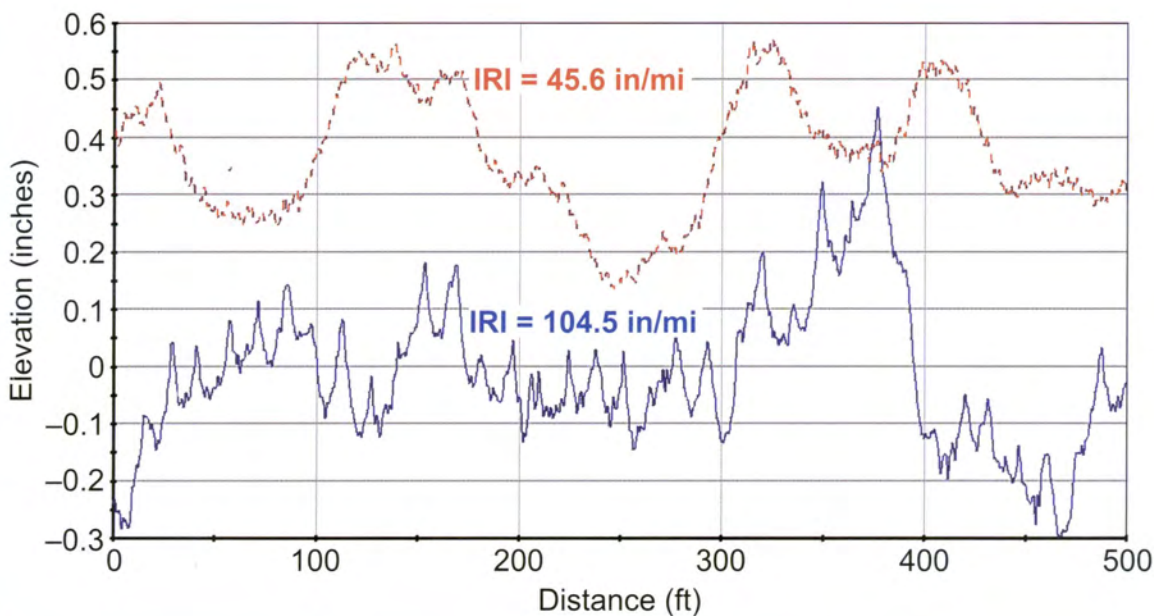
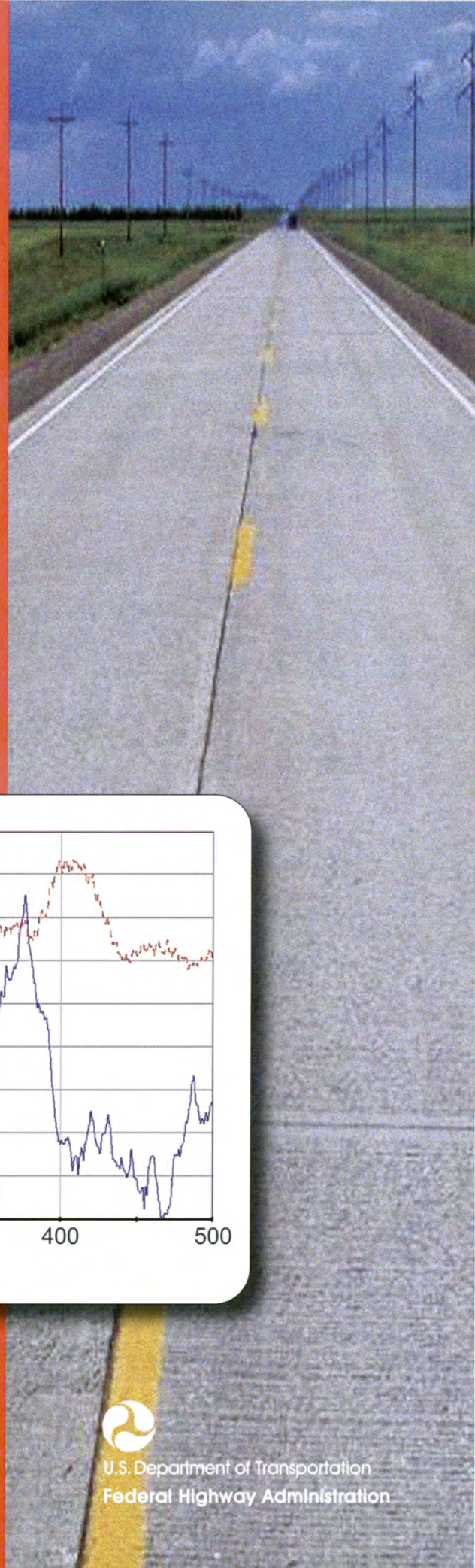


PCC PAVEMENT SMOOTHNESS

Characteristics and Best Practices for Construction



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16. Abstract Smoothness is an important feature of modern pavement facilities. To begin with, it is one of the most important factors that the traveling public uses to judge the quality of a roadway, as it contributes to the safe and efficient movement of vehicles. Furthermore, high levels of initial smoothness have been shown to influence the future smoothness of the pavement and have also been linked to increases in pavement life. In recognition of the importance of pavement smoothness, many State Highway Agencies (SHA) have adopted smoothness specifications that require minimum levels of smoothness for new pavement construction, with some specifications incorporating significant incentive/disincentive provisions. Although considerable information exists on the mechanics of measuring and expressing pavement smoothness and on the construction of smooth PCC pavements, that information is dispersed among numerous sources. It is the purpose of this document to provide concise technical guidance on the "best practices" for measuring, expressing, specifying, and achieving smoothness for PCC pavements. Particular emphasis is given to the PCC pavement construction activities that affect the resulting smoothness (and the resulting quality of the pavement).					
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH					LENGTH				
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
AREA					AREA				
in ²	square inches	645.2	square millimeters	mm ²	mm ²	square millimeters	0.0016	square inches	in ²
ft ²	square feet	0.093	square meters	m ²	m ²	square meters	10.764	square feet	ft ²
yd ²	square yards	0.836	square meters	m ²	m ²	square meters	1.195	square yards	yd ²
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi ²	square miles	2.59	square kilometers	km ²	km ²	square kilometers	0.386	square miles	mi ²
VOLUME					VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL	mL	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft ³	cubic feet	0.028	cubic meters	m ³	m ³	cubic meters	35.71	cubic feet	ft ³
yd ³	cubic yards	0.765	cubic meters	m ³	m ³	cubic meters	1.307	cubic yards	yd ³
NOTE: Volumes greater than 1000 L shall be shown in m ³									
MASS					MASS				
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.202	pounds	lb
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")	Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact)					TEMPERATURE (exact)				
°F	Fahrenheit temperature	5 (F-32)/9 or (F-32)/1.8	Celcius temperature	°C	°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
ILLUMINATION					ILLUMINATION				
fc	foot-candles	10.76	lux	lx	lx	lux	0.0929	foot-candles	fc
fl	foot-Lamberts	3.426	candela/m ²	cd/m ²	cd/m ²	candela/m ²	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS					FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N	N	newtons	0.225	poundforce	lbf
lbf/in ²	poundforce per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	poundforce per square inch	lbf/in ²

*SI is the symbol for the International Symbol of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.



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INTRODUCTION

Importance of Pavement Smoothness

Pavement smoothness is probably the single most important indicator of performance from the standpoint of the traveling public. Where technical terms such as faulting, spalling, and corner breaks hold little meaning to the typical road user, everyone understands the difference between a smooth and rough road. National surveys conducted of road users list smooth pavements as a top highway characteristic (NQI 1996; Keever, Weiss, and Quarles 2001). Because of the public's focus on smoothness, any improvements made in both the initial and long-term smoothness of a roadway should lead directly to greater customer satisfaction.

Smoothness also plays a significant role in the construction, functionality, and performance of roadways. In construction, for example, many State Highway Agencies (SHA) have adopted specifications that require minimum levels of smoothness for newly constructed pavements, with some specifications incorporating significant incentive/disincentive provisions to try and ensure that SHAs get what they want. Achieving a high level of initial smoothness during construction is often considered a surrogate for overall paving quality, signifying that the contractor made a strong commitment in all key areas of the paving operation.

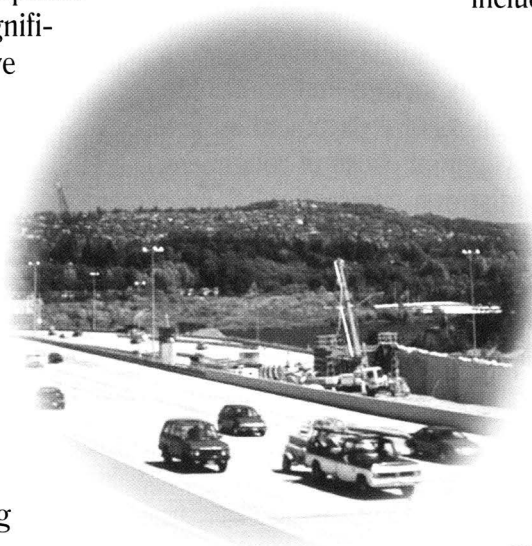
The functionality and performance of smooth pavements is also better than that of rough pavements. In addition to increased user satisfaction, smooth pavements allow more efficient movement of vehicles and are safer to operate on; they also provide for increased fuel efficiency (Sime, Ashmore, and Alavi 2000). Furthermore, high levels of initial smoothness have been shown to have a significant effect on the future smoothness of pavements, and have also been linked to increases in pavement life (Smith et al. 1997).

Smoothness Defined

“Smoothness” and “roughness” are often used somewhat interchangeably when describing the surface characteristics of a pavement, but they actually describe opposite ends of the same scale. Smoothness is probably used more frequently, perhaps because of its more positive connotation, but roughness is what is actually measured on a pavement. Smoothness is simply the absence of roughness. Other terms often used to describe pavement smoothness include evenness or trueness.

As defined by ASTM (2001) roughness is described as:

The deviations of a surface from a true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic loads, and drainage, for example, longitudinal profile, transverse profile, and cross slope.



Of primary importance to roadway users are *longitudinal* deviations along a longitudinal profile. Roughness is the summary of the deviations that occur over a longitudinal profile of fixed length. These deviations in the profile consist of many different wavelengths (horizontal distance between deviations) and amplitudes (vertical height of the deviation) (see figure 1).

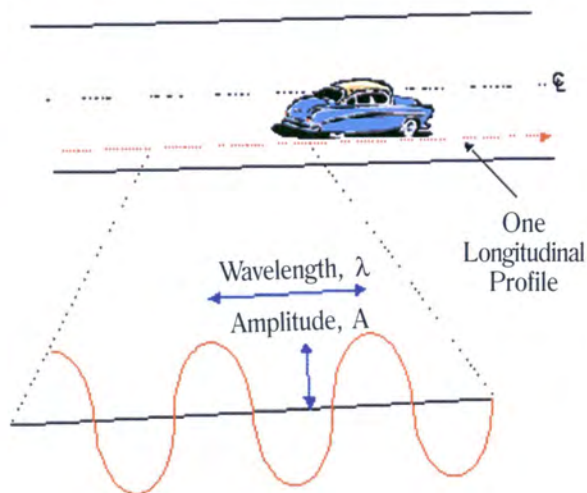


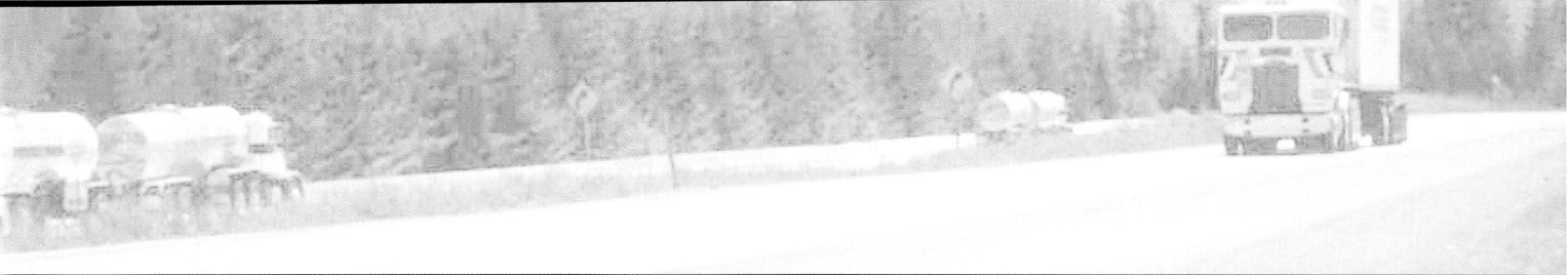
Figure 1. Sampled longitudinal pavement profile and describing characteristics.

There are many factors that contribute to the roughness of a pavement surface. The most common cause of roughness is pavement distress; common portland cement concrete (PCC) pavement distresses that contribute to roughness include joint faulting, spalling, deteriorated transverse cracks, and punchouts. Over time, swelling soils or frost

heave can also contribute to the roughness of a pavement. Roughness can also be “built in” during construction because of such factors as variability in the base and subgrade, inconsistency in the paving operations, the presence of embedded items in the pavement, and random construction deviations.

Purpose and Overview of Document

Clearly, pavement smoothness is important to both users and owner agencies alike: a smooth pavement indicates that a safe and comfortable ride is being provided to highway users, and that pavement is likely to perform better and reflect more positively on the owner agency. However, achieving smoothness on a new pavement does not just happen; it requires a deliberate and concerted effort on the part of the contractor. Furthermore, in assessing pavement smoothness, it is important to understand how roughness is measured and expressed. Although considerable information on these topics exists, it is dispersed among numerous sources. Therefore, it is the purpose of this document to provide technical guidance on the “best practices” for measuring, expressing, specifying, and achieving smoothness for PCC pavements. Only the key points and recommendations are presented in this document, with more detailed information found in the documents provided in the reference list.



MEASURING AND SPECIFYING SMOOTHNESS

Equipment

Over the years, SHAs have used many different devices for measuring pavement smoothness, ranging from simple straightedges that indicate very localized deviations in the pavement surface, to high-speed, inertial profilers equipped with laser sensors that record actual elevation measurements along the pavement. Furthermore, it is quite common for agencies to use one device to perform construction quality control and a separate device for network monitoring of in-service pavements. For new PCC pavement construction, the profilograph has been the device of choice to monitor initial pavement smoothness, as it can be operated as soon as the PCC pavement can be walked on, and thereby provides more rapid feedback to the paving contractor. However, new lightweight profilers have been recently developed that can also operate on PCC pavements at an early age.

For the monitoring of network roughness conditions, devices capable of traveling at highway speeds are used. These devices enable an agency to collect a significant amount of roughness data on their entire pavement network, thus providing additional information that can be used in monitoring the performance of their pavements and in planning and programming pavement rehabilitation activities. More and more agencies have adopted inertial profilers for this activity (Karamihas et al. 1999). It must be emphasized that at least in the past, the different devices that were used varied considerably in terms of their output, accuracy, repeatability, and the pavement roughness characteristics that they measured.

Descriptions of the different types of roughness-measuring equipment are provided in the following sections.

Profilographs

Profilographs consist of a rigid beam or frame with a system of support wheels that serve to establish a datum from which deviations can be measured using a “profile” wheel located at the center of the unit (Woodstrom 1990). The profile wheel is linked to a mechanical strip chart recorder, which produces a permanent record of the deviations along the traveled path. Although this output does not represent a true pavement profile, it can be analyzed using manual or computerized techniques to compute an overall “profile index” and to indicate the location of bumps or “must grinds.”

Two basic models of profilographs are in use: the California profilograph (of which there are several manufacturers) and the Rainhart profilograph. The California profilograph uses between four and twelve wheels mounted on a 7.6 m (25 ft) frame, whereas the Rainhart device uses twelve support wheels evenly spaced along its 7.5 m (24.75 ft) frame at offsets up to 560 mm (22 in) so that no wheel follows the same path (Smith et al. 1997). Consequently, the datum for the Rainhart device is established over the entire length of the unit and over a width of 1,118 mm (44 in), whereas the datum for the California type is established near the end of the 7.6 m (25 ft) beam (Smith et al. 1997). The profilograph measures wavelengths between 0.3 and 23 m (1 to 75 ft), amplifying or attenuating wavelengths that are factors of the profilograph

length (Smith et al. 1997). Figure 2 shows a California-type profilograph.



Figure 2. California-type profilograph.

The amplification and attenuation of the pavement profile has led several people to question the validity of this device for construction control. Kulakowski and Wambold (1989) reported on this amplification/attenuation issue as shown in figure 3. This figure demonstrates that the California profilograph attenuates the amplitude of wavelengths between 3 and 5.2 m (10 and 17 ft) and amplifies the amplitude of wavelengths between 2.3 and 3 m (7.5 and 10 ft) and between 5.2 and 12.2 m (17 and 40 ft).

Profilographs are used exclusively for construction quality control, and because of their light weight can be used on the pavement the day after paving. Based on extensive work done in California in the 1940s and 1950s, the profilograph has continued to evolve and in the 1990s gained widespread use in PCC pavement construction as more and more highway agencies placed controls on initial pavement smoothness. Currently, 38 SHAs specify the profilograph for measuring initial pavement smoothness (Rizzo 2001).

Advantages and disadvantages of profilographs include the following (Woodstrom 1990; Smith et al. 1997):

- Advantages:
 - ◆ Lightweight.
 - ◆ Low cost.
 - ◆ Provides analog trace of pavement deviations.
 - ◆ Identifies location bumps and must grinds.
 - ◆ Easily operated and understood by field personnel.
- Disadvantages:
 - ◆ Slow operating speeds (3 to 5 km/hr [2 to 3 mi/hr]).
 - ◆ Lack of precision.
 - ◆ Does not provide a true pavement profile.
 - ◆ May not relate to user response.

Response-Type Road Roughness Measuring Systems

Response-type road roughness measuring systems (RTRRMS) measure the dynamic response of a mechanical device traveling over the pavement at a specified speed (Woodstrom 1990). Either an automobile or a standardized trailer may be used for this purpose, with measurements taken from the vertical movements of an axle with respect to the vehicle frame. Common RTRRMS devices include the Mays Ride Meter, the Bureau of Public Roads (BPR) Roughometer, and the Portland Cement Association (PCA) Roadmeter.

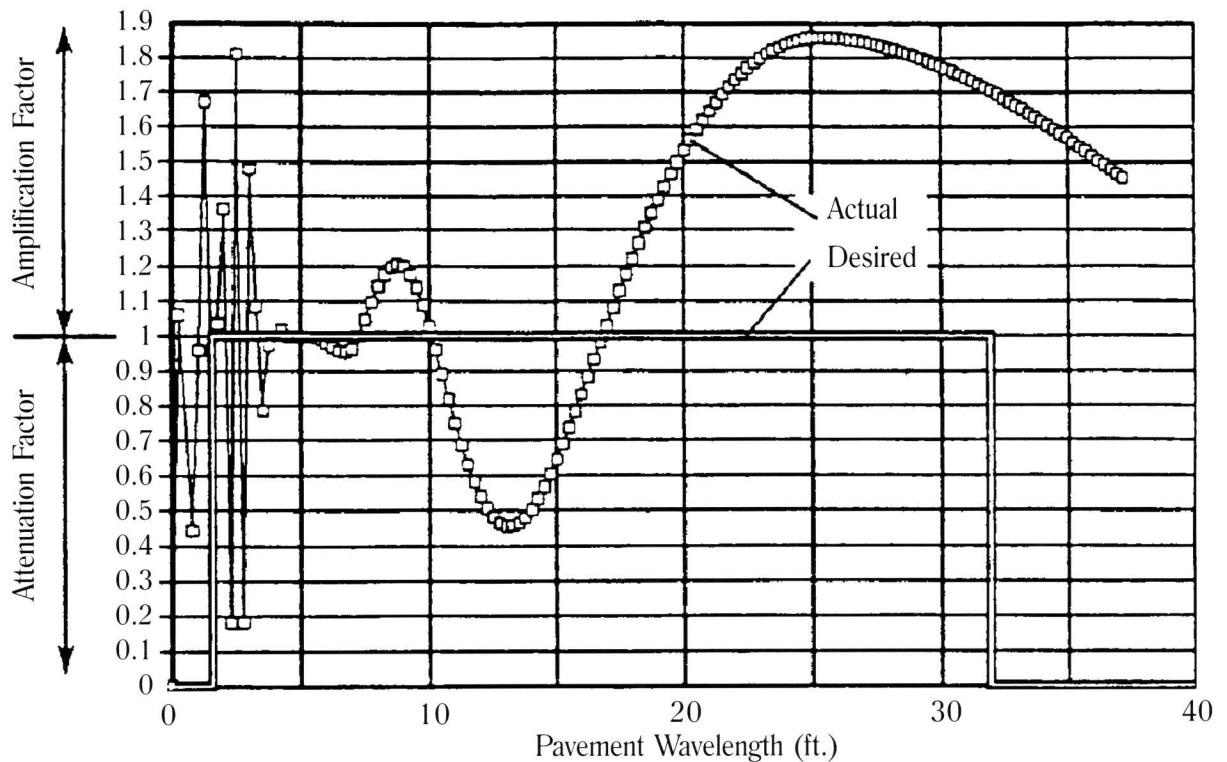


Figure 3. Desired and actual frequency response of a 12-wheel California style profilograph (Kulakowski and Wambold 1989).

RTRRMS are primarily used to collect data over highway networks as part of an agency's pavement management system, although a few agencies have used these devices for controlling smoothness on new pavement construction (Woodstrom 1990). Although no agencies are using RTRRMS for construction control of PCC pavements, four agencies do use this type of device for new hot mix asphalt (HMA) pavement construction (Rizzo 2001). Due to significant variability in their measurement of roughness, these devices must be regularly calibrated.

Major advantages and disadvantages of RTRRMS include the following (Woodstrom 1990; Smith et al. 1997):

- Advantages:
 - ◆ Initial and operating costs are low.
 - ◆ Data are normally collected at a speed of 80 km/hr (50 mi/hr).
 - ◆ Reasonably accurate and reproducible roughness data can be collected if the device is properly and regularly calibrated and maintained.
- Disadvantages:
 - ◆ Roughness results are greatly affected by the mechanical system (vehicle type, suspension system characteristics, tire pressure, and vehicle weight distribution) and the speed of travel.

- ◆ Devices measure the dynamic effect of roughness, but do not define the true pavement profile features.
- ◆ Devices require frequent, costly, and time-consuming calibration over a range of speeds and pavement roughness levels.
- ◆ Comparability of roughness results between devices is poor.

Inertial Road Profiling Systems

Inertial road profiling systems (IRPS) are high-speed devices that produce a scale reproduction of the “true” pavement profile. These devices use noncontact sensors (ultrasonic, laser, infrared, or optical) to measure the relative displacement between the vehicle frame and the road surface. These displacements are sampled at designated intervals to produce a simulation of the actual road profile, which can then be analyzed in many different ways to yield information on the roughness and rideability of the pavement.

IRPS are commonly used for pavement management surveys because of the accuracy of the results and the rapid rate at which the data can be collected. According to a recent survey, almost all SHAs have now moved to the use of IRPS for network pavement monitoring, and most of these devices are using laser sensors (Ksaibati et al. 1999).


Traditionally, IRPS are not used for construction smoothness control because of their relatively high cost and the magnitude of the load that such a vehicle would place on new PCC pavements (Woodstrom 1990). However, the last decade has seen significant

advancements in the development of lightweight inertial profilers that are capable of being used on PCC pavements shortly after paving (Swanlund and Law 2001). As shown in figure 4, these devices are golf cart or all-terrain type vehicles that have been equipped with a profiling system (Perera and Kohn 2001); they can travel up to 32 km/hr (20 mi/hr) and can easily be used within the confines of construction projects (PennDOT 2001). Six states now specify IRPS for construction ride quality control (Rizzo 2001).

The primary advantage of IRPS is that they yield relatively accurate and repeatable profile measurements that can be used to compare projects to one another and can be used for the calibration of RTRRM systems (Smith et al. 1997). In addition, profiles obtained from IRPS can be used to simulate output from other devices, such as the profilograph, thereby providing some continuity with current smoothness control devices. Disadvantages of IRPS include their relatively high capital and operating costs (for full size systems) and the



Figure 4. *Lightweight profiler (Swanlund 2000).*



complexity of the electronic and data acquisition systems.

Expressing Pavement Smoothness

Many different roughness indices have been used to mathematically express the roughness of a pavement. These are common expressions of the total vertical deviations over a length of pavement, and hence have units of mm/km (in/mi). These indices are often tied to the use of a specific device, such as profile index output from the profilograph or the Mays Ride Number output from the Mays Ride Meter.

Currently, the two most common roughness indices are profile index (PI) and international roughness index (IRI), with the former commonly used for quality control of new PCC pavement construction and the latter primarily used for network monitoring. This use of two different roughness indices to describe initial and long-term roughness of a pavement makes it difficult to track the performance of pavement sections, particularly as it has been shown that there is little correlation between these two indices (Perera and Kohn 2001). Because of this, some highway agencies have now adopted the IRI for new pavement construction acceptance testing so as to provide a “cradle-to-grave” roughness statistic for monitoring pavement performance (Perera and Kohn 2001).

Profile Index

The profile index is used for quality control of initial pavement smoothness by agencies using a profilograph. It is based on the trace of pavement profile and is computed using

either manual or computerized reduction procedures. In computing the PI, essentially the sum of all individual high and low values exceeding a pre-determined elevation is computed over a set pavement length and then normalized to a per km (per mile) basis (ACPA 1990). Historically, the pre-determined elevation is based on a 5 mm (0.2 in) blanking band for California profilographs, meaning that any deviations that fall within that blanking band are not counted. Some agencies, however, have adopted a zero blanking band because certain wavelengths that just fall within the 5 mm (0.2 in) blanking band often were found to produce noticeable, high-frequency vibrations (Hancock and Hossain 2000).

Figure 5 shows a profilograph trace and illustrates the way that the PI is computed, assuming a 5 mm (0.2 in) blanking band (ACPA 1990). Deviations within the blanking band are not computed, but those above or below the blanking band are counted (to the nearest 2.5 mm [0.1 in]) and summed over the length of the pavement segment.

The profile index can also be computed from actual pavement profiles obtained from IRPS devices through computer simulation modeling. There is a big advantage in measuring actual pavement profiles in that almost any roughness index can be computed from that profile.

Since profile index is derived from the profilograph (or from simulated profilograph plots), it is limited by the frequency response of the profilograph. Roughness felt by the road user from wavelengths in excess of 15 m (50 ft) is not reflected in the profile index.

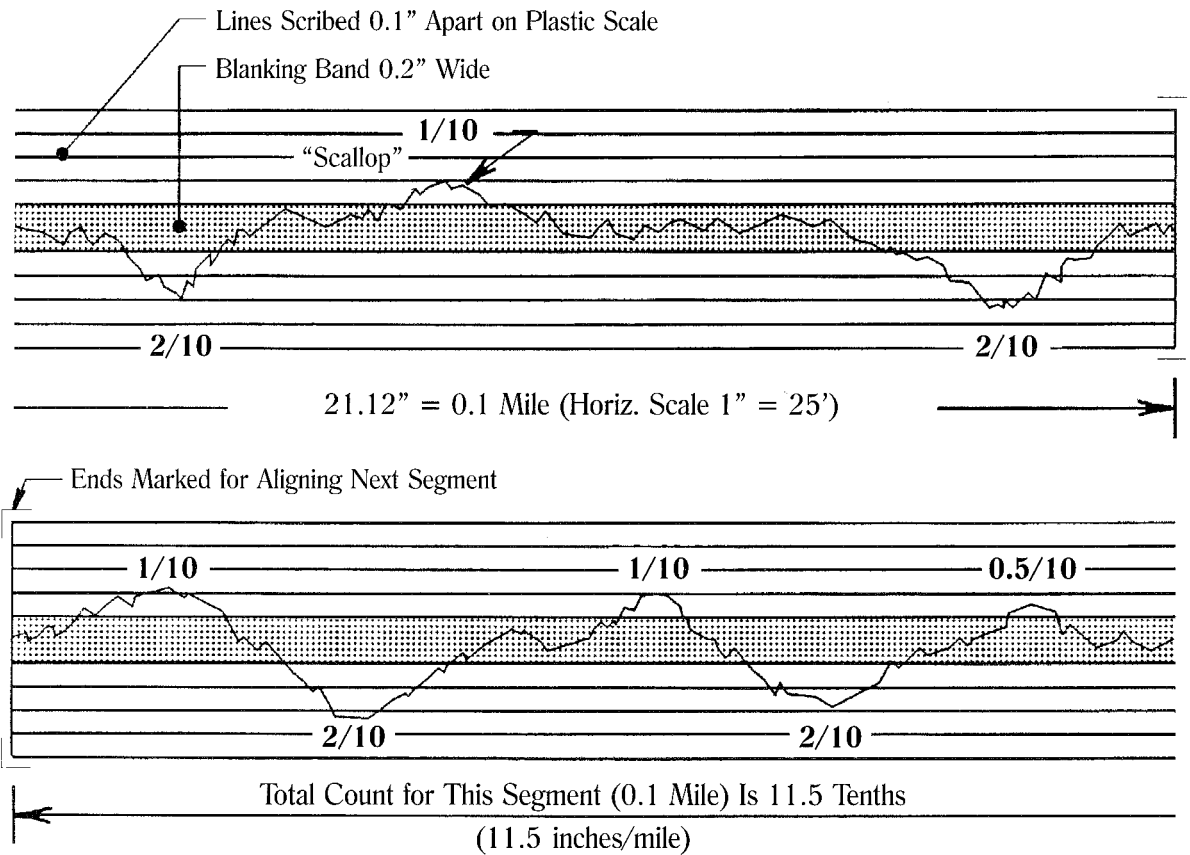


Figure 5. Profilograph trace and PI computation (ACPA 1990).

International Roughness Index

The IRI is the most widely used index used to describe the roughness of highway pavements (Perera and Kohn 2001). It is currently being used in the U.S. for reporting roughness in the FHWA's Highway Performance Monitoring System (HPMS), which tracks the condition of pavements nationwide. IRI has also become the standard for monitoring roughness of pavement sections in FHWA's Long-Term Pavement Performance (LTPP) program.

The IRI was developed in 1982 as part of a World Bank effort to establish correlation and calibration standards for roughness measurements (Sayers 1995). It is based on a quarter-car mathematical model that calculated the suspension deflection of a simulated mechanical system with a response similar to a passenger car, as shown in figure 6 (Sayers and Karamihas 1998). Typical IRI ranges by different classes of road are shown in figure 7 (Sayers and Karamihas 1998).

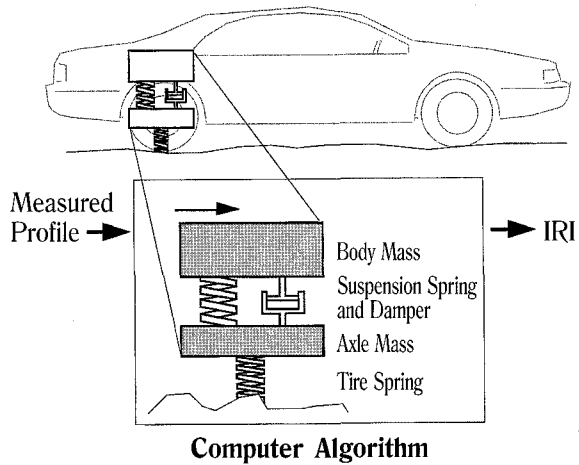


Figure 6. Quarter car simulation used for IRI (Sayers and Karamihas 1998).

The IRI is a property of the true pavement profile, and as such can be measured with any valid profiler (Sayers and Karamihas 1998). Influenced by wavelengths ranging from 1.2 to 30.5 m (4 to 100 ft), the IRI has been shown to describe profile roughness that causes vehicle vibrations and is correlated to user response (Sayers and Karamihas 1998). Furthermore, it has been shown to be reproducible, portable, and stable with time. Sayers (1995) provides details on the calculation of IRI. Free computer software for computing IRI from pavement profiles may be found at <http://www.umtri.umich.edu/erd/roughness/rr.html>.

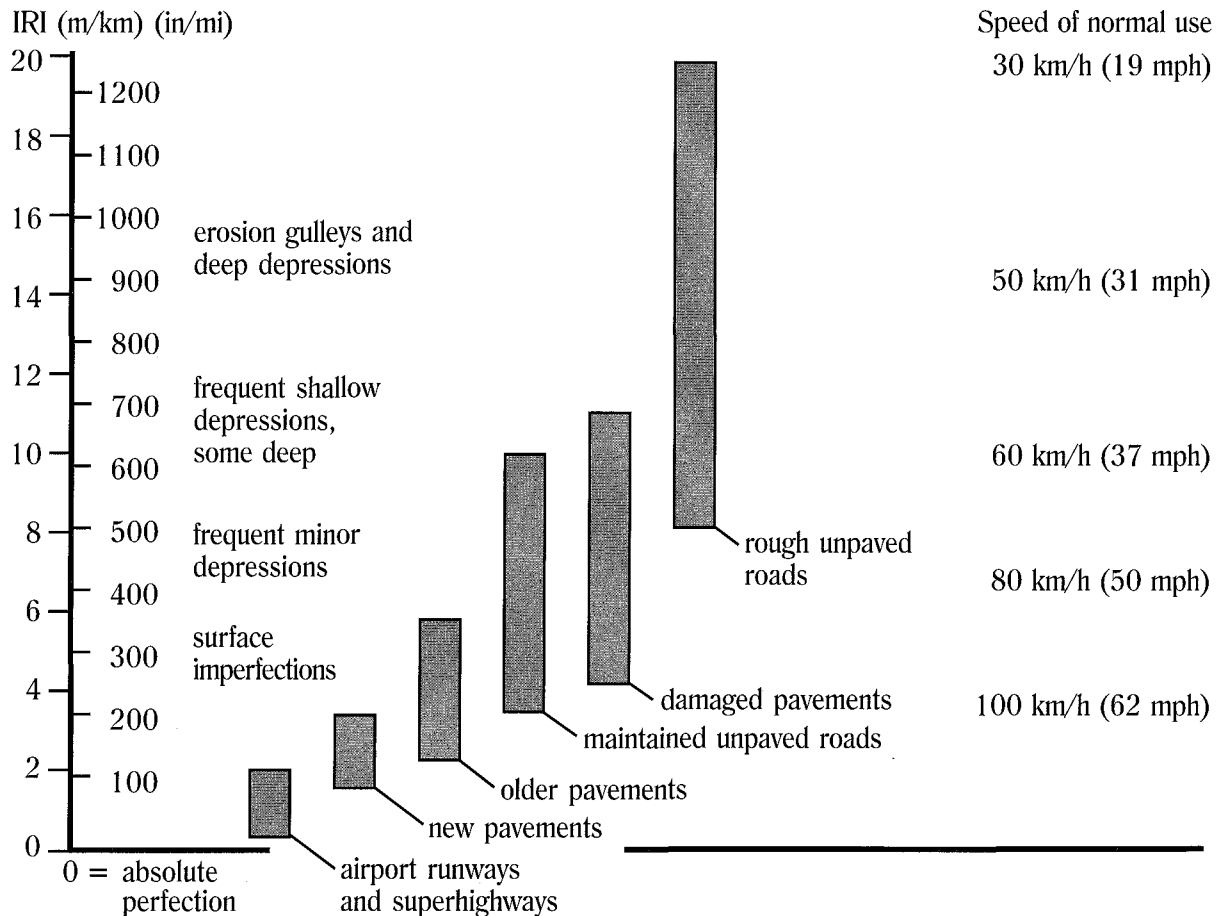


Figure 7. Ranges of IRI by different classes of road (Sayers and Karamihas 1998).

Smoothness Specifications

Highway agencies have increasingly been adopting smoothness specifications for both new pavement and overlay construction. According to a recent survey, 45 of 52 highway agencies (including Puerto Rico and the District of Columbia) currently employ a smoothness specification for new PCC pavement construction (Rizzo 2001). However, these specifications vary widely in terms of the equipment used, the acceptable range of smoothness values, and the inclusion of incentive or disincentive provisions.

Smoothness specifications have been shown to be effective in producing initial smoothness values much higher than those obtained before the implementation of the smoothness specification (Smith et al. 1997). They also were found to reduce the overall variability of initial smoothness values (Smith et al. 1997).

Smoothness specifications typically include provisions on the following elements:

- **Equipment used to measure pavement smoothness.** The type and properties of the equipment to be used in the evaluation are described here. As previously indicated, 38 highway agencies are currently using profilographs for new PCC pavement construction, and six states now specify or allow the use of IRPS for measuring initial pavement smoothness (Rizzo 2001). Several other states are currently studying this technology and developing specifications to utilize this equipment.
- **Specified surface tolerances.** The surface tolerances (in terms of the smoothness statistic being used) are specified in terms of the smoothness statistic being used for the particular project. Common target surface tolerances for the PI are 0.11 m/km (7 in/mi) when using a 5 mm (0.2 in) blanking band and 0.47 m/km (30 in/mi) when using a zero blanking band; common target surface tolerances for IRI are 0.95 to 1.26 m/km (60 to 80 in/mi).
- **Smoothness evaluation procedures.** This includes information on the location of the smoothness testing and the evaluation procedures to be used in interpreting the resultant smoothness data.
- **Corrective actions.** Information on identifying areas requiring corrective action are described in this section. This includes limits on bumps and remedial measures.
- **Pay adjustments.** If included, this section describes positive pay adjustments based on smoothness levels that are higher than specified (incentives) or negative pay adjustments based on smoothness levels that are lower than specified (disincentives). A pay schedule tied to different smoothness levels is generally provided.

CONSTRUCTING SMOOTH PCC PAVEMENTS

The keys to achieving smooth PCC pavements include education, attitude, and attention to details. All three of these are in the control of the crew involved in the construction of the pavement.

To understand the elements that contribute to PCC smoothness or roughness, one needs to have a basic understanding of the dynamic forces acting on a paver. PCC pavers are very large, heavy machines. This weight is required in order to be able to place a flat, smooth surface for the motoring public. A cubic meter (1.3 yd³) of plastic PCC weighs approximately 2322 kN (5120 lbf). In addition, slipform paving requires a very stiff mix, typically with a slump less than 38 mm (1.5 in). The combination of the weight of the paver and the movement of the PCC mix requires a large amount of tractive force to be developed to move the paver forward.

As the paver places the PCC, vibrators are used to decrease the viscosity of the PCC mix to facilitate the placement and increase the consolidation of the PCC. An auger-spreader at the front of the paver strikes off the PCC to an approximate finished grade of the pavement. The PCC material then flows under the extrusion plate as a final finish is applied to the pavement. A schematic of a paver and the forces that act upon it are shown in figure 8.

As the paver proceeds down the grade, any action that changes the balance of these forces will result in a change in the elevation or angle of attack of the paver and

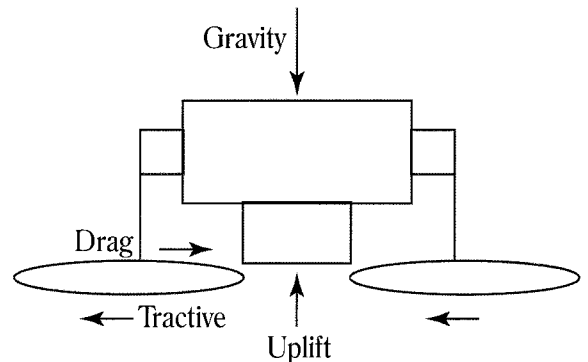


Figure 8. Schematic of dynamic forces acting on a PCC paver.

consequently cause a change in the profile of the PCC pavement. For example, if the vibrators on the paver were to suddenly shut off, the drag and lift caused by the paver traveling over and compacting the plastic PCC would immediately increase. This would lead to an upward movement of the paver. After the paver has traversed a short distance, a new equilibrium of the forces would be established, but the upward bump caused by the vibrator failure would be in place. Likewise, changes in paver speed, PCC viscosity, tractive forces, and so on will all result in changes to the pavement profile, otherwise known as bumps that will be felt by motorists or that must be ground by the contractor.

The following sections outline several of the key construction details necessary for achieving smooth PCC pavements. The general outline of this section follows the *Great Eight* rules for constructing smooth PCC pavements discussed by FHWA (2000).

PCC Materials and Mix Design

The prerequisite for any quality pavement is a well-designed mix consisting of quality materials. Such a mix is not only necessary to aid in the placement of the pavement, but also to ensure the long-term durability of the pavement and the profile. Key items to consider include (CMI 1987):

1. A strong durable stone that is not affected by freeze-thaw cycles.
2. Fine aggregate consisting of a blend of natural and manufactured sands that provide the mix with the necessary workability, strength, and frictional properties.
3. Cement to provide the necessary strength.
4. A balanced water-cement ratio (w/c) considering both the strength of the mix and its workability.
5. Admixtures as required to increase the workability and durability of the mix.

Besides obtaining quality components for the mix, the designer should also be concerned with the interaction of these components in the mix. Both short- and long-term interactions of the components can affect the smoothness of the pavement. No matter how smooth the initial construction, premature deterioration of the pavement surface due to materials problems such as D-cracking, scaling, and alkali-silica reactivity (ASR) will quickly decrease the motorist's satisfaction.

In addition, a long-term factor that affects the roughness is the curling (due to temperature gradients) and warping (due to moisture gradients) of the PCC slab. Certain combinations of coarse aggregate, fine aggregate, and cement may result in slabs that

curl and warp excessively and change the profile of the slab. One of the factors influencing curling is the coefficient of thermal expansion, for which a new test was recently adopted by AASHTO (TP60-00, *Standard Test Method for the Coefficient of Thermal Expansion of Hydraulic Cement Concrete* [AASHTO 2000]). Presently, no test exists to identify mixes that have a higher potential for warping.

Segregation and workability are key factors to consider in the design of PCC mixes. Segregation can cause uneven loading on the paver as well as provide an uneven surface finish. Workability is not only the ability of the mix to be finished but also for the mix to be consolidated sufficiently and to avoid vibrator trails. The mix design needs to be optimized to provide strength, workability, and ease of finishing, all in an economical manner.

In examining SPS sites from the LTPP program, Perera, Byrum, and Kohn (1997) found that jointed reinforced concrete pavement (JRCP) designs with higher compressive strengths and higher water and cement contents had lower initial roughness values. For continuously reinforced concrete pavement (CRCP) designs, lower IRI values were measured for pavements with higher water-cement ratios. The researchers felt that the higher w/c provided an easier mix to finish and consolidate around the reinforcing steel.

Developing an effective PCC mix design is only the beginning of the process. Continuous, rigorous quality control is necessary to ensure that the mix produced by the contractor is uniform and adheres to the mix design requirements. Slump and air content should be continuously monitored, and trucks should be checked to ensure that all wash water has been removed before the PCC is added. Aggregate should be



removed from stockpiles in a manner that maintains consistent moisture contents. Many plant operators use amperage meters for the motors of their mixing drums as a “slump meter” to provide a consistent mix to the paving operation. Delivering an inconsistent mix to the paver will change the hydraulic forces of the pavement acting on the paver and on the final pavement profile.

Grade Control

Stringline

The final profile of any pavement can only be as good as the method used to control it. Automated grade control has evolved over the years from the use of single stringlines to pavers that today use signals from laser levels and global positioning systems (GPS).

The state of practice for constructing smooth PCC pavements is to use two stringlines. The stringline should be constructed of aircraft cable, not nylon string. This allows a higher tension to be applied, thereby decreasing sags in the stringline. To also reduce sagging, supports for the stringline should be spaced at no more than 8 m (25 ft) intervals. Figure 9 illustrates the pavement profile that resulted from staking the stringline at 15.2 m (50 ft) intervals and allowing some sag in the stringline. A repeating cyclic variation in the pavement profile elevation is observed, corresponding to the spacing of the stringline supports. The vertical lines in this figure represent transverse joints spaced at 6 m (20 ft) intervals.

Profile Elevation, mm

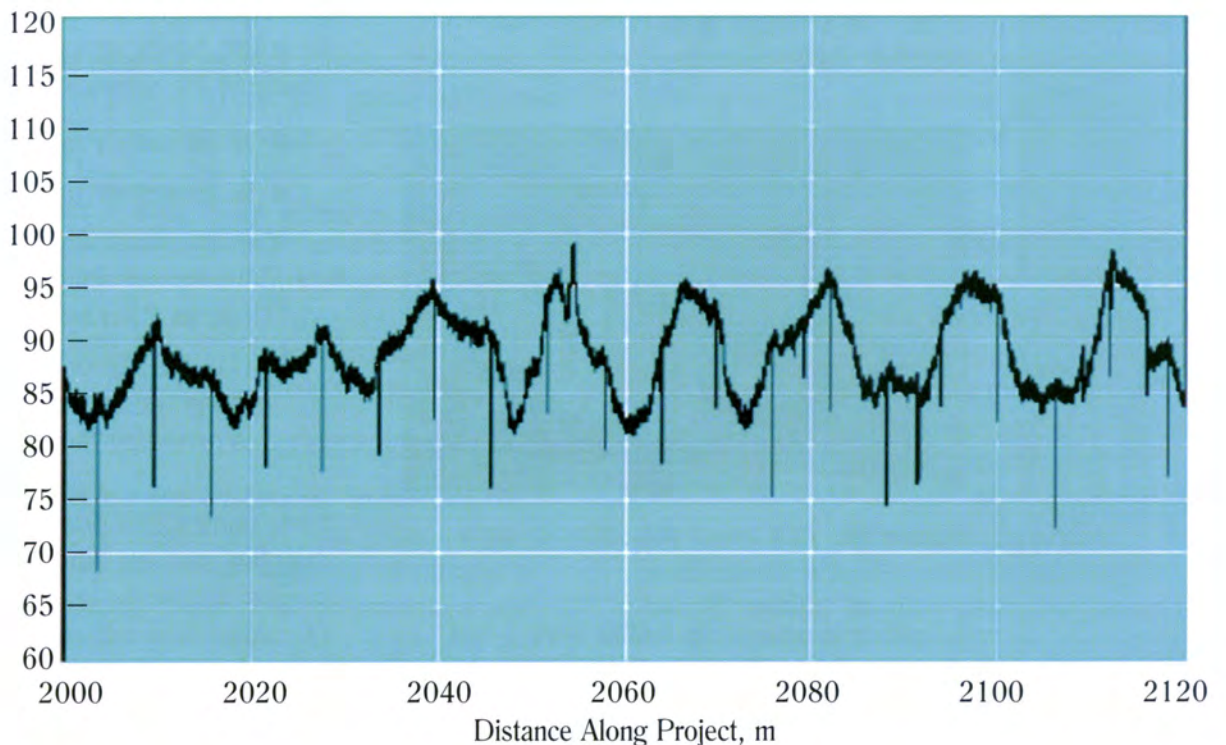


Figure 9. Profile of PCC paving due to stringline sag.



Care also needs to be taken at areas where stringlines begin and end to ensure a smooth transition. The stringline is just as critical when trimming the subgrade as when providing the final pavement profile.

Due to the time and expense necessary to set up a stringline to this level of quality, many contractors want to ensure that it is not disturbed during construction. For this reason, the stringline may be placed well outside the limits of the paving. Extension arms, or even trusses, are then used to move the sensors from the paver to the stringline. Offsetting the stringlines also avoids the problems of trucks and other paving equipment deflecting the stringline. A loaded tandem dump truck may cause a 2.5 mm (0.1 in) deflection in the stringline if the wheels pass within 0.6 m (2 ft) of the stringline support posts. An example of an offset stringline is shown in figure 10.



Figure 10. PCC paver with offset stringline.

As with mix design, the initial work is but the beginning. The stringline needs to be continually monitored and maintained. Construction personnel should continually “eyeball” the stringline to ensure that

straight grades and smooth transitions are being used. Common problems to be aware of include:

- An object is placed on the stringline.
- Workers bump the stringline when crossing it.
- PCC delivery operations move the stringline.

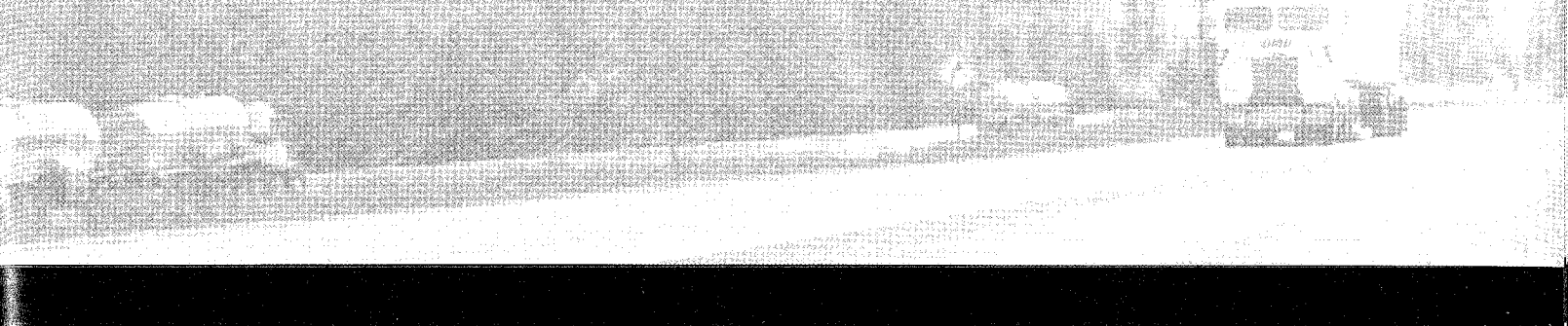
If a problem is detected during the “eyeball” inspection of the stringline, surveying equipment should be used to check the grade of the stakes and stringline. It takes a very experienced eye to correct a stringline through only a visual inspection.

Sensors

Automatic sensors should be checked at the beginning of the project and throughout the entire paving process. Key items to include in the review of the sensors are:

- Is the sensor operating?
- Is the sensor properly connected?
- Is the sensitivity and delay on the sensor set properly to avoid overreaction by the paver?
- Has the sensor been correlated to the grade so the paver or trimmer is providing the proper elevation?

Some contractors prefer to run off of one stringline and use automated controls to provide transverse grade control. An alternative is to use stringlines to trim the subgrade and then use the trimmed subgrade to control the grade for the trimming of the base and grade control of the paving process. The theory is that the “wheelbase” of the



paver smoothes out any abrupt transitions built into the subgrade. Some contractors have used long skis, similar to those used in HMA paving, to facilitate this operation.

Design Features

Certain geometric design features complicate the issue of staking and constructing a smooth pavement. These include the longitudinal grades, horizontal curves, superelevation transitions, intersections, bridges, and railroad crossings.

Longitudinal grades in excess of 3 percent can affect the dynamics of the interaction between the paver and the PCC because the PCC is either pushed uphill or it flows downhill away from the paver. Steep grades also change the angle of attack of the screed and strike-off plates, changing the lift on the paver.

Horizontal curves with a radius less than 305 m (1000 ft) can also create difficulties in achieving smoothness. Curves with tight radii tend to have steep superelevations. Closer staking of the stringline supports may be required to provide smooth transitions through the curve. Stringlines supports as close as 1.2 m (4 ft) have been used by contractors to construct curves with these radii and meet smoothness requirements (ACPA 1990).

Superelevation transitions provide another challenge, especially on multi-lane urban freeways. Not only must the elevations of the outside edges of the pavement change to provide the needed cross slope, but the paver operator must also be inserting or removing crown from the pavement. Electronic features on new pavers have improved this operation and have made

these transitions more gradual than when performed manually. Once again, proper staking and a decreased distance between stringline supports are helpful in providing a smooth transition.

Bridges, railroad crossings, and intersections can also adversely affect the ability to obtain a smooth pavement surface. In some cases, the paving contractor is also responsible for these appurtenances. In other cases, the contractor merely inherits the work of others and must work within those existing constraints. Surveying of the bridge deck or intersection and some field engineering can help to obtain the best possible profile. Removal of the pavement crown and maintaining drainage also complicates the layout issue. Many agencies are still struggling with whether or not to include intersections, railroad crossings, and bridge decks in the profile surveys. While contractors state that these items are out of their control, the traveling public must traverse these transitions and deal with the constructed profile.

Care is also required in placing pavements against curb and gutter. Since the gutter line must be matched for proper drainage, it controls the profile of the PCC pavement. Contractors should take as much care in staking and constructing the profile of the curb and gutter as they do the pavement itself.

Manholes and inlets can be especially troublesome when it comes to achieving a smooth profile. In many cases, the pavement surface needs to be "warped" to meet manhole box outs and other drainage structures. Minimizing the inclusion of utility structures in the pavement will benefit ride and eliminate road closures in the future due to utility work.



Pavement Foundation

A stable, smooth pavement foundation is critical for constructing and maintaining a smooth PCC pavement. At the time of construction, the foundation is critical in supplying a firm construction platform. Perera, Byrum, and Kohn (1997) and Khazanovich et al. (1998) found that PCC pavements constructed on granular subgrades or on subgrades with higher modulus of subgrade reaction (k) values had lower roughness levels over time than those constructed on weaker, fine-grained soils. There is some belief that poor subgrade support can be offset by the construction of a thick, high quality base.

Subgrade

The subgrade provides a stable platform so that the base can be placed without deforming. Generally a subgrade with an in-place CBR of 6 or higher is considered sufficiently stable for the construction of the base. The subgrade is then trimmed to provide the grade necessary for placement of the base. While the smoothness of the subgrade and base are not normally specified, any abnormality in the subgrade and base will likely be reflected in the PCC pavement.

Base

As with the subgrade, the base must provide both a smooth and stable work platform for the paver. The base serves multiple functions in the pavement structure. It provides long-term structural support for the PCC pavement, a foundation for attaching dowel bar baskets, and stable tracklines for the paving equipment. Extending the base 0.9 m (3 ft) beyond the edge of the pavement provides

this stable trackline. If a stable trackline is not used, more corrections by the automated grade control are required, which induces almost constant movement of the paver's legs and increases the opportunities to induce roughness in the pavement.

Construction of the trackline has been a controversial issue in the PCC paving industry for years. The position of contractors has been that the owner should specify and pay for the materials necessary to construct stable tracklines so a smooth pavement may be placed. The owner's position is normally that the base will only be constructed 0.3 m (1 ft) outside the edge of the pavement. The owner expects the contractor to place any additional material required for constructibility at the contractor's expense.

With the introduction of incentives, specifying an adequate trackline should ensure the owner of equal bid terms among the contractors and a better quality product. Figure 11 shows a contractor checking the profile of the trackline prior to PCC paving.



Figure 11. Contractor checking profile of trackline prior to paving.

Paving Speed and Delivery Rate

A contractor's ability to match delivery of PCC with the forward speed of the paving train is crucial in producing a pavement with a smooth profile. The first step is to always keep the paver moving. It is preferred that the paver move at a constant speed to reduce changes in the hydraulic forces acting on the paver from the plastic PCC. Slowing the paver down is preferable to stopping the paver.

To keep the paver moving, the contractor needs to ensure that there is an adequate supply of delivery vehicles that are coordinated with the production rate of the plastic PCC. The contractor also needs to coordinate the delivery vehicles, somewhat like an assembly line. Having a queue of delivery vehicles either at the plant or at the paver creates a potential problem in achieving the desired level of smoothness. In the first case, it is likely that there is no PCC being delivered to the paver if all the trucks are at the plant; in the latter case, PCC sitting in the trucks for extended periods of time may cause different degrees of workability, creating problems for both the paver and the finishers, as well as possibly compromising the long-term durability of the PCC.

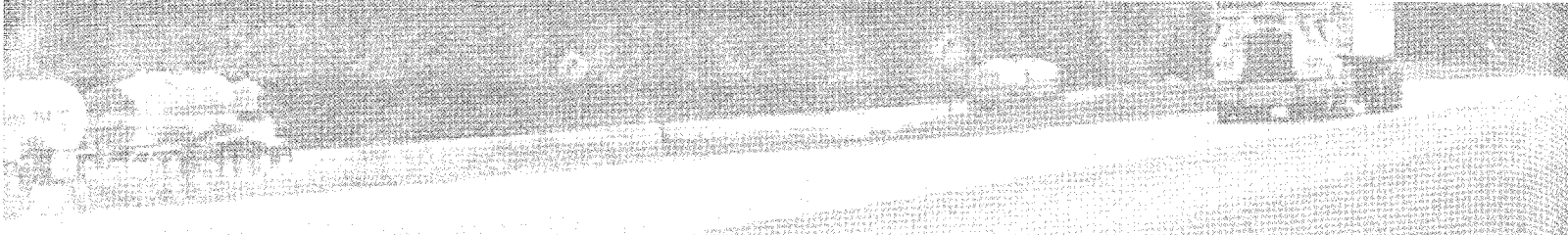
To achieve the smoothest pavement profile, a constant speed is necessary. If the paver speed is changed to accommodate inconsistent delivery, project personnel should review the amount of vibration energy being applied by the paver to keep from over- or under-consolidating the PCC.

PCC Head In Front of Paver

A paver is designed to shape, consolidate, and finish a PCC pavement, and is not meant to move mounds of plastic PCC. In previous sections, the need for uniform delivery of a consistent mix has been discussed. The key here is to place that mix on the base in a fashion that maximizes the ability of the paver to perform its function. The mix should be uniformly spread across the base. Enough material should be placed to keep a constant head above the strike-off bar. If the head of material varies in front of the paver, it will change the nature of the hydraulic forces acting on the bottom of the paver, causing either a rise or dip in the pavement profile. If this head change occurs over a long period of time, the change in elevation may be negligible. However, if the supply of concrete suddenly slows and the operator keeps the paver moving forward at the same speed, this sudden decrease in PCC head will likely cause a noticeable dip in the pavement.

Keeping a reasonable head of PCC is also important to control the drag on the paver. If the force required to move the paver forward becomes too great, the tracks can begin to slip and tear at the tracklines, which will change their profile, and may be reflected in the pavement profile.

Segregation is also a concern with the delivery and placement of the PCC. Belt placers have a tendency to segregate the mix transversely across the pavement. Coarse



aggregates are thrown, while the fines and paste fall directly beneath the end of the conveyor. This segregation will not only affect the performance of the pavement but may also require extra finishing and differential uplift on the paver; both may affect the ride of the pavement. Placing a chute at the end of the belt may minimize this problem. End dumping PCC on the grade may also result in segregation and may result in a less uniform supply of PCC. With end dumping, the operator must take more care to uniformly spread the PCC transversely across the grade.

Many contractors use one or two spreader-placers in their paving trains to minimize many of these placement concerns. The spreader-placers provide a uniform head of concrete for the paver to consolidate and finish. The paver operator can concentrate on matching his speed to delivery, consolidation, and the profile of the pavement. The spreader operators concentrate on providing a uniform, nonsegregated mix. The key to remember is that a paver is a finishing machine, not a bulldozer.

Embedded Items

Embedded items, such as reinforcing steel, tie bars, and dowel bars, can also present challenges in obtaining a smooth pavement. These items represent potential discontinuities in the pavement that can lead to the development of either dips or bumps in the pavement surface. For example, if the presence of dowel baskets disrupts the consolidation of the PCC, the PCC later could settle and create a dip. Alternatively, if the paver applies too much pressure as the PCC is extruded from the back of the paver, the dowel basket

could be deflected downward. The basket then rebounds upward after the paver has passed, resulting in a bump in the pavement.

In reinforced PCC pavements (especially CRCP) reinforcement ripples can be created if the vibrators are allowed to come in contact with the reinforcing steel. The reinforcing bar then vibrates and creates a ripple in the surface of the finished PCC behind the paver.

These items can be checked with the finish straightedge behind the paver. If surface variations are found, the method of vibration needs to be modified.

Minimal Hand Finishing

If the paver has done its job (as discussed in the previous section), only minimal hand finishing should be required. In many cases, the finished profile of the pavement is worsened, not enhanced, by hand finishing. Hand finishing should be kept to edging, surface sealing with a bullfloat, and checking the pavement profile with a 3 to 7.6 m (10 to 25 ft) straightedge.

Careful observation of the finishing operation may reveal potential problems. For example, if the bullfloat finisher is not working the surface in a uniform manner to get it to seal, it may be an indication that segregation is taking place. Edge slump repairs may be an indication of PCC workability problems, nonuniform delivery of concrete, or segregation. In some cases, profiles of the finished pavement surface show surface waves that were likely induced or augmented by the improper use of the straightedge. Figure 12 illustrates the

proper use of a straightedge in checking the pavement profile.



Figure 12. Using a 7.6 m (25 ft) straightedge to check the profile of a pavement.

Curing and Environmental Conditions

The environmental conditions at the time of paving can also play a key role in the resulting profile of a newly constructed pavement. Hot, dry, windy conditions can lead to difficult finishing and other workability issues with the PCC.

Timely application of the curing medium is crucial in maintaining the profile that has been constructed. As soon as the water and cement are mixed in the drum, two forces are at work to consume the water: hydration of the cement and evaporation. A lack of timely and effective curing may lead to excessive evaporation and initial warping of the slab. Not all curing methods and compounds control evaporation equally. Further information may be found in a report prepared by the Minnesota Department of Transportation (Vandenbossche 1999).

Timely saw cutting of joints is also critical to constructing a smooth pavement. If random transverse cracking develops in a plain PCC pavement, faulting will likely follow with an increase in measured roughness.

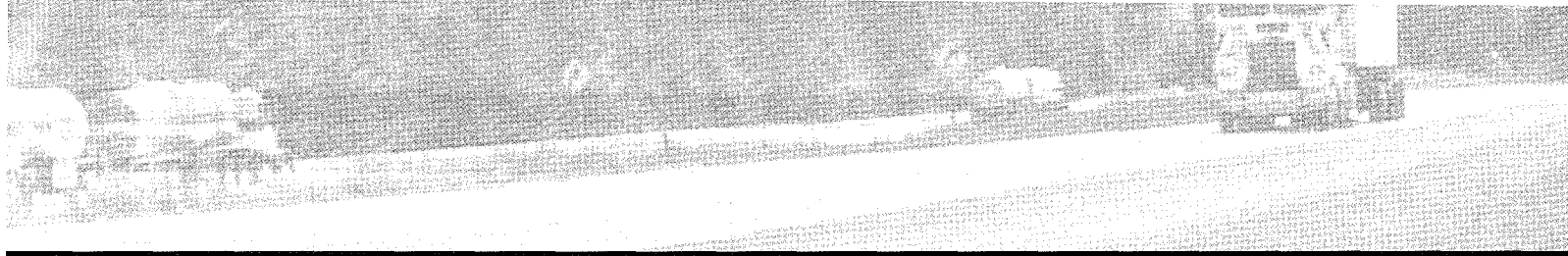
Equipment Maintenance

Well-maintained, clean equipment plays a key role in producing a smooth profile. The equipment should be in good operating order to minimize the potential for breakdowns. Breakdowns in any piece of equipment used in PCC production, delivery, or placement may bring the paver to a halt and induce a bump in the pavement. Something as simple as having to stop and change a flat tire on a truck can disturb the uniform delivery of PCC to the paver.

Cleanliness is also a virtue for a paver and other pieces of equipment. Finishing pans with mortar left on them from previous paving operations will not provide the smooth surface finish that is desired and will likely lead to over-finishing by hand. Likewise, old PCC left in delivery trucks or mixing drums can create surface defects. This is why the mechanics and cleanup crew play a crucial role in the successful delivery of a smooth pavement.

Motivated and Trained Workforce

For every aspect of PCC material placement and finishing, a crucial factor in the quality of the final product is the people that mix, deliver, place, and finish the PCC pavement. First, the contractor must be motivated by the amount of incentive being offered by the owner of the pavement. Without a sufficient “carrot in front of the horse,” the contractor’s



goal will be to supply the minimum required by the specifications. Second, many of the contractors that have been successful at constructing smooth pavements and receiving incentive payments for them share the incentives with the construction crew. These “smoothness bonus” payments are distributed across the workforce, not just given to the paver operator. Additionally, immediate feedback is provided to the crew on how much bonus they each received for the previous day’s paving.

Training of the workforce is also paramount. All crew members need to understand their roles and the effect they have in creating (or destroying) a smooth pavement profile.

Profile Measurement

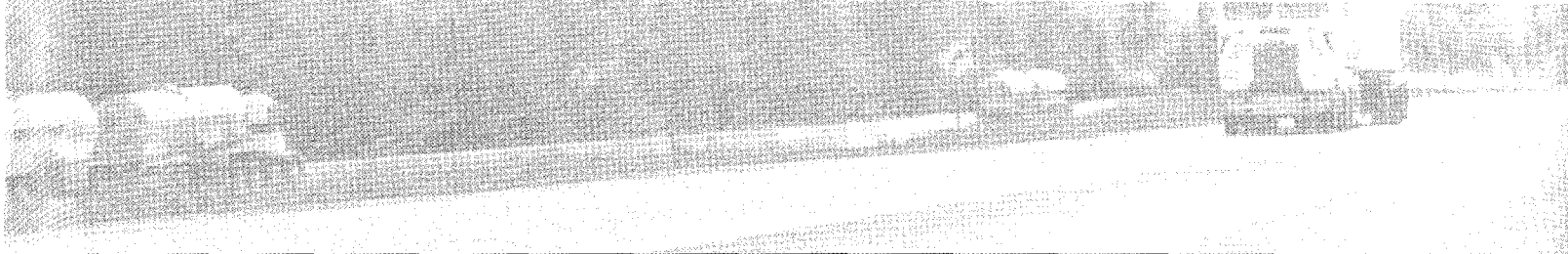
To best achieve the desired pavement profile, daily measurement of the completed pavement profile is necessary. This minimizes the amount of pavement placed before anomalies in the construction method are detected. Daily profile traces should be reviewed for compliance with the specification; the effect of the results on the incentive payments and the identification of opportunities for improvement should be part of the measurement and tracking process. Profiles can be analyzed to look for trends that provide an indication of where roughness is developing. As an example, if the traces show a series of a particular wavelength, the paving process should be examined to identify what may be inducing this particular wavelength. Is the finisher using a straightedge that could be contributing to this wavelength? Is the profile reflecting the stopping and starting of the paver due to

PCC delivery or equipment breakdown? Informing the paving crew may also be helpful in correcting many of these items and improving the smoothness of the pavement.

As previously discussed, both profilers and profilographs are presently used to collect profile data on PCC pavements. Before profiles are collected, project personnel should ensure that the equipment has been properly calibrated and is in good working order. The profile is generally collected for both wheel paths although some states have reported that using only one wheelpath is more cost effective and provides quicker feedback to the paving crew (ACPA 1990).

Data analysis of the collected profile is usually performed using some type of index and a “must grind” bump template. For profilographs, a profile index (PI) with an appropriate blanking band is usually specified. If true profile is collected, most states use either the International Roughness Index (IRI) or Ride Number (RN) (Law 2001). Some states also allow the collection of profile with an inertial profiler, but the data is analyzed to emulate a profilograph.

Precision, repeatability, and reproducibility continue to be critical issues in the area of construction quality control of smoothness. A comparison test of 24 profilographs in the Midwest resulted in a standard deviation of 0.011 m/km (0.71 in/mi) and a bias from the “Standard Profilograph” of 0.004 m/km (0.26 in/mi) (Fick 2001). Round robin tests of various profilers held around the United States have also shown that comparison of data between profilers is difficult.



PCC Pavement Smoothness Checklist

Table 1 provides an example of a pavement smoothness checklist that can be used by project personnel. This checklist can go a long way to help ensure that high levels of initial smoothness are achieved, but agencies should customize this listing to fit their local conditions, specifications, and experiences.

SUMMARY

Pavement smoothness is a key factor in how the traveling public judges the quality of the roadways that they drive on. Highway agencies have recognized this and are specifying smoother pavement and providing incentives to contractors who build them.

A variety of equipment is used to quantify the initial smoothness of a pavement. Currently, a majority of the states use the profilograph as the method of determining the initial smoothness of a pavement. However, more and more agencies are using inertial profilers to measure the true profile of a pavement. One item to keep in mind when selecting profiling equipment is that the profilograph tends to amplify the magnitude of wavelengths from about 5.2 to 12.2 m (17 to 40 ft) while attenuating the magnitude of wavelengths between about 3 and 5.2 m (10 to 17 ft).

Various indices have also been introduced over the years to mathematically express the roughness of the pavement. These indices are generally tied to the equipment that was used to collect the pavement profile. Profile index is commonly used with profilographs while IRI is the most commonly used index for inertial profilers. Zero blanking band profile index and IRI are becoming more commonly used as the specified indices for construction quality control.

The next item necessary to construct smooth PCC pavements is a specification. The key elements for a smoothness specification

are: equipment for measuring roughness, tolerance of the selected index, a testing procedure, required corrective action, and pay adjustments. Calibration and/or correlation of the profile measuring equipment should also be included in the specification to avoid conflicts when the contractor and owner may be using different equipment to measure the roughness of a pavement. Various guide specifications are available when developing or modifying a smoothness specification.

Finally, the construction of a smooth PCC pavement is dependent upon the following key factors:

- PCC material and mix design.
- Grade control.
- Pavement foundation.
- Paving speed and material delivery rate.
- PCC head in front of the paver.
- Embedded items.
- Minimal hand finishing.
- Curing and environmental conditions.
- Equipment maintenance.
- Motivated and trained workforce.

Smooth PCC pavements are an achievable goal and one that the traveling public expects and demands. As with most tasks of this type, there are numerous details that must be successfully completed by both the owner and contractor in order to achieve this goal.

Table 1. PCC pavement smoothness checklist

Item	Yes	No
<i>PCC Materials and Mix Design</i>		
1. Has the mix design been optimized considering workability, durability, segregation, and cost?		
2. Is there an adequate plan for checking the consistency of the produced mix and correcting deficiencies or inconsistencies in the produced and delivered mix?		
3. Are visual observations of the mix made behind the paver to check for workability, segregation, or finishing problems?		
4. Is a method available to modify the job mix formula if workability or finishing problems are encountered?		
<i>Grade Control</i>		
1. Has the contractor developed a procedure for control of the pavement profile, such as the use of dual stringlines?		
2. Has the contractor established a quality control procedure for checking the finished grade (or profile) of the subgrade, subbase, base, and pavement?		
3. Is the stringline installed precisely?		
4. Is the stringline adequately supported?		
5. Is the stringline offset outside the area affected by construction traffic?		
6. Has the contractor established a procedure for regularly checking and maintaining the stringline?		
7. Has the contractor checked the sensors for proper height and sensitivity?		
8. Have the design features of the roadway (grade, superelevation transitions, bridges, railroad crossing, intersections, manholes, and so on) been accounted for in the layout and staking of the pavement?		
<i>Pavement Foundation</i>		
1. Has a smooth, stable subgrade been constructed and trimmed properly?		
2. Has a smooth, stable base been constructed and trimmed properly?		

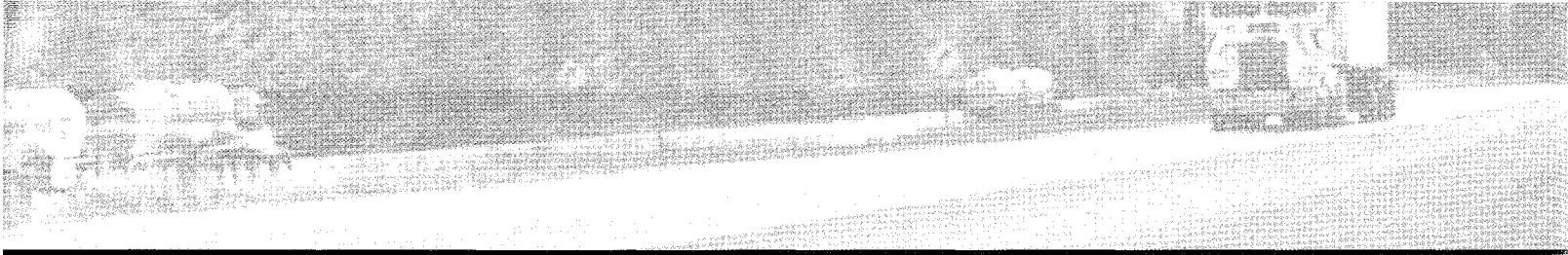


Table 1. PCC pavement smoothness checklist (continued)

Item	Yes	No
3. Are 0.9 m (3 ft) stable tracklines provided for the paver's operation?		
<i>Paving Speed and Delivery Rate</i>		
1. Are adequate delivery vehicles available to match the production rate of the plant and the planned forward speed of the paver?		
2. Are there contingency plans in place if the production or delivery of PCC to the paver is slowed or halted?		
3. Is the head of concrete in front of the paver consistent?		
<i>Embedded Items</i>		
1. Has the paver and vibrator setup accounted for the use of embedded items (reinforcing and dowel bars) in the pavement?		
<i>Finishing</i>		
1. Is the majority of the finishing being performed by the paver, not the finishers?		
2. Are the finishers limiting their work to edging, surface sealing with a bullfloat, and checking the pavement profile with a 3 to 8 m (10 to 25 ft) straightedge?		
<i>Curing and Environmental Conditions</i>		
1. Are the environmental conditions conducive to the placement and curing of PCC concrete (temperature, humidity, and wind speed)?		
2. Is an adequate curing medium being applied to the PCC pavement as soon as practical?		
3. Are transverse and longitudinal joints cut into the pavement in a timely manner to prevent random cracking?		
<i>Equipment Maintenance</i>		
1. Has PCC production, delivery, and placement equipment been checked and maintained properly to minimize breakdowns during the paving process?		
2. Is equipment cleaned on a regular basis to prevent old concrete from being introduced into the mix?		

Table 1. PCC pavement smoothness checklist (continued)

Item	Yes	No
<i>Motivated and Trained Workforce</i>		
1. Has an adequate incentive for smoothness been included in the contract to motivate the contractor?		
2. Is the contractor passing part of the incentive along to the paving crew?		
3. Has training for the paving crew been provided on the importance of pavement smoothness and their role in achieving it?		
4. Is feedback provided to the paving crew on the level of smoothness obtained?		
<i>Profile Measurement</i>		
1. Do the contractor and the data collection team understand the pavement smoothness specification?		
2. Has the profiling equipment been properly calibrated/correlated per contract requirements?		
3. Are smoothness data collected on a daily basis?		
4. Are the pavement profiles analyzed to identify potential areas of improvement?		

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