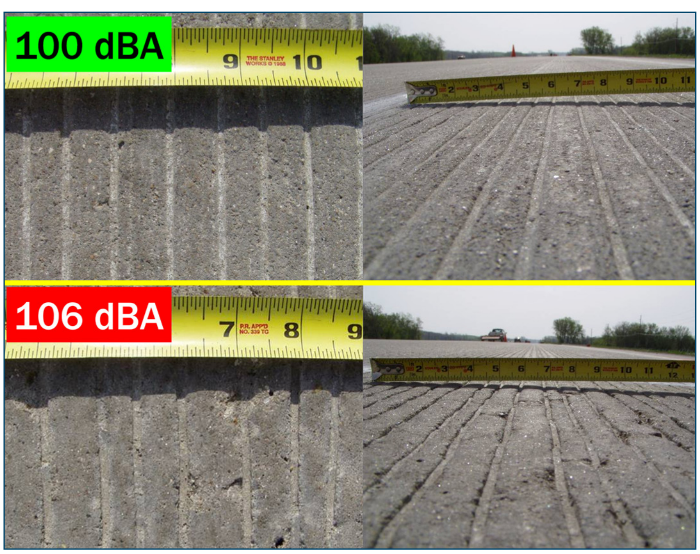

Figure 11. Variability of longitudinal tined surface and its effect on overall OBSI level

Figure 13 further illustrates the transverse tining section by way of a texture scan measured with the three-dimensional texture profiler, RoboTex (illustrated in the center of Figure 9) (Ferragut 2007). From this, subtle curvature of the lands between the tine grooves can be noted in the louder section, while the tine grooves are much less aggressive in the quieter section. It should be noted that the

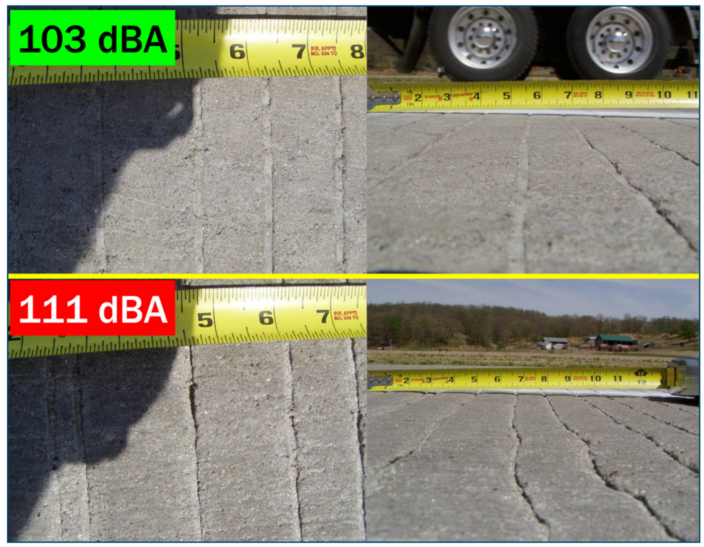

Figure 12. Variability of transverse tined surface and its effect on overall OBSI level

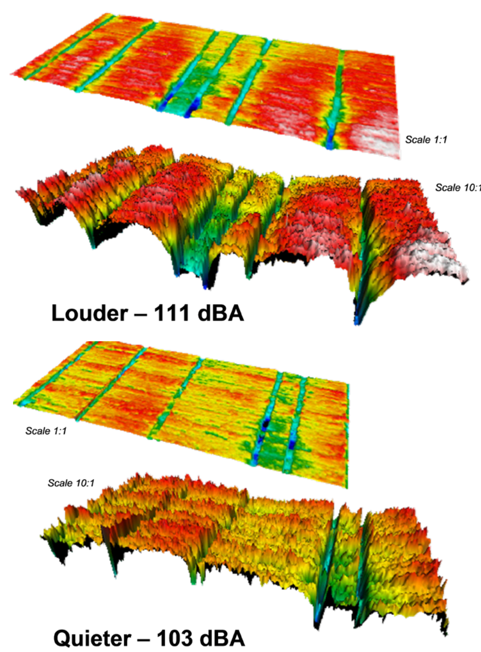

Figure 13. RoboTex scans of 4×8 inch samples showing variability of transverse tined surface and its effect on overall OBSI levels

texture depth in both cases was very similar. The differences in geometry of the lands was the major contributor to noise—largely due to the land (tine) spacing, which was in excess of 1 in. in many cases. This as-constructed variability in texture is another example of the impetus for better practices. Ideally, the probability of constructing the nominal texture should increase as better practices are followed.

The differences in the as-constructed texture are the impetus behind these better practices. The techniques described herein are intended to increase the probability of constructing the nominal texture, as well as to increase the consistency in the as-constructed texture. The following sections summarize some of these practices in more detail. However, a decision will ultimately have to be made by the user about what degree of control is reasonable to ensure that a proper and consistent texture is constructed.

3.1 Concrete Materials

For each of the texturing methods that will be subsequently described, the effect of concrete materials will be mentioned. However, in terms of controlling batch variability, the contractor might consider some of the following suggestions (ACPA 2003):

1. Moisture control—monitor aggregate stockpile moisture contents, adjusting the batch proportions as needed. Stockpiles can also be sprinkled to ensure a saturated surface dry condition or wetter; this is especially important for highly absorptive aggregates. Consistency in the mix is arguably most affected by the water content. If this varies, then the as-constructed texture as imparted will vary as well. Proper stockpile management can help significantly. This includes not only moisture control, but also better practices such as maintaining a minimum three-day supply of each aggregate throughout the paving process.
2. Cementitious material control—there is variability of relevant properties of both cement and other supplementary cementitious materials. The properties of relevance with respect to the pavement surface would be those linked to the concrete set time, plasticity, and durability. Periodic evaluation of the constituent materials should be made, and mix adjustments should be made as appropriate to ensure as consistent of a product as possible.
3. Aggregate control—consistency in the response of the concrete during the slipform process will depend in part on the consistency in the concrete volumetrics. Segregation during batching, transport, or depositing/spreading of the concrete can lead to problems in achieving a uniform surface. Mix designs that minimize the potential for segregation should be sought, along with controls in handling the fresh concrete.

To illustrate the significant impact that mix consistency can have, Figure 14 shows the result of tining a fresh concrete surface that was constructed with a highly segregated mixture, leading to a surface with a highly variable thickness of mortar. This is often due to a combination of poor mixture design and/or inadequate batching.

For additional guidance in controlling variability, refer to the Integrated Materials and Construction Practices (IMCP) manual developed by the National CP Tech Center (Taylor 2006).

3.2 Tining

Tining is the most commonly used texturing method for concrete pavements. Both longitudinal and transverse tining are used, sometimes with other variants such as a skewed or "wave" pattern. The following section presents guidance to help control texture produced by various tining methods.

3.2.1 Concrete Material

Because tining will result in the mortar fraction as the wearing surface, it is vital that the mortar be durable. A

Figure 14. Variability in tined texture due to mix segregation/consistency problems

surface of high strength and low permeability is desired, especially on projects that will be subject to heavy traffic and/or winter maintenance activities. Use of siliceous sand will not only increase the durability, but increase friction, all else being equal. Concrete mixes with a low water-cement ratio are ideal. The use of supplementary cementitious materials is also recommended, as this can help increase both the durability and workability of the mixture.

While potentially contradictory to meeting the objective of a durable mixture, it is believed that the concrete should not possess too many intermediate-sized aggregates. A more gap-graded mixture will facilitate adequate mortar depth near the surface (1/8 to 3/16 in.) so that the grooves imparted by the tines maintain their intended shape. If too much aggregate is present, the tines will constantly work around and displace the particles, resulting in a more aggressive and potentially noisy texture. The result of this is illustrated in Figure 15. The fine aggregate particle shape may also be of particular importance, as an overly sticky mixture can lead to displacement and shearing of the surface mortar, which in turn can distort the intended texture.

Again, caution should be exercised in adopting the recommendation given herein. It has been shown that the durability of a pavement mixture is closely related to the mortar content. While increased mortar contents may lend themselves to more consistent and quieter textures, they will also have increased shrinkage (and thus increased crack potential) and higher permeability (and thus reduced durability). A knowledge gap exists where optimization of the concrete mixture may balance the need for a dense, low-permeability mix that can be constructed (finished) in such a way as to ensure adequate mortar volume in the immediate vicinity of the pavement surface.

On the other extreme, too much fluidity in the mortar can also prove problematic, as the tined grooves will tend to "slump," and, in the worst case, close off pockets being created, as illustrated in Figure 16. To avoid this, the sand type and gradation should be selected for stability in terms of flow under low to moderate levels of vibration.

Finally, segregation of the mixture should be avoided, since not only will the tining process respond differently to concrete of varying volumetrics, but also the wear of a concrete surface will be nonuniform, eventually leading to a "modulation" in the noise level and/or frequency characteristics that can prove annoying to vehicle occupants.

3.2.2 Equipment

The industry continues to learn about the particular aspects of paving and texture equipment that affect the as-constructed texture. Given that variability is undesirable, an automated texture/cure cart is mandatory. Manual application of tining cannot achieve the same degree of

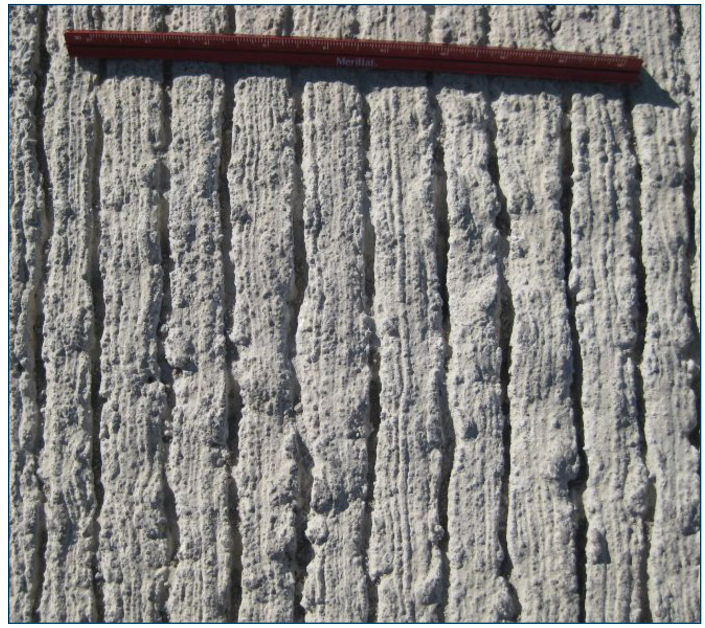

Figure 15. Excessive intermediate aggregates in close proximity to the surface leading to undesirable texture

Figure 16. Excessively fluid mortar leading to closing of tined grooves

consistency in uniformity and depth, as illustrated in Figure 17. When transverse tining is used, this control should be present along the tining rake to prevent one end of the rake from imparting texture different from the other, as illustrated in Figure 18.

Vibrations of various sorts at both the paver and tining rake should also be avoided. Section 4 of these guidelines includes very specific guidance on how this might be accomplished through an elevated awareness of the equipment operation and maintenance.

In addition to minimizing vibrations, any alterations to the equipment that will minimize the variability of the concrete that is displaced might be preferred. As illustrated in Figure 19, mortar that is displaced by the tines will redeposit somewhere else on the pavement surface (typically the lands between the grooves). In many circumstances, these "random" deposits will contribute to additional noise being generated. While such equipment modifications are not readily known, this guidance should serve as a target for innovation.

Figure 17. Manual longitudinal tining leading to undesirable texture variability (photo courtesy of Jim Grove)

Figure 18. Nonuniform texture depth across width of transverse tining rake

While these guidelines do not serve to recommend texture type or geometry per se, it is known that when transverse tining is used, small (1/2 in. or less) spacings must be used to produce the quieter surfaces among this nominal texture category. Adding some degree of randomness to this spacing will further minimize annoying "tones" that may develop when driving this pavement.

3.2.3 Construction Technique

A completely smooth concrete surface is not quiet. Some (smaller) texture is necessary in order to minimize the noise that is generated. Pre-texturing the pavement with a drag texture prior to tining is therefore important. As illustrated in Figure 20, a heavy drag surface is recommended, with specific recommendations on techniques found in Section 3.3.

Figure 19. Redeposited mortar on the surface of the lands between the tined grooves

Figure 20. Drag pretexture applied prior to tining operations

Since the durability of the mortar at the surface is so critical to the success of a tined surface, excellent curing techniques become mandatory. The use of multiple applications of conventional curing compound or, in more extreme circumstances, wet curing techniques should be considered for those projects where noise is a particular concern. The timing of the curing application is also important, with the recommendation that it be applied as soon as possible after placement (and texturing). Alternatively, more conventional curing techniques can be used as long as the evaporation rate is constantly monitored during and immediately after placement.

In terms of constructability, longitudinal tining tends to produce more consistent surfaces than transverse tining. The process of longitudinal tining is more conducive to consistent texturing and curing since it involves not having as much "start and stop" motion, particularly when compared to transverse tining.

3.2.4 Spacing

On tined surfaces, texture spacing is controlled by ensuring that the individual tines are spaced to meet the specification. This step is mandatory when ordering the rake from the manufacturer, at the beginning of paving, and each time that the texturing equipment is transported on a project. Tines are often bent or damaged during transport. The spacing of tines should be checked frequently to identify missing, bent, and misaligned tines.

3.2.5 Width

The width of the tined groove is a function of the tine width dimension. Depending on the concrete mix properties, there may be some change in the width of the groove immediately after tining. Plastic (fluid) concrete can close back together after tining, for example. This can be altered by increasing the hydration time before tining, or through mix adjustments.

Alternatively, an increase in the groove width can result from a buildup of dried concrete paste on the tine, as illustrated in Figure 22. This can be remedied by cleaning the tines periodically. A broomstick or similar object can be dragged across the bottom of the tines regularly to break loose concrete paste that is clinging to the tines. Hand tools can also be used to break hardened mortar free of the tines, as illustrated in Figure 23. It is much easier to clean the tines regularly before the mortar has hardened than it is to replace tines if the mortar is too hard to remove.

Figure 22. Excessive buildup of hardened mortar on tines

Figure 21. Bent tines on rake that can lead to nonuniform tine depth

Figure 23. Simple technique to clean hardened mortar from tines

Finally, worn tines should be replaced as soon as practical when the nominal tine dimension is believed to be critical. Worn tines, as illustrated in Figure 24, result in rounded edges that will impart texture that is different from what is specified.

3.2.6 Depth

Tine depth is arguably the most difficult variable to control. It is a function of the following variables:

- Quantity and size of aggregates near the concrete surface that can be dislodged by the tines
- Density (stiffness), workability, and combined gradation of the concrete mixture near the surface of the pavement

Figure 24. Worn tine

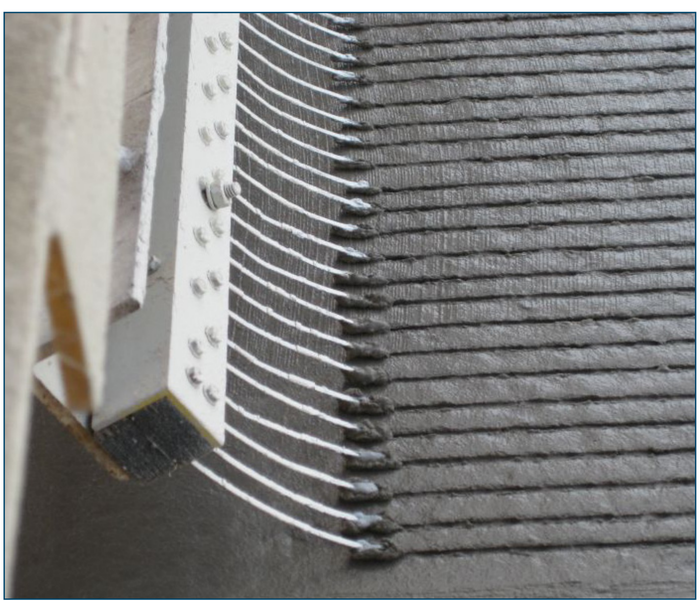

Figure 25. Angle of tines affecting contact with concrete surface

- Overall mix uniformity
- Downward force applied to the tine
- Surface area of the tine in contact with the concrete—affected by the tine dimension and the angle of the tine with respect to the pavement
- Localized roughness—high spots in the pavement surface will likely be tined deeper than low spots, therefore measures to improve smoothness can similarly improve noise

As the tine applies pressure to the pavement surface, the slab provides resistance to that pressure, resulting in two springs pushing against each other, one spring being the tine and the other spring being the plastic surface of the slab. For a given mix with consistent stiffness, the pressure of the tine against the concrete surface decreases as the surface area of the tine in contact with the slab increases, and thus the texture depth will decrease. This pressure is a complex function of the elevation of the tine rake and the angle of the tines (see Figure 25). It should be noted that as the mixture changes in consistency, the depth will also change, leading to undesirable variations in texture.

Additionally, the quantity and size of aggregate particles that are dislodged by the tining process will have an impact on the consistency of texture depth. Decreasing the angle between the tine and the pavement surface may reduce this variability, but no field experiments have been conducted to confirm this.

Appendix A contains information pertaining to the hypothesized relationships between tine length, angle, and height. Although each of these variables can be adjusted in an attempt to control the texture depth, little is known about the true correlation of texture depth as a function of field adjustments to these variables. The material in this appendix has been developed as a first step in providing supplementary guidance based on theory.

3.2.7 Knowledge Gaps

With respect to better practices of tining, a number of gaps remain. Probably most pressing is the need to identify nominal tining patterns that are suitable to meet not only low noise demands, but also all of the potentially competing demands of the concrete pavement surface, including comfort, safety, durability, etc.

With the nominal tining pattern defined, the next gap is to define what tolerances are necessary for construction. Within this area, the sensitivity of deviations from the nominal texture needs to be understood with respect to their impact on noise and other critical responses.

A concrete mix design system is also needed that is capable of balancing the demands for the concrete at the surface to hold the intended texture, and yet remain smooth and durable.

Finally, to achieve a higher order of control, more automated means to impart and monitor texture on a concrete pavement will likely be necessary.

3.3 Drag

Drag texturing is commonly the least expensive texturing technique that is available. The process involves "dragging" a material through the fresh concrete surface. The material is commonly artificial turf, burlap, or possibly a broom. In common practice today, artificial turf is most often used, and the surface is dragged in the direction of travel (longitudinally). While seemingly simple, there are still better practices that can be followed to produce a more ideal surface.

Like tining, the mortar fraction of the concrete is effectively the wearing course. A durable mortar is therefore vital to the success of a drag texture surface. Specific guidance for this can be found in Section 3.2.1.

3.3.1 Drag Material

The material that is used for the drag texture will affect the final product. Drag textures using virtually all types of materials have been used successfully for high-speed roadways. The FHWA, as part of the most current Texture Advisory, will approve the use of broom or artificial turf drag for roadways with design speeds of 50 mph or greater when adequate safety performance is demonstrated (FHWA 2005). Minnesota, for example, has adopted the use of artificial turf drag, but it has instituted texture depth controls and stresses the need for a high-quality mortar (Mn/DOT 2008).

The CPSCP has recommended specific characteristics about artificial turf that have demonstrated good performance. For example, the turf is specified to have a molded polyethylene pile face with blades that are curled and/or fibrillated instead of straight and smooth monofilament blades. Blade lengths of 0.6 to 1.3 in. are preferred, along with a minimum turf weight of 60 oz/sq yd. Two examples of compliant turf are illustrated in Figure 26, and a non-compliant material is shown in Figure 27.

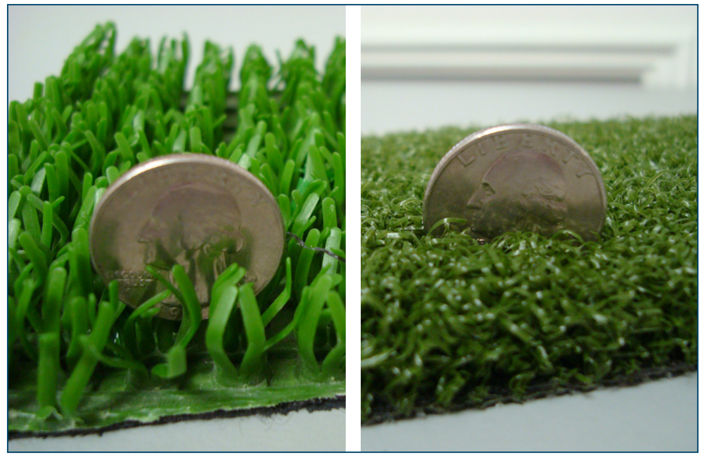

Figure 26. Recommended artificial turf materials, both meeting the newly developed specification

Figure 27. Non-compliant artificial turf material

3.3.2 Construction Technique

Like with tining, better practices for curing are critical to the success of drag textures. Vibrations of the paver and, in this case, the bridge supporting the drag material should be minimized. More on these can be found in Sections 3.2.2 and 3.2.3.

The geometry, weight, saturation, and conditioning of the drag material are all important too. All else being equal, drag surfaces that produce "deep" and uniform striations will not only produce lower noise, but will maintain the lower noise levels for a longer period of time as more wear of the surface occurs. The length of the drag material that should remain in contact with the fresh concrete should be a minimum of 5 ft. When burlap is used (for lower speed roads), the material should be heavy (AASHTO M 182, Class 3 or 4) (AASHTO 2005). Burlap should also remain visibly damp during the drag process and be frayed along the trailing edge for a length of 2 to 6 in.

If performed successfully, drag surfaces will produce deep and uniform striations like that illustrated in Figure 28.

To maintain a consistent surface, the drag process should proceed at the same rate as the paving process, with minimal time between these operations. One way to do this is to have the bridge with the drag material towed by the paver; however, the paver should advance at a consistent rate for this technique to be most effective.

All drag materials will collect mortar and paste because of the texturing process. Most of this material will be continually redeposited. However, depending on the specific mix and other variables (see Figure 8), the drag material may eventually collect so much mortar/paste that it loses its effectiveness to produce a surface with deep striations. At this point, the material should be replaced and/or cleaned to restore the intended function. At a minimum, the material should be thoroughly washed and/or replaced at the end of a day's paving. Drag materials containing hardened mortar are illustrated in Figure 29, and should not be used for texturing concrete.

3.3.3 Knowledge Gaps

The need for an improved concrete mix design process that was identified in Section 3.2.7 also applies for drag surfaces. In addition, a need exists to identify the sensitivity of the various drag materials and conditioning in terms of their impact on the as-constructed texture.

3.4 Diamond Grinding

Diamond grinding is a texturing technique that can be used for both newly placed concrete as well as for rehabilitating existing concrete pavements. The process involves removing the surface of the concrete via a gang-mounted spindle of saw blades (and spacers), as illustrated in Figure 30. The resulting "corduroy" surfaces are among the quietest concrete pavement surfaces that can be constructed.

3.4.1 Project Selection

Unlike conventional "wet" textures such as tining and drag, diamond grinding will result in a surface that largely consists of the coarse aggregates in the concrete mixture. As a result, concrete containing durable, wear-resistant coarse aggregates will provide a longer life, all else being equal.

Of particular relevance to noise is the degree of homogeneity (uniformity in type) of the aggregate. Individual particles of coarse aggregates that are of the same nominal mineralogy (e.g., limestone, granite) will tend to wear at the same rate. In contrast, aggregates that are blends of numerous types (e.g., "river rock") can result in uneven wear that can further introduce additional noise over time.

3.4.2 Grinding Head

Details of the grinding head that is used will affect the as-constructed texture. On the head, blades and spacers of various size and type are traditionally selected in such a way as to ensure that the target functional standard (e.g., smoothness) is achieved while further considering the potential for wear (of both the grinding head and of the pavement under traffic). Figure 30 shows a close up of a diamond grinding head, including the blades with embedded industrial-grade diamonds that are separated by spacers.

There is no optimum combination of blades and spacers that will achieve the quietest surface. Numerous aspects of the final texture will affect both the noise characteristics and the durability of the surface. For example, "fins" are sometimes left behind between the sawed grooves (see Figure 31). Fins are not something to be concerned with, as they are a natural artifact of the grinding process,

Figure 28. Deep and uniform striations from proper drag texture

Figure 29. Hardened mortar on drag materials

particularly when grinding concrete with hard aggregates. However, the presence of fins can lead to additional noise, which will subside as they wear down under traffic. The grinding head should be built according to the best practices within the grinding industry, which is represented by the International Grooving and Grinding Association (IGGA).

3.4.3 Equipment Operation

Section 4.3 of these guidelines identifies specific operations and maintenance activities that may warrant renewed diligence if noise is a concern. In addition to this guidance, other improvements to control the texturing operation include real-time sensing of the as-ground surface. This type of system could provide operators with information that can allow them to adjust forward speed, power, or other operational characteristics to reduce unwanted texture features that may contribute to noise.

3.4.4 Knowledge Gaps

Since the durability of the coarse aggregate is an important factor in determining the longevity of a diamond ground surface, additional work is needed to classify aggregates in terms of their ability to hold texture. While surrogate tests for wear are used today, little has been done to even correlate these results to the performance of diamond ground surfaces. In addition to traffic wear, additional consideration should be given to the effect of winter maintenance activities on the durability of ground surfaces.

A better understanding of the operation and maintenance of a diamond grinder is also necessary. It would be advisable for standard operating procedures to be documented in addition to more formal on-the-job training. In the future, clearer links between the changes in operating characteristics of the equipment and the resulting texture should be better documented.

Finally, while evidence exists that no single grinding head configuration is quieter, the selection of blades and spacers is known to affect wear rate. The need exists to optimize the selection of the grinding head as a function of the project-specific conditions (especially the concrete type). Tolerances on these dimensions should also be investigated in terms of their sensitivity to the resulting noise, other surface characteristics, and durability. While experienced grinding operators have the ability to design a grinding head that is close to optimum for a given job, the means to for doing so remain largely proprietary.

3.5 Making Field Adjustments

Prior to construction, adjustments in the field to control texture can be accomplished in the following steps:

- Verify that the equipment and materials being used are set up to meet the nominal texture per the project specifications.
- For tining, verify that the tine width and spacing meet project specifications. Furthermore, use the appropriate tine length for expected conditions. Use shorter tines for hot dry weather, firm pavement surface, and deeper texture; use longer tines for cool damp weather, soft pavement surface, and shallower texture.
- For grinding, verify that the correct grinding head is being used for the concrete being textured, and that the wear on the head is within recommended tolerances.
- As appropriate, set the crown and/or cross-slope of the texture equipment to match the pavement cross-section. The tips of the tines should be parallel to the proposed pavement surface. The supports for drag textures should also be at equal heights from the pavement surface across the width.

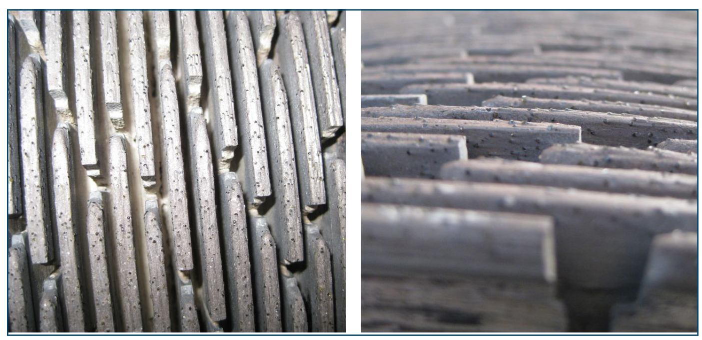

Figure 30. Diamond grinding head showing blades (with embedded diamonds) separated by spacers

Figure 31. Concrete fins that can remain immediately after grinding operation

Recognize that some adjustments to texturing equipment cannot be readily done "on the fly." Because consistent surface texturing is time dependent, any changes that are made must be done using the parameters under the control of the operator. Changing the tine length or grinding head, for example, cannot be practically done. However, depending on the equipment, it may be possible to adjust the tine angle or grinding speed in a timely manner without adversely affecting the efficiency of the overall operation.

3.6 Other Considerations

3.6.1 Steering and Elevation Controls

Controlling the steering of the texture machine off of the stringline used for paving is a suggested method for improving the uniformity of a pavement surface texture. Utilizing automated elevation control for longitudinal texturing is not mandatory, but it is highly recommended. If automatic elevation controls are used, the speed of the machine should be kept within a limit that allows the hydraulic system being used to react as intended. A smooth track line for the texture machine is mandatory to reduce the variability of the texture.

Since variability in the texture is a characteristic that should be avoided, it is recommended that equipment be sought that possesses a rigid frame capable of transmitting steering forces from one end to the other, along with a quality propulsion and steering system. The combination of these will increase the probability that the texture-cure machine will steer accurately, resulting in a more uniform texture. In other words, a texture-cure machine being used for longitudinal tining that does not steer accurately will result in "wavy" longitudinal grooves that can contribute to the overall noise level of that surface.

3.6.2 Crown and Cross-Slope Changes

Many pavements have variations in the typical section due to super-elevated curves, matching existing pavement cross-slopes, etc. These cross-section changes must be accounted for in the surface texturing process. For non-crowned pavements, controlling the elevation of the texture machine with the paving stringline should keep the texture rake or drag supports parallel to the width of the slab surface.

When the cross-section of a crowned pavement changes (for example, when transitioning between tangents and curves), some texture-cure machines, because of their design, must sometimes be manually adjusted to match the pavement cross-section. This is sometimes the case even if automatic elevation controls are being used. Suggested methods for cross-section adjustments are listed below:

- Transverse texturing

  Each time the texture machine is advanced to make the next transverse texturing pass, verify that the texture machine frame is parallel to the pavement cross-section for the full width of the pavement. Since the tine rake travels across the pavement in a carriage that is attached to the machine frame, the crown adjustment in the frame will need to be adjusted for cross-section changes. One simple way to check the frame's crown relative to the pavement is to hang four plumb bobs from the frame on equal-length strings (two on either side of the crown point and two near the pavement edges). A visual check will reveal if the frame is parallel to the pavement surface, or both sides of the machine may be lowered until all four plumb bobs are in contact with the pavement at the same time, and then raised in unison to maintain a parallel plane. Some texture machines may optionally include or be adapted to have automatic sensors that assist in this process.

- Longitudinal Texturing

  Longitudinal texturing is similar to transverse in the way that cross-section changes are made at stop/start points. Plumb bobs or sensors are not necessary, since the tips of the tines or position of the drag material provide a visual reference across the width of the pavement. Additionally, the crown adjustment of the texture machine may need to be adjusted simultaneously with the texturing process. The degree of this "on-the-go" adjustment will depend on the length of pavement being textured and the rate of pavement cross-slope change. For example, if the texture machine operator is texturing and curing the pavement in 100 ft increments, the outside edge of the pavement could rotate up approximately 2 in. in a 100 ft segment of a super-elevation transition. This degree of change would require a crown adjustment while texturing. This adjustment is completely operator-dependent, and at this time no automatic controls are available for texturing equipment.

- Cross-section changes should be visibly marked with signs on the project so that the texture machine operator is aware of the location and rate of cross-slope changes. These types of changes are illustrated in Figure 32.

To overcome some of the inherent limitations of manual

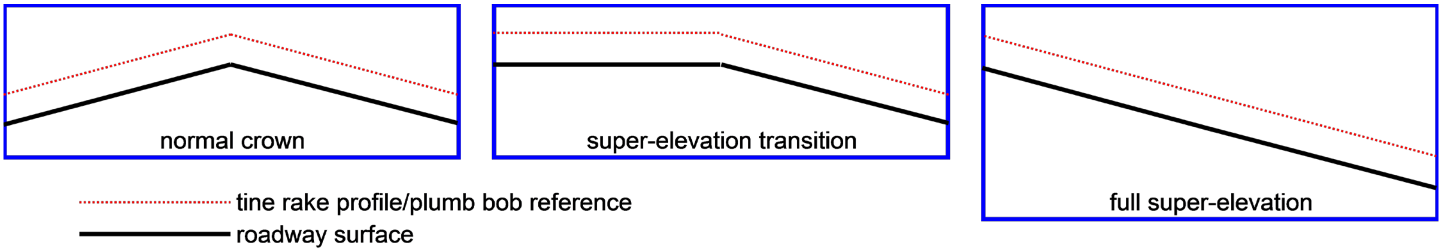

Figure 32. Pavement cross-slope adjustments

elevation adjustments, it is recommended that automated controls be used whenever possible. Sensors that can gauge the cross-section of the pavement section are particularly useful and will increase the quality as a result. These sensors can include a combination of stringline and height (e.g., sonic) sensors located at strategic points across the width of the pavement.

3.6.3 Workmanship and Ownership

Constructing more uniform surface texture will require equipment operators that are properly trained and skilled in their craft. It will also require a change in some management philosophies to emphasize the importance of having the same operator day-in and day-out to improve texture consistency.

Traditionally, texture-cure equipment has been deemed less important than other equipment, such as a slipform paver. In response to more stringent specifications and new incentives for thickness and smoothness, many contractors have chosen to upgrade their pavers. However, since the as-constructed texture is often overlooked in inspection, much less considered a pay item, there is much less incentive to invest in higher quality equipment.

3.6.4 Texturing Speed

Normal ground speed for longitudinal texturing is typically on the order of 25 to 75 feet per minute. While this is significantly faster than the paving speed (which is typically 5 to 7 feet per minute); it is not necessary or preferred to texture at such a high speed. The operator should instead find an operating speed that minimizes machine vibrations and/or oscillations that can possibly be transmitted to the pavement surface. Equipment should not be operated at excessively slow speeds either, since this can sometimes result in “crab-walking” of the texture machine due to the steering response. This too can be problematic in terms of introducing unwanted texture variability. Ideally, the texture speed should be set so the machine can steer accurately; it should advance in such a way as to maintain alignment with the stringline, as well as to minimize unwanted vibrations.

The speed of transverse texturing across the width of the slab has been observed to be on the order of 30 feet per minute. As with longitudinal texturing, equipment vibration and oscillation transferred to the pavement surface is one concern with determining the optimum speed for transverse texturing. The texture equipment should be set-up and maintained in a condition that will result in a consistently smooth operation of lowering the texturing medium, pulling it across the width of the pavement, and raising it at the end.

3.6.5 Matching Start and Stop Points

Both longitudinal and transverse texturing are interrupted processes. The operator should pay particular attention to matching the texture at start and stop locations. This may be especially critical for transverse texturing with respect to noise. A simple plumb bob on both sides of the texture machine can be used as a reference to gauge both overlap and alignment of the tine rake (Figure 33). However, equipment with flexible frames and/or lower quality steering mechanisms will find it more difficult to achieve point matching.

The primary concern with matching start and stop points for longitudinal texturing is the steering/alignment of the texture machine. When tining, each stop and start re-

Figure 33. Poor transverse start/stop point matching – left: holiday; right: overlap

quires that the tine rake is raised and the texture machine be backed up to allow some forward movement before the tine rake is lowered into contact with the pavement surface. This slow speed backing up can lead to "crab walking" of the texture machine, causing one side of the machine to back up further than the other. The texture machine should be backed up far enough so that it can be walked forward and realigned with the pavement centerline in preparation for the next texturing section. As mentioned above, longitudinal tining is generally preferred over transverse tining in terms of the potential for constructing a more uniform texture that has improved noise characteristics.

3.6.6 Curing Impacts on Texturing

Curing of the pavement is sometimes performed using the same piece of equipment as texturing. As a result, texturing equipment is often referred to as "texture-cure" equipment. The fact that uniform surface texture is time dependent demands that special attention be given to the curing operation. Specifically, the curing equipment should be maintained to prevent clogging and/or breakdowns, and the refilling of the cure tank should be well planned to minimize delays. Larger cure tank capacities can be beneficial in this regard. When problems occur, curing should always take priority over texturing.

Longitudinal tining typically has a potential advantage over transverse tining in terms of the ability to provide a high quality curing. During longitudinal tining, the forward motion of the texture-cure equipment can be uninterrupted. This allows the curing compound to potentially be applied concurrently with the tining operation, resulting in a quicker and more consistent curing operation. Most conventional texture-cure equipment used today, when used for transverse tining, requires that the equipment stop periodically and then "back up" in order to apply curing compound.

3.6.7 Segregation and Improper Vibration

Segregation of the concrete mix, including that due to improper vibration on the paver, can lead to inconsistencies in surface texture, among numerous other problems. If the vibrators are not operating properly, a concentration of paste (lack of larger aggregate) can occur at the pavement surface in the path of one or more of the vibrators. The effect on texture results from the variability of the firmness of the pavement surface across the width of the slab.

Segregation due to improper vibration is visible is what is commonly referred to as "vibrator trails." These trails are most easily seen on transversely textured pavements where the texture depth is deeper in the "vibrator trails" because the tines penetrated further into the softer, segregated mix directly over the vibrators. In addition to contributing to inconsistent surface texture, segregation can lead to premature pavement failures. Any time the texture machine operator notices that segregation has occurred, the vibrators on the paver should be checked for proper operation.

Quite often, what is commonly attributed to a "vibration problem" is the result of segregation due to the concrete mixture being used. Mixtures that are extremely gap graded will tend to segregate during handling and placing. Any excess vibration of these mixtures will only exacerbate their shortcomings. The mixtures will tend to be inconsistent across the width of the slab and especially in the vicinity of the vibrators. While there is a need for a uniform layer of mortar near the surface in order to retain the intended texture, the mixture should be optimized for this, and avoid the use of poorly graded aggregates.

3.7 Inspecting Surface Textures

Until new measurement procedures such as the RoboTex can be adapted for construction quality control, the inspector is left with limited options for comprehensively ensuring the quality and consistency of the pavement's surface texture. Prior to construction, the contractor's equipment should be inspected with regard to tine spacing and cleanliness. During construction, the inspector should first observe whether the texture is uniform across the slab and then take measurements of the texture depth. Even though specification tolerances may exist for texture depth, it is unrealistic to representatively measure the texture to the extent that a pavement should be rejected. When it is obvious that the texture is not acceptable, the contractor should be notified immediately so that the processes can be corrected.

4 Equipment Operation and Maintenance

It is in the best interests of nearly all stakeholders to construct concrete pavements as well as possible with the resources given. The “best” pavement is one that offers the requisite structural capacity while providing a surface that is safe, smooth, and quiet. It has been found that the condition of the equipment used to construct concrete pavements can have a direct effect on the texture and thus noise level as vehicles traverse the road. More specifically, machines that are not properly maintained can introduce unwanted vibrations in the equipment that is in contact with the fresh concrete. These vibrations, in turn, can lead to subtle texture that will adversely affect tire-pavement noise and possibly smoothness.

The following guidelines describe better practices for maintaining and operating the paver, texture-cure cart, and diamond grinder in such a way as to minimize these unwanted vibrations. Explanations of both the necessity and consequences associated with each maintenance and operation topic are provided herein. It must be emphasized that the following recommendations are generalized; the the equipment documentation provided by the manufacturer should be referenced for application of this guidance to specific equipment models.

4.1 Concrete Paver

We begin with some general principles of a concrete paver that can help build a smoother ride with minimal vibration-related texture (ACPA 2003; FHWA 1996):

1. Weight—the heavier the better, up to a point. During the slipform process, a large mass of concrete is being forced into a specific geometry during the course of a few seconds. The laws of physics require that significant forces be imparted into this mass during this time. As a result, there is an inherent advantage to heavier machines in shaping the concrete to a higher tolerance. Lighter machines can be used paving a quality product; however, in these situations, careful pre-spreading of the concrete in front of the paver by a placer-spreader or some other effective means is important. This will help avoid overloading the paver and thus should be an integral part of the paving process.
2. Traction—requires weight, power, and friction. With these extreme forces at play, the natural response of a paver will be to resist the concrete being placed, and thus resist forward motion. Only with sufficient weight and good traction can the paver advance in a uniform fashion. Traction is enhanced greatly by a stable track line for the paver during operation.
3. Uniformity—the more consistent, the better. The concrete paver works best when operated in a steady state. Forward motion, vibrator frequency, and other mechanical systems should be operated at a constant rate during placement to the greatest degree possible. Any changes in these due to varying mix, weather, or other factors can inherently introduce changes to the pavement surface. For example, forces acting on a paver are effected by the nature of the concrete mixture. Changes in the mix volumetrics due to segregation, alterations in the batch quantities, admixture dosage (including air), or other factors can change the response of the paver. If these responses are sudden and/or numerous, imperfections in the pavement surface can result.

Regarding the principal aspects of the equipment that introduce the vibrations, the following three sources are arguably the most significant (Hite 2007):

1. Engine—most concrete pavers operate on a diesel engine that operates on the order of 2,000 rpm. Vibrations from rotating machinery such as an engine cannot be avoided. However, measures are commonly taken to isolate these vibrations using dampening mounts. Still, these mounts are imperfect, and their effectiveness is subject to maintenance.
2. Vibrators—used on concrete pavers in order to temporarily fluidize the mixture and allow it to be formed to the proper geometry; the vibration frequency is critical and is often “tuned” to provide optimum consolidation of the concrete. Rates of 6,000 to 11,000 vibrations per minute (VPM) are common. This vibrational energy is, of course, introduced into the concrete, and to some degree it will affect the concrete surface. Keeping the vibrational energy constant across the slab by monitoring individual vibrator operation and limiting variations in the load/concrete head heights is important. Variations in these will lead to inconsistencies across the slab that will be reflected in the subsequent texturing. It is also worth noting that some of the vibrational energy will likely be transferred through the paver and may introduce additional imperfections in the surface. Proper mounting (and dampening) of this vibrational energy should limit this potential.
3. Maintenance—specifically, neglected or poor practices. A modern concrete paver is very complex. Numerous

mechanical systems work simultaneously and thus make maintenance a priority. A poorly maintained paver is likely to adversely affect quality. Excess vibrations can be introduced at a number of locations on the paver. Figure 34 illustrates some of these locations in a broad sense (FHWA 1996). The following sections will describe proper maintenance activities in more detail.

4.1.1 Frame

The frame of a concrete paver is the platform upon which the power plant and paving kit are fixed. Its weight and rigidity affect the ability of the paver to handle the large volumes of concrete associated with paving, especially thick sections typical of highway paving.

Supporting the frame are tracks, with two- and four-track systems commonly available by the various manufacturers, as shown in Figure 35 (FHWA 1996).

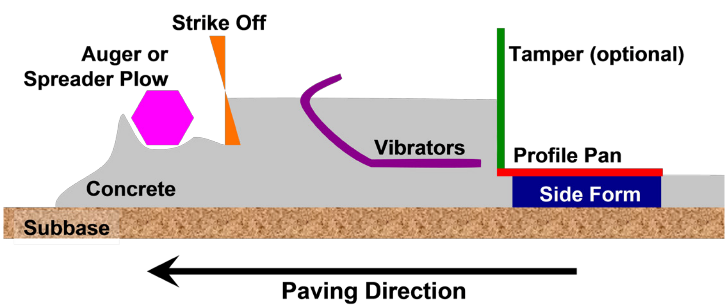

Figure 34. Typical components of a slipform paver

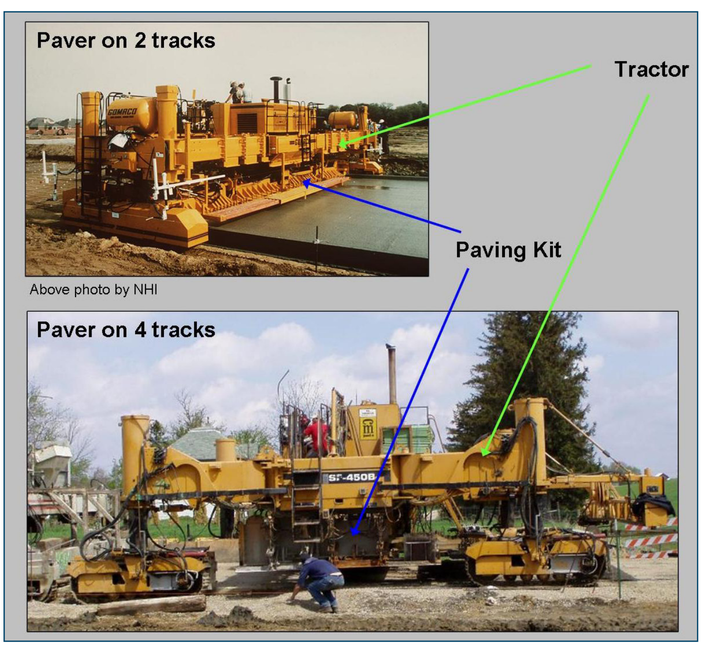

Figure 35. Two- and four-track pavers

The following are specific maintenance activities that are specific to the paving frame:

- Square up the paving kit (Figure 36) (ACPA 2003; Terex undated,a; Huron undated; MBW 1998; G&Z 2008a). This should be done before any day's paving begins. It is most important when the paver is supported by four tracks instead of two. Although the tracks may seem to be lined up and riding straight, the frame could be skewed, and additional vibrations may result from resulting eccentricities.
- Tighten the bolts (ACPA 2003; FHWA 1996; Terex undated,a; Huron undated; MBW 1998). All bolts and connections should be checked daily. Loose bolts can cause a shift in equipment alignment and shaking. Loose connections can hinder sensor response. Both situations result in additional vibrations and a nonuniform placement of concrete.
- Check the engine. As mentioned previously, the engine is one of two main components from which vibrations are generated. As a result, the frame of the paver is constructed in such a way as to isolate these vibrations. Neoprene pads are used to minimize the engine's vibrations (Hite 2007). However, these pads need to be checked on a regular basis to ensure that excess vibrations are not transferred into the frame and ultimately into the concrete. The pads should be replaced when sufficient wear is noticed. Refer to the equipment manual and contact the manufacturer for specific maintenance details. In addition to these mounts, care should be taken that the engine is clean of any trash and that fluid levels are maintained daily (FHWA 1996; Hite 2007; Terex undated,a; Huron undated; MBW 1998). Trash and improper fluid levels will result in additional vibrations that may transfer to the fresh concrete.

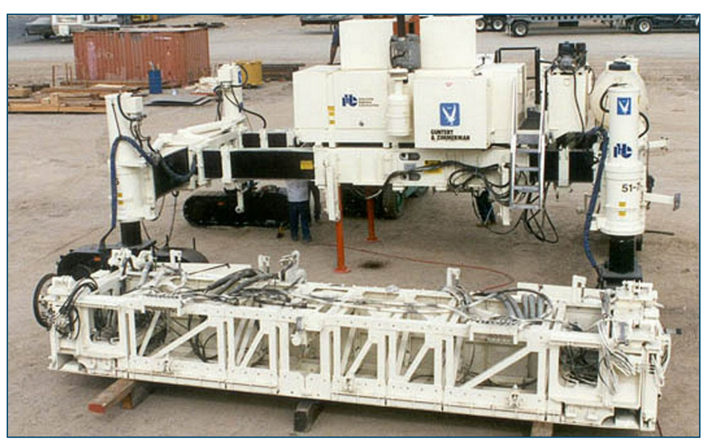

Figure 36. Paving kit for a slipform paver

4.1.2 Sensors

Concrete pavers utilize sensors to help guide the direction and elevation of the pavement. Typically, a stringline is used that is sensed by one or more rods, as illustrated in Figure 37.

Movements of these rods are picked up by transducers that, in turn, assist a computer in controlling the steering and elevation systems. The following are guidelines to ensure the proper operation of these sensors:

- Align sensors according to the manufacturer's guidelines. Sensors should be checked daily, ideally throughout the day's paving (FHWA 1996). The paver will respond to improperly installed sensors by adjusting its elevation and alignment incorrectly. As a result, placement will not be uniform, and bumps and sags can be introduced into the pavement surface.
- Dampen sensor response time (ACPA 2003; FHWA 1996). As part of the sensor checks, it is important to note how fast the paver responds to sensor movement. If the paver responds too quickly or too slowly, bumps and dips will occur. There are two types of sensor systems (ACPA 2003):

    Hydraulic system that affect flow rate of oil.

    Electric systems that change voltage or current when outside of a null band.

- Align sensors with the slipform pan. When aligning the forming pan, it has been suggested to position the pan as parallel as possible to the stringline, as illustrated in Figure 38 (ACPA 2003; G&Z 2005; G&Z 2008a). By keeping the pan as flat as possible, the attack angle is reduced, providing a smoother finish on the pavement surface. If the pan is not aligned with sensors, it will adjust itself incorrectly, resulting in improper concrete depths, a nonuniform placement leading to differential shrinkage cracking, and surface imperfections.

Figure 37. Sensor rods that track alignment and elevation

- Check for leaks from hydraulic system. This should be done daily. Leaking hydraulic fluid will affect how the machine responds to sensors. Bumps and dips can occur as a result.

4.1.3 Augers/Spreader (Plow)

Illustrated in Figure 39 and Figure 40 (Terex undated,a; G&Z 2008a), augers or spreaders are used at the front of a paver to help distribute the fresh concrete along the width of the paver and control head height over the vibrators. Their effectiveness is a function of the characteristics of the mix and the mass of concrete that is present. Their proper operation is critical, as they may introduce inconsistencies into the slab that will not necessarily be corrected elsewhere on the paver.

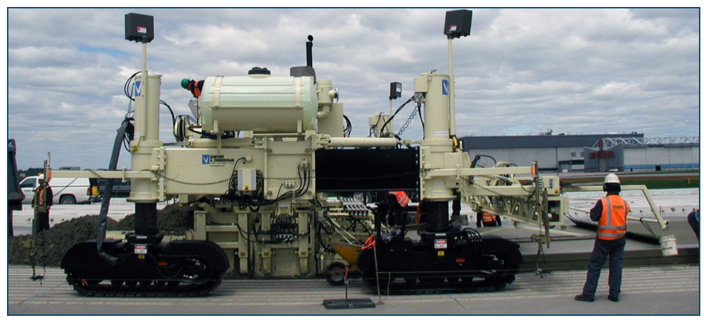

Figure 38. Side forms should be parallel to the stringline

Figure 39. Auger located at the front of a paver

Figure 40. Spreader (plow) at the front of a paver

The following are guidelines to ensure the proper operation of the augers or spreaders:

- Check wear on all augers or spreaders. At the very least, auger flighting should be checked at the beginning of the season and replaced if worn out. Ideally, these components should be checked periodically during the paving season for damage or wear and build-up or otherwise repaired as required. The auger or spreader is essential in spreading concrete and providing an even head in front of the vibrators. If a component is broken or worn out, the concrete will not spread as evenly and it will be difficult to control the head height over the vibrators. If unchecked, this can overload the front of the machine, which may result in a loss in traction or "spinning out."
- Maintain the auger or spreader per the manufacturer's guidelines (Hite 2007; GOMACO undated,a). For example, greasing the bearing seals will prevent grout from penetrating into the auger bearings. If this happens, the grout must be purged as soon as possible. Otherwise, the performance of the auger will suffer and severe damage may occur. This will also lead to the potential for nonuniform placement.
- Keep the auger or spreader clean. These components should be cleaned after every day of paving. Any concrete left that hardens onto the auger or spreader will affect the ability to distribute concrete evenly in front of the vibrators.

4.1.4 Vibrators

While much of the general guidance provided herein includes taking measures to minimize excess vibration, some vibration is required in order for the concrete pavement to consolidate properly during the slipform process. As illustrated in Figure 41 (Terex undated,a), vibrators are an integral part of nearly all pavers, and because they intentionally impart vibration to the concrete, their function should be carefully monitored.

- Check vibrator performance by monitoring the frequency (FHWA 1996). This should be done daily. The best time to check is after a day's paving because the oil is hot and the vibrators are working near their optimal level; cold oil can potentially mask a problem vibrator that is leaking internally. It has been shown that, even when properly tuned, vibrator frequency can drift and eventually vary by several thousand VPM from one another. The frequency must therefore be maintained within job-specific recommendations. Vibrators working outside of the specified range of VPMs (or broken) will cause nonuniform consolidation of the concrete at the location of the vibrator, as illustrated in Figure 42 (FHWA 1996). Adjust or replace vibrators immediately according to the manufacturer's recommendations. Nonuniform consolidation of the concrete at a vibrator will lead to differential shrinkage cracks, higher permeability, loss in smoothness, loss in strength, and ultimately damage to the surface.
- Check the spacing and alignment of the vibrators (FHWA 1996). This should also be done daily, optimally before paving begins, with adjustments made accordingly. The manufacturer will have recommendations on spacing requirements. However, experience with the machine and knowledge of the mix design is essential for determining the best spacing arrangement. Horizontal alignment may be off because of loose bolts. Improper spacing and horizontal misalignment will cause nonuniform consolidation of concrete.

Figure 41. This photo shows a typical line of vibrators mounted to the paver

Figure 42. A difference in vibrator frequency will influence the volume of concrete that is consolidated

- Keep all the vibrators clean. Clean them after every day's paving. Dirty vibrators will be rendered inefficient, cause poor consolidation, and will result in surface defects that negatively affect smoothness.

4.1.5 Strike Off, Floats, and Forming Pan

Prior to the texturing, the last parts of the paver to encounter the concrete are the various floats and pans at the aft side of the paver. Ensuring that these components are in good working order will better ensure a uniform surface. Specific guidance includes the following:

- Keep any/all additional paving kit tools, such as the main conforming pan, oscillating correcting beam or screed, floats, and the finishing pan, clean (Figure 43). Clean these tools after every day's paving. Concrete left to harden onto these conforming finishing devices will affect the height of the concrete that is defined by the main conforming pan. As a result, the finishing devices, such as the finishing pan and oscillating beam or longitudinal float, may not be capable of correcting the change in height. Dips or sags in the main conforming pan surface can occur, and smoothness of the surface will suffer. Hardened concrete on the conforming pan and/or various finishing devices will cause damage to the surface of early-age concrete, require excessive hand work, and result in overworked surfaces by hand finishers (Grogg 2001).
- While automatic longitudinal floats (Figure 44 and Figure 45 (G&Z 2008a; FHWA 1996)) have been used in some instances to improve smoothness, they have also been shown to introduce unintended texture because the reciprocating action displaces mortar at the surface. This is illustrated in Figure 46 (G&Z 2008a).

Figure 43. Forming pan set for a crowned pavement

- Check wear on all of these parts at least weekly. As cleaning is done daily, a quick daily inspection should be done. However, these tools should be inspected more thoroughly at least weekly. A damaged strike off tool will result in too much concrete introduced to the conforming pan, and surface roughness will result. Broken or damaged finishing devices will adversely affect the smoothness of the fresh concrete surface.

Figure 44. Automatic longitudinal float attached to the back of a paver

Figure 45. An alternative chevron-type float attachment for a paver

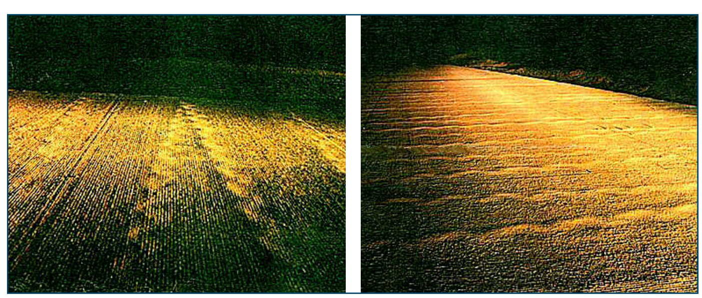

Figure 46. Unintended texture introduced by automatic longitudinal float

4.1.6 Tracks

Due to the repeated impacts of the pads, the tracks of a paver (see Figure 47 (Terex undated,a)) will inherently impart some degree of vibration into the paver and possibly the fresh concrete surface. Proper maintenance and operation is therefore important to minimize potentially adverse texture from being introduced.

Specific guidance includes the following:

- Keep tracks lubricated according to the manufacturer's recommendations. This will help to ensure tracks are running optimally. Tracks not lubricated properly or track links that are "frozen" can result in jerky forward motion, or even damage to the track. Bumps and dips will result within the concrete surface.
- Check track pads and chain tension at least monthly. Ideally, weekly or even daily checks should be conducted. Check the manufacturer's documentation for more specific recommendations. Improper chain tension or worn pads will result in nonuniform placement of concrete.
- Use studs or cleats on tracks if slippage is possible during placement. This is often the case when paving on fine-grained or tender hot-mix asphalt or a lean portland cement concrete base. The paver's ability to achieve traction on its intended riding surface is essential for uniform placement of concrete. If the paver slips, dips and bumps will occur in the concrete.
- Care should be taken when running crawler tracks that are "locked to grade" on adjacent slabs for grade reference. Rubber belting is sometimes used in this case to protect the sawn joints from the track grouser running on the adjacent slabs. In this case, care must be taken that the rubber strips are of the same thickness. Otherwise, unintended texture features may be introduced as a result of the grade changes.

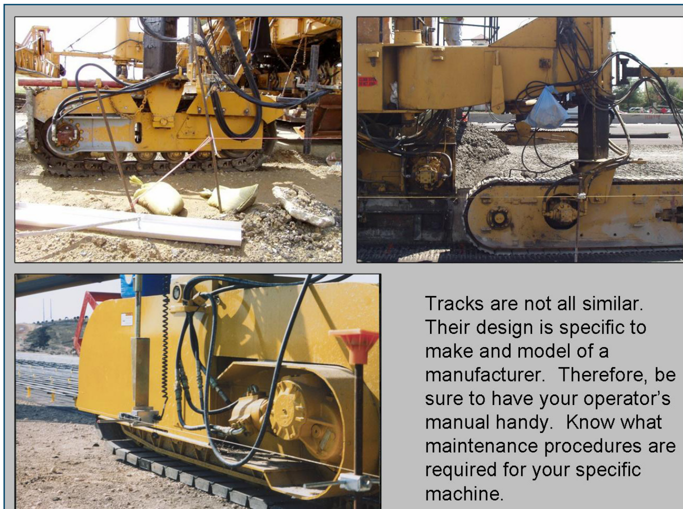

Figure 47. Paver tracks

4.1.7 Miscellaneous

Equipment should be maintained per the manufacturer's guidelines in order to ensure optimum equipment performance. The result will be a more uniform concrete surface.

4.1.8 Cleaning Techniques

Maintaining the cleanliness of the paver and its tools is very important. Cleaning should be done on a daily basis after every pour. Several effective techniques for cleaning the paver are as follows:

- Use release agents.
- Use high pressure spray.
- Steam clean. While normally done for seasonal cleaning, it does provide the most benefit , and should be a consideration for more routine operation.

4.2 Texture Equipment

In most concrete paving operations, some variant of a texture machine follows the paver. One instance in which a separate texture machine might not be used in paving operations is when construction conditions are too tight and the width of the machine cannot be accommodated. For obvious reasons, the texture machine is an important part of paving operations, and one that will affect the final surface characteristics.

Said simply, the texture equipment applies the final texture to the surface of the paved concrete. Quite often, liquid curing compound is applied from this equipment, when specified. Figure 48 illustrates a Guntert & Zimmerman texture-cure machine, and Figure 49 shows a similar device manufactured by GOMACO.

Most texture machines consist of a truss-like frame that extends the width of the concrete slab (see Figure 50 (GOMACO 2006)). Above the truss frame are mounted the engine, curing tank, and operator's controls. Attachments to the truss frame are used for texturing and curing operations. The machine is powered by a combustion engine (often diesel) and maneuvers on either wheels or tracks depending on the make and model (GOMACO 2006).

Like the paver, unwanted vibrations can result from texture equipment if not properly maintained. If these vibrations are transferred into the fresh concrete, unintended texture may be introduced. The following sections

Figure 48. Texture-cure machine manufactured by Guntert & Zimmerman

Figure 49. Texture-cure machine manufactured by GOMACO

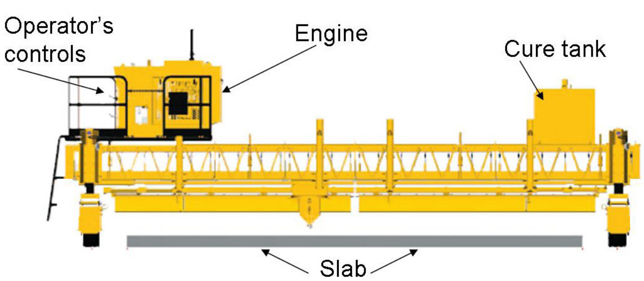

Figure 50. Schematic of texture-cure machine

discuss general maintenance guidelines with respect to the effect they might have on the resulting concrete pavement surface.

It is important to note that the following guidelines do not necessarily cover all components of a typical texture machine. Instead, the guidelines include those parts that, when neglected, will likely affect the pavement surface. Be aware that these are just general recommendations, as each texture machine comes with its own specific maintenance routines supplied by the manufacturer and usually found in the operator's manual. To be sure maintenance is done properly and completely, operators must be familiar with these manuals.

4.2.1 Frame and Engine

The frame of a texture machine can be described as a self-propelling truss-like box. Maintenance for the frame should start with daily checks to make sure nothing is broken. The frame should also be kept as clean as possible by removing any excess concrete after paving operations have completed for the day. Do not let the concrete set onto the machine; keeping the frame clean will ensure longevity of the equipment and better performance. Establishing even a simple maintenance routine will not only have the potential for improving surface characteristics, but also save money in the long run, because parts will not have to be replaced as often when kept clean. Such a routine should at a minimum include greasing all bogie axles, carriage wheels, and fittings weekly. If the texture machine runs rough, or exhibits "jerky" motion of any kind, it will ultimately affect the texture applied to the surface of the concrete slab (Meskis&Cantu 2008; GOMACO undated,c). Steering problems should be addressed rapidly and corrected.

Bolts are used to hold the texture machine frame together and keep the texture equipment attached. A tendency exists for these bolts to loosen as a result of regular use, and they should therefore be checked on a daily basis. Loose bolts can result in an unstable frame and/or rattling that, in turn, create vibrations. Often, the operator's manual will have a chart that lists each bolt and how much torque should be applied. Over-tightening can be harmful to the equipment; therefore, it is imperative to follow the manufacturer's recommendations when tightening bolts (Meskis&Cantu 2008).

Fuel, oil, and coolant fluid levels on the power plant should be checked daily. Fuel should be filled at the end of each day's paving to help prevent condensation in the tank. Oil should be changed on a regular basis, ideally every 3–4 weeks (Terex undated,b; GOMACO undated,c). This will keep the engine running smoothly and minimize unwanted vibrations. Sudden increases of vibrations from the engine, puttering noises, or "jerky" movement may be indicators that an oil change is due. Finally, check and change the air filter weekly, if not daily (Terex undated,b; GOMACO undated,c).

4.2.2 Tracks or Tires

Like the paving machine, texture machines (depending on make and model) ride on tracks (two or four tracks; see Figure 51 (GOMACO 2006) or tires (see Figure 52 (GOMACO 2006)). The tracks or tires are guided either by an operator or by sensors set to follow the stringline for the paver. As a result, the same sensor sensitivities experienced on a paver are also an issue with texture machines; the sensors should therefore be maintained in a similar fashion.

Tracks should be maintained by checking the condition of the links weekly and keeping tracks lubricated daily or per the manufacturer's recommendations. Frozen links can cause serious problems for grade control. The elevation jacks (legs), tracks, and individual wear pads should be routinely checked and adjusted accordingly, ideally every 2–3 weeks. This will help minimize vibrations that can transfer from the tracks to the frame and ultimately into the fresh concrete. Poorly maintained tracks can result in a bumpy or jerky forward motion, which will cause a nonuniform texture.

If tires are used, pressures should be checked daily (GOMACO undated,c). Tires can be either foam or air filled. If not inflated properly, tires may result in poor steering performance of the texture machine and a nonuniform application of texture.

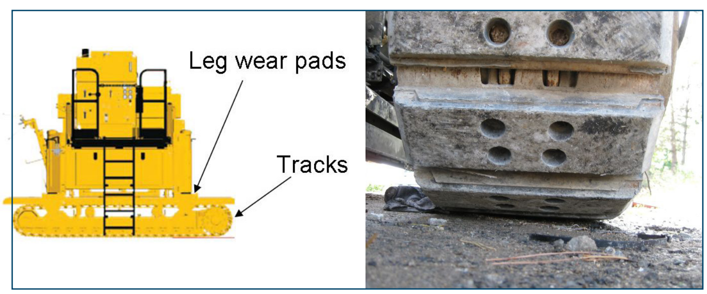

Figure 51. Side view of texture-cure machine on single track, and close up of track

Figure 52. Side view of texture-cure machine on tires, and close up of tire

4.2.3 Texture Attachments

Equipment for texturing the concrete surface is attached to the frame of a texture machine. The equipment (directly or indirectly) moves across the surface of concrete pavement. Specific attachments are used, including supports for a burlap or turf drag, a special tool to provide a broom-like finish, and tining rakes. In all cases, it is essential that the attachment be maintained in the best condition reasonably possible. Maintenance for the texture attachment includes ensuring that it moves as intended and that it is kept as clean as reasonably possible. The specific movement of the attachment will depend on the type of texture being applied. Figure 53 (G&Z 2008a) and Figure 54 show texture equipment for turf and burlap drag, respectively.

Texturing attachments are used to lower and lift the texturing medium from the surface of the concrete pavement.

Figure 53. Turf drag attachment on a texture machine

Figure 54. Burlap drag attached to a work bridge

This movement is often assisted by use of the leg barrels, hydraulic cylinders that fix an attachment to the frame, or a combination of both. It is important to check for leaks in the hydraulic system daily and to change the hydraulic fluid and filters per the manufacturer's recommendations. A poorly maintained hydraulic system may result in nonuniform movement of the texture attachment (or even failure, in extreme cases of contamination) (GOMACO undated,c). As a result, the texture applied to the surface of the concrete pavement will not be consistent.

When used, maintaining the tining rakes is important. Imparting a tined surface involves pulling the brush of individual tines at an angle across the surface in either a longitudinal or a transverse direction. As the tines are raked across the surface, the pavement is effectively grooved. The angle of the tine rake to the pavement, distance the rake is lowered, and the cleanliness of the individual tines can all affect the as-constructed pattern. Daily maintenance should include checks to ensure that the angle remains constant, lowering distances remain constant, and the condition of the tines remain consistent. Connecting bolts should be appropriately tightened, and broken or damaged tines should be replaced as needed. Texture cart tracks and carts should be maintained to the manufacturer's tolerances in order to optimize performance.

Tining in the longitudinal direction will require that the tining rakes be adjusted to the crown of the pavement. These adjustments are usually made possible by hydraulic control systems. The hydraulic fluid and filters for these controls must be routinely changed (at least annually) to ensure the rakes can be adjusted properly (GOMACO undated,c). Figure 55 illustrates a texture machine on tracks with a longitudinal tining rake attachment.

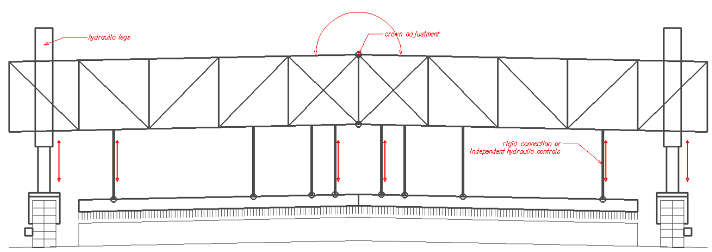

Figure 55. Schematic of longitudinal tining texture equipment

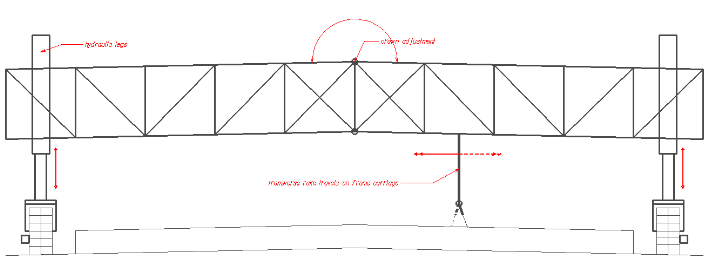

Figure 56. Schematic of transverse tining texture equipment

The transverse tining movement (Figure 56) is controlled by a chain and must also be maintained. Transverse tining rakes must be able to come into and out of contact with the surface and must be able to move in a transverse direction over the slab. Checks to make sure the chain is greased, not broken, and has enough tension should be done daily before construction begins. At a minimum, the condition of the chain should be checked weekly. If neglected, the rake will not move smoothly and the tined grooves will not be uniform (Meskis&Cantu 2008).

Tining attachments should be kept clean. Built-up hardened concrete on the attachments decreases the longevity of the equipment and results in an uneven application of texture to the surface. The equipment should be well cleaned after every day's paving.

4.2.4 Curing Equipment

Curing equipment is often affixed to texturing equipment and warrants special consideration, especially since good curing practices are paramount to the durability of the pavement surface. Curing equipment typically includes a spray bar, curing compound tank, and a pumping system. The curing compound tank is generally mounted to the top of the machine's frame, but it is directed away from the operator's control panel to avoid getting curing compound overspray on the operator. The spray bar is located along the backside of the equipment. Spray nozzles are aligned along the spray bar and aimed at the surface of the concrete slab. Hoses connect the tank and the spray bar to the nozzles. Cure is applied by pumping compound liquid through the spraying nozzles (GOMACO undated,c). Figure 57 shows curing equipment on the texture machine.

Figure 57. Illustration of curing equipment on texture-cure machine following good practice

There are a few general maintenance procedures to keep in mind. Pressure gages should be checked daily, the nozzles kept clean, and the cure strainer changed weekly. The pressure used to pump the curing compound from the tank and through the nozzles should not exceed the manufacturer's recommended thresholds. Otherwise, damage to the pump system can result, and the system may require replacement.

The nozzles should be kept clean, as dirty or clogged nozzles will result in poor curing compound application (GOMACO undated,c). Examples of poor practice are illustrated in Figure 58. Poor curing will, in turn, leave the surface of the concrete vulnerable to early-age damage (Taylor 2006). It is a good idea to soak the nozzles after every day's use, but at minimum after every couple days. Use a soak solution recommended by the manufacturer to keep them working properly longer. The spray bar bearings should be greased at least weekly to maintain the bar's ability to rotate properly (GOMACO undated,c).

4.2.5 Summary

Maintaining the texture machine is essential for constructing the intended surface on a concrete pavement. There are different makes and models of texture machines, but the basic schematic is the same: a truss-like box that extends the width of the pavement slab and rides (forwards and backwards) on either tracks or wheels. Attached to the frame are the engine, operator's controls, and various surface texturing attachments, including those for drags and tining. Curing equipment is also often an integral part of this equipment, in which case a cure tank and spray bar are included. The frame and all of its attachments require proper maintenance to minimize the potential of unwanted vibrations and thus texture in the pavement surface.

The general maintenance described herein focuses on daily checks, regular fluid and filter changes, and keeping all parts as clean as possible. However, the recommendations provided are only general in nature, and the operator's manual should be consulted for more detail specific to the make and model of the equipment being used. It should be noted that the timing for routine maintenance will depend on the duty cycle of the texture machine. General recommendations suggest maintenance routines based on average workloads. If there is a peak paving time and the work load is greater than normal, maintenance operations are required more often.

Figure 58. Poor curing practice

4.3 Diamond Grinder

Diamond grinding machines specific to large-scale concrete pavement resurfacing applications are not widely manufactured. Instead, contractors that specialize in the process tend to build their own equipment. Typical equipment is illustrated in Figure 59 and Figure 60 (Kraemer 2008).

For the most part, general maintenance and upkeep of the equipment is left to the expertise of the operator. There are often no formal operator manuals. Operators learn on the job and therefore "just know" when the equipment is not working as it should; there are often no explicit daily, weekly, or annual maintenance routines.

Figure 59. A grinding large-scale concrete pavement resurfacing operation

Figure 60. Grinder used for large-scale concrete pavement texturing operations

Troubleshooting is based on that same expertise (Aamold 2007). A consensus exists, however, about the importance of the machine's head in the quality of the final product, along with the type and frequency of more general "common" maintenance routines (Aamold 2007; Knish 2007).

4.3.1 Grinding Heads

The head of the machine is very important. It consists of blades that are spaced according to the type of concrete being ground. Stronger concrete with harder aggregates requires smaller spacing between blades. Each blade is tipped with diamond fragments that are strong enough to grind grooves into the concrete. The condition of the individual blades and their spacing has an impact on the performance of the grinding machine and, ultimately, the vibrations transferred into the concrete (Aamold 2007; Knish 2007).

Blades should be checked daily (see Figure 61). Any blades that are obviously worn or damaged should be replaced. If worn blades are left in place, the surface will not experience an even grinding application. Job quality will suffer. Damaged blades may lead to damaged surfaces if not replaced. It is a good idea to measure uniformity at least weekly. To do so would require measuring the depths of each blade's respective groove in the concrete surface (Knish 2007). More frequent checks may be necessary if grinding concrete with hard aggregates and/or operating long days.

The spacing of blades should also be checked daily and after every blade replacement. Spacing should not change arbitrarily during the course of a job. It should be based on the demand inherent with the concrete being ground.

Figure 61. Measuring blade wear

4.3.2 General Maintenance

Improving the quality of diamond grinding often can be achieved through proper maintenance of the equipment. General guidance for better practice in this regard includes the following:

- Check all fluid levels daily.
- Inspect the machine frame and all welds for cracks. Repair as appropriate.
- Check drive wheels annually for cracks or tears and fix as necessary. See Figure 62.
- Check profile (bogie) wheels (see Figure 63). Replace when half the urethane life is gone, if cracked, or when flat. Be sure bearings are within specifications, and check brackets for cracks, loose pins, or loose bushings.
- Be sure all bushings, pins, and bearings are not loose. Check at least annually.
- Be sure the vacuum system is working appropriately. Recommended as an annual check, this should be observed more regularly and addressed as soon as possible if something is not working properly. The effectiveness of the vacuum system will affect the longevity of the blades.

Figure 62. Cracked drive wheel

Figure 63. Bogie wheels supporting grinding head should be checked periodically

- The hydraulic system should be thoroughly inspected annually. Pumps and motors should be removed and sent for cleaning. Disassemble pump drives to replace bearings and seals. Replace gears and shafts as needed and reassemble. Drain the hydraulic tank, open the tank, clean it, and refill it. Replace bad hydraulic hoses and fittings. Start up the machine, set pressures, and inspect for leaks.
- The engine (Figure 64) should also undergo annual maintenance. Take and send oil samples to lab. Change all fluids and filters. Inspect the engine for oil leaks and fix any that are found. Replace the rear main seal. Inspect the exhaust system for leaks, rust, and cracks. Inspect engine belts and replace as needed. Inspect the low oil pressure shutdown system, switches, and other instrumentation for proper operation and fix as needed.

4.3.3 Hydraulic Systems

Regarding hydraulic systems, some practical guidance includes the following (GOMACO undated,b):

- Keep it clean! Dirt kills the hydraulic system. Change filters regularly as per the user's manual. Filters should be changed at least once every 50 hours or 2 weeks.
- Prevent dirt from getting in downstream of the filters.
- Dirt is able to infiltrate downstream of the filters when repairs are made out in the open.
- If repairs are necessary, provide as much protection as possible from even the slightest of breezes.
- Rough handling of components during assembly and disassembly could cause chipping, resulting in diminished service life.
- Over tightening bolts could also cause chipping and reduce service life. Be sure to follow the user's manual on proper tightening techniques.
- Replace leaking seals or cylinders as necessary. Otherwise, damage to vital components may result. Refer to the user's manual for ideal maintenance routines for specific models.

Figure 64. 500 HP, 15 liter engine used to power grinding head

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Appendix A: Tine Length, Angle, and Height

Assuming that the concrete delivered to the project has consistent density, workability, and gradation, the texture as constructed can possibly be controlled by adjustments to the angle of the tines, tine length, and the height of the tines relative to the pavement.

The surface area of the tine that is in contact with the slab is one factor that determines the depth of surface texture. The primary methods for controlling the surface area of the tine that is in contact with the pavement surface are as follows:

- Adjusting the length of the tines.
- Adjusting the angle of the tines.
- Adjusting the height of the tines with respect to the pavement surface.

It is difficult to quantify the degree to which each of these adjustments will impact the texture depth, due to the interaction of the material properties and the environment. However, the general relationship between these adjustments and texture depth can be stated qualitatively for a given concrete mix and environmental conditions. These relationships, listed independently, are as follows:

- As tine length increases, texture depth decreases.
- As the angle of the tine decreases, texture depth decreases.
- As the height of the tine relative to the pavement surface increases, texture depth increases.

Figure 65 illustrates these relationships.

It should be noted that although these factors are listed independently, actual texture dimensions are a function of all three factors combined.

The interrelationship of tine length, angle, and height is illustrated in Figure 66.

Note that the tine angle values in Figure 65 and Figure 66 are for illustration purposes only. No quantitative data exists to establish the limits of maximum or minimum tine angle.

Appendix B: Texturing Better Practices Checklist

In addition to the guidance provided in Figure 3 and Figure 4, the following checklists can be used to establish priority items to check during construction.

Mixture Design/Mix Proportioning—check the following for consistency:

- Gradation
- Paste volume
- Mortar volume
- Check bleeding of concrete per ASTM C 232

Pre-Construction

- Drag

  Check for adequate drag width—for full paving width coverage.

  Check for adequate drag length to attain nominal depth.

  Clean drag material—remove latency from previous days' paving or replace material.

  Ensure that replacement drag material is on hand—should be readily available.

  Confirm that all texturing and curing equipment has been properly maintained and is ready for uninterrupted operation.

  Check that the correct amount of curing compound is on the project and available at the correct refill interval.

  Ensure adequate drag connection and support.

- Tine

  Check the tine spacing—confirm that nominal spacing is met.

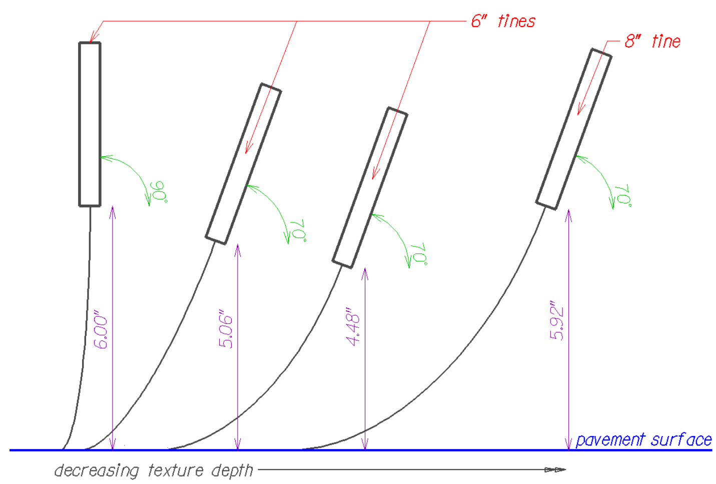

Figure 65. Relationship of texture depth to tine length, angle, and height

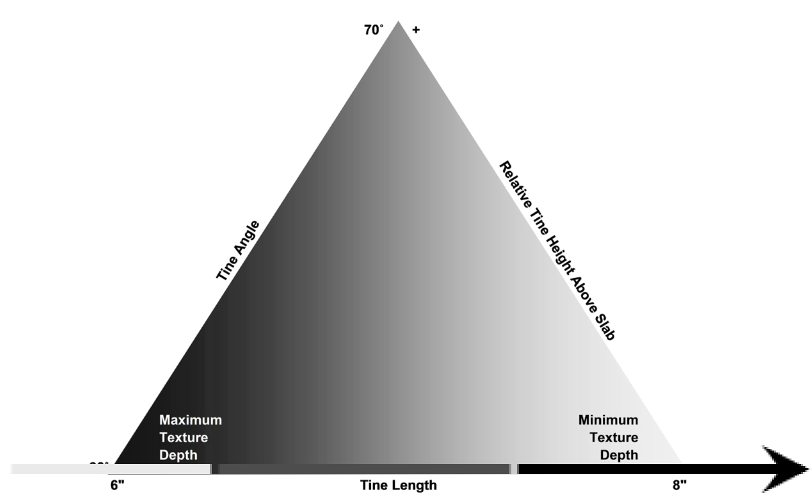

Figure 66. Combined effect of tine length, angle, and height

Check that all tines are the same length.

Confirm that all tines are straight.

Clean the tines.

Mark super-elevation transitions to allow for operator to make crown adjustments as appropriate.

Confirm that all texturing and curing equipment has been properly maintained and is ready for uninterrupted operation.

Check that the correct amount of curing compound is on the project and available at the correct refill interval.

Construction

- Drag

Moisten the drag material before commencing the texturing operation, especially burlap.

Finish texturing before the surface of the pavement experiences any drying, and then apply curing compound without delay.

Remove excess buildup of mortar as necessary to maintain the intended texture.

Replace the drag material as necessary to ensure desired texture.

- Tine

Operate the texture equipment at a consistent speed.

Adjust tine angle, length, and downward pressure to achieve the nominal texture depth required.

Finish texturing before the surface of the pavement experiences any drying, and then apply curing compound without delay.

Adjust the timing of texture operations as weather and mixture conditions change.

Clean paste buildup off of the tines as necessary.

Adjust elevations through super-elevation transitions.

Replace bent or broken tines as necessary.

Table 1. Checklist of equipment operation and maintenance activities.

Paver Parts	Daily	Weekly	Monthly	Annually
Frame	- Clean well after day's work. - Check and align paving kit before paving. - Check and tighten bolts and connections. - Check the engine.			
Sensors	- Check alignment. - Check gages. - Dampen appropriately.			
Auger	- Check for and replace broken blades. - Clean well after day's work. - Grease and check bearing seals.			
Strike off, floats, plows	Clean well after day's work.			
Vibrators	- Check spacing and horizontal alignment before paving. - Check individual speeds at end of day's paving. Replace broken ones; adjust those that vibrate too fast or too slow.			
Racks/Tires	- Check track lubrication. - Check tire pressure. - Assess trackline traction requirements.			
Miscellaneous (Dependent on manufacture's recommendations.)	- Lube fittings - Check all fluid levels and make sure they are full before paving.	- Check the battery and alternator. - Change oil in gearboxes. - Change engine oil and filters.	- Change breather filter element in hydraulic oil tank. - Check the belts.	Change oil and filters for hydraulic system.

Appendix C: Definitions

The following include some simple definitions of a few of the unconventional terms used in this document:

- A-weighting—a commonly used means to adjust sound levels in such a way as to more accurately represent human sensitivity to different frequencies. Levels that are A-weighted are sometimes reported in units of A-weighted decibels, or dBA.
- CPSCP—the Concrete Pavements Surface Characteristics Program, a collaborative effort that has been jointly funded by the FHWA, ACPA, National Concrete Pavement Technology Center, and various state DOTs under Pooled Fund TPF-5(139). The objectives have included development of a catalog of surface characteristics of existing concrete pavements, exploration of innovative techniques for improving surface characteristics, and development of guidance to improve concrete pavement surface characteristics.
- Decibels (dB)—the units of sound level. This is a logarithmic transformation of sound pressure or sound intensity with a basis of a reference sound level.
- Frequency—how often sound pressure impulses (or texture) repeat. When expressed in Hertz (Hz), this is simply frequency in impulses per second. The inverse of this is wavelength, which for sound is sometimes reported in seconds and, for both sound and texture, can be reported as a distance in inches or feet.
- Noise—any sound believed to be objectionable. This is therefore a subjective thing.
- On-Board Sound Intensity (OBSI)—a measurement technique that evaluates tire-pavement noise closely by placing specialized microphone probes near the tire-pavement contact area. Measurements are commonly performed at 60 mph using an ASTM F 2493 Standard Reference Test Tire. OBSI is currently standardized by AASHTO as method TP 76.
- Sound level—a scientific measure of the pressure, intensity, or power of a sound.
- Traffic noise—noise generated by a traffic stream. This includes all sources generated by the traffic, including propulsion noise, tire-pavement noise, and aerodynamic noise.
- Tire-pavement noise—noise generated by tires rolling along a pavement surface.

Appendix D: For More Information

The following reports and websites provide practical information that was not included herein for the sake of brevity.

Reports

To better understand tire-pavement noise…

FHWA, *The Little Book of Quieter Pavements* (Rasmussen 2007)

To better understand good practices for concrete paving…

CP Tech Center, *Integrated Materials and Construction Practices for Concrete Pavement* (Taylor 2006)

Websites

National Concrete Pavement Technology Center

http://www.CPTechCenter.org

Concrete Pavement Surface Characteristics Program

http://www.SurfaceCharacteristics.com

American Concrete Pavement Association

http://www.ACPA.org

International Grooving & Grinding Association

http://www.IGGA.net