

Implementation of Best Practices for Concrete Pavements

Guidelines for Specifying and Achieving Smooth Concrete Pavements



Final Report
December 2019

National Concrete Pavement
Technology Center



Sponsored by
Federal Highway Administration
Office of Infrastructure

IOWA STATE UNIVERSITY
Institute for Transportation

About the National Concrete Pavement Technology Center

The mission of the National Concrete Pavement Technology (CP Tech) Center is to unite key transportation stakeholders around the central goal of advancing concrete pavement technology through research, tech transfer, and technology implementation.

About the Institute for Transportation

The mission of the Institute for Transportation (InTrans) at Iowa State University is to develop and implement innovative methods, materials, and technologies for improving transportation efficiency, safety, reliability, and sustainability while improving the learning environment of students, faculty, and staff in transportation-related fields.

Iowa State University Nondiscrimination Statement

Iowa State University does not discriminate on the basis of race, color, age, ethnicity, religion, national origin, pregnancy, sexual orientation, gender identity, genetic information, sex, marital status, disability, or status as a US veteran. Inquiries regarding nondiscrimination policies may be directed to the Office of Equal Opportunity, 3410 Beardshear Hall, 515 Morrill Road, Ames, Iowa 50011, telephone: 515-294-7612, hotline: 515-294-1222, email: eooffice@iastate.edu.

Notice

This document is disseminated under the sponsorship of the U.S. Department of Transportation (USDOT) in the interest of information exchange. The U.S. Government assumes no liability for the use of the information contained in this document.

The U.S. Government does not endorse products or manufacturers. Trademarks or manufacturers' names appear in this report only because they are considered essential to the objective of the document. They are included for informational purposes only and are not intended to reflect a preference, approval, or endorsement of any one product or entity.

Non-Binding Contents

The contents of this document do not have the force and effect of law and are not meant to bind the public in any way. This document is intended only to provide clarity to the public regarding existing requirements under the law or agency policies.

Quality Assurance Statement

The Federal Highway Administration (FHWA) provides high-quality information to serve Government, industry, and the public in a manner that promotes public understanding. Standards and policies are used to ensure and maximize the quality, objectivity, utility, and integrity of its information. FHWA periodically reviews quality issues and adjusts its programs and processes to ensure continuous quality improvement.

Front Cover Image Credits

The Transtec Group, Inc.

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Implementation of Best Practices for Concrete Pavements: Guidelines for Specifying and Achieving Smooth Concrete Pavements		5. Report Date December 2019	
		6. Performing Organization Code:	
7. Author(s) Gary Fick, David Merritt, and Peter Taylor		8. Performing Organization Report No.	
9. Performing Organization Name and Address National Concrete Pavement Technology Center Iowa State University 2711 South Loop Drive, Suite 4700 Ames, IA 50010-8664		10. Work Unit No.	
		11. Contract or Grant No. DTFH61-14-D-00005 Task Order 693JJ318F00272	
12. Sponsoring Agency Name and Address Office of Infrastructure Federal Highway Administration 1200 New Jersey Avenue, S.E. Washington, DC 20590		13. Type of Report and Period Covered Final Report	
		14. Sponsoring Agency Code	
15. Supplementary Notes Visit the National Concrete Pavement Technology Center's website at http://www.cptechcenter.org/ for color pdfs of this and other reports. The FHWA Contracting Officer was Tom Yu.			
16. Abstract Real-time smoothness (RTS) technology is arguably one of the most impactful technologies for concrete pavement construction quality control resulting from the Second Strategic Highway Research Program (SHRP2). Contractors participating in equipment loans through the SHRP2 Solutions Implementation Assistance Program have quickly realized the benefits of RTS for improving smoothness for as-constructed concrete pavement in order to achieve smoothness specification requirements while maximizing incentives and minimizing disincentives and corrective actions. Over the course of implementing this technology through equipment loans and workshops, it has become apparent that additional guidance for specifying and achieving concrete pavement smoothness is needed. Many agencies struggle to understand what a reasonable specification looks like with respect to smoothness limits and incentive/disincentive levels. Frequently, agency staff do not fully understand the impacts of design factors (curvature, grade and super-elevation changes, leave-outs, etc.) and prescriptive requirements for materials, mixtures, and construction equipment, on the contractor's ability to achieve pavement smoothness requirements. Likewise, many contractors do not fully understand the impacts various construction factors, such as the concrete mixture, paving equipment, and paving crew, have on pavement smoothness. Staff often do not understand the importance of continually checking pavement smoothness to adjust operations to ensure the requirements for the final product are achieved. The purpose of this project was to continue implementing RTS technology through field trials, while also using what has been learned to-date to generate guide specifications and develop best practices for concrete pavement smoothness. In short, the objective of this document is to provide guidelines on how to specify and build smooth concrete pavements.			
17. Key Words concrete pavement construction—concrete pavement guidelines— concrete pavement smoothness—pavement ride quality—real-time smoothness		18. Distribution Statement No restrictions.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 52	22. Price N/A

Implementation of Best Practices for Concrete Pavements

GUIDELINES FOR SPECIFYING AND ACHIEVING SMOOTH CONCRETE PAVEMENTS

**Final Report
December 2019**

Principal Investigator

Peter Taylor, Director
National Concrete Pavement Technology Center, Iowa State University

Authors

Gary Fick and David Merritt, The Transtec Group, Inc.
Peter Taylor, National Concrete Pavement Technology Center

Sponsored by
Federal Highway Administration
Office of Infrastructure

A report from
National Concrete Pavement Technology Center
Iowa State University
2711 South Loop Drive, Suite 4700
Ames, IA 50010-8664
Phone: 515-294-8103 / Fax: 515-294-0467
<http://www.cptechcenter.org/>

TABLE OF CONTENTS

ACKNOWLEDGMENTS	vii
EXECUTIVE SUMMARY	ix
BACKGROUND	1
SPECIFICATIONS AND DESIGN	4
Specifications for Initial Smoothness	4
Design Features that Influence Initial Smoothness.....	5
CONSTRUCTING SMOOTH CONCRETE PAVEMENTS.....	9
Materials and Mixtures	9
Paving Equipment Setup.....	18
Construction Practices to Achieve Initial Smoothness	20
SMOOTHNESS MEASUREMENTS	35
Real-Time Smoothness Measurements.....	35
Hardened Pavement Smoothness Measurements.....	37
Profile Data Analysis	38
REFERENCES	41

LIST OF FIGURES

Figure 1. Graphical representation of the interdependence of factors affecting initial smoothness and the sweet spot.....	2
Figure 2. Mixture factors and paving factors that render finding the smoothness sweet spot impossible for a hypothetical project	2
Figure 3. Adjusted mixture factors and human factors that enhance the smoothness sweet spot.....	3
Figure 4. Example of matching existing pavement, design of adequate clearance for slipform paving equipment, and stabilized base for paver track line.....	7
Figure 5. Plot of a tarantula curve.....	12
Figure 6. Two mortar thickness depths at the top of a vibrated sample: approximately 0.25 in. (left) and approximately 1.00 in. (right)	13
Figure 7. Box test specimen after stripping the mold	14
Figure 8. Visual rating of Box Test surface voids	14
Figure 9. VKelly testing apparatus	15
Figure 10. VKelly indices of 0.60 to 1.10.....	15
Figure 11. Multiple sets of variables that impact the quality and smoothness of a concrete pavement	20
Figure 12. Maintaining the concrete head in the grout box	22
Figure 13. Properly graded and stable paver track line	23
Figure 14. Stringline pins anchored in an unstable pavement foundation.....	23
Figure 15. Paver sensor in contact with the stringline.....	24
Figure 16. Stringless 3D machine control for a slipform paver.....	25
Figure 17. Real-time profile data illustrating fluctuation of IRI corresponding to distance from the paver to the robotic total station	26
Figure 18. Close spacing between the concrete spreader and paver to allow quick response to changes in concrete head.....	27
Figure 19. Effect of paving with too much lead/draft.....	29
Figure 20. Improved IRI results from sensitivity adjustment.....	30
Figure 21. Comparison of power spectral density (PSD) data for real-time (blue) and hardened (red) profiles demonstrating that hand finishing removes roughness at the 5 ft wavelength.....	31
Figure 22. Example of localized roughness removed by hand finishing.....	31
Figure 23. Hand finishing with two 16 ft straightedges.....	32
Figure 24. Uniform macrotexture as a result of good construction practices.....	33
Figure 25. Full and complete coverage of curing compound, which can reduce curling and warping.....	34
Figure 26. RTS devices installed on slipform pavers	36

LIST OF TABLES

Table 1. Sample combined gradation.....	11
Table 2. Concrete production factors that influence the uniformity of workability between batches.....	17

ACKNOWLEDGMENTS

The authors would like to thank the Federal Highway Administration (FHWA) for sponsoring this work. They would like to extend their gratitude to the following individuals for their contributions in reviewing and providing commentary during the development of these guidelines:

- Craig Hughes, Cedar Valley, Corp., LLC
- Zebulon (Zeb) Zuk, Shafer Contracting Co., Inc.
- Matt Zeller, Concrete Paving Association of Minnesota

EXECUTIVE SUMMARY

Pavement smoothness (more accurately, ride quality), has long been an important factor in the design and construction of roadways. As far back as the American Association of State Highway Officials (AASHO) Road Test in the 1950s, it was recognized that users judge the quality of a roadway primarily by the ride quality of the pavement surface. In other words, even if we can design and build a pavement to last 100 years with minimal to no maintenance, public opinion will be based primarily upon the ride quality of the finished surface and not on how long the pavement lasts.

It has also been recognized that pavement smoothness has an impact on the structural performance of pavements. When roughness exacerbates dynamic loading from heavy vehicles, stresses in a concrete pavement can significantly increase, resulting in distresses and ultimately failure.

With an understanding of the importance of pavement smoothness, state highway agencies (SHAs) have placed a high priority on smoothness in the form of continually evolving pavement smoothness specifications. Agencies strive to strike a balance between producing pavements that are “smooth enough” and ensuring that smoothness requirements are achievable by the contractor. Most current smoothness specifications offer incentives for exceptional smoothness to help encourage innovation and attention to the factors that affect smoothness while at the same time requiring corrective action or assessing a negative pay adjustment for unsatisfactory smoothness for new construction.

The concrete paving industry also recognizes the importance of pavement smoothness and has responded by identifying a number of best practices to help ensure that smoothness requirements are achieved. This document presents a number of these general best practices along with key recommendations for quality control processes specifically as they relate to pavement smoothness.

BACKGROUND

Since the original American Association of State Highway Officials (AASHO) Road Test conducted after WWII, it has been recognized that, from the road user's perspective, the primary measure of quality for a concrete pavement is smoothness (Carey and Irick 1960). The initial (as-constructed) smoothness of a concrete pavement also affects its performance; smoother pavements last longer and stay smooth longer (Fick et al. 2018). It has also been shown that smoother pavements provide public benefits, from improved fuel efficiency, which reduces vehicle emissions and operating costs (Amos 2006), to reduced vehicle repair expenses (Chatti 2010). Given these benefits of smoother concrete pavements, there has been a renewed interest in specifying and constructing concrete pavements to an initial smoothness standard that cost-effectively captures these benefits.

As an important means of measuring smoothness as placed by the paver, real-time smoothness (RTS) technology is arguably one of the most impactful technologies for concrete pavement construction quality control resulting from the Second Strategic Highway Research Program (SHRP2). Contractors participating in equipment loans through the SHRP2 Solutions Implementation Assistance Program have quickly realized the benefits of RTS for improving the smoothness of as-constructed concrete pavement. In addition to measuring smoothness, the RTS profile of a newly placed pavement reflects the workability of the mix, in that a mix with good workability consolidates well and does not segregate, resulting in uniform, high-quality concrete without voids and with a smooth paved surface. Workability, in turn, can indicate the construction quality of concrete pavements because a workable mix allows for good dowel alignment and consolidation of concrete around reinforcing steel, dowel bars, and/or tie bars.

Although the focus of this document is to provide guidance on how to achieve improved initial smoothness results for concrete pavements, it must be understood that the long-term durability of a concrete pavement should take precedence over any functional characteristic such as smoothness. Therefore, the approach recommended by these guidelines is to begin with a performance engineered mixture (PEM) that is optimized for long-term durability in the local environment. Construction methods should then be employed to ensure that the durability is not compromised and yields the desired initial smoothness results.

There are many factors that influence the initial smoothness of a concrete pavement. Although not exhaustive, the following list categorizes these factors:

- Mixture factors:
 - Workability.
 - Finishability.
 - Edge stability.
 - Uniformity.
- Paving factors:
 - Design factors – project staging, time-related incentives and disincentives that dictate accelerated construction schedules, vertical and horizontal curves, the need to match existing lanes, track line clearance, etc.

- Project factors – paving sequence, track line clearance issues, climate, etc.
- Equipment.
- Human factors:
 - Experience.
 - Training.
 - Communication.
 - Fatigue from accelerated construction schedules or too much multi-tasking.

It is critical to understand that these broad categories are not independent of each other and that numerous factors within each category impact the ability to achieve the desired initial smoothness. In addition, a balance must be struck between the desire for a certain level of initial smoothness and the cost impacts of each of these factors. One way to represent this interdependence is shown in Figure 1, where the potential to achieve the desired initial smoothness is shown in Figure 1, where the potential to achieve the desired initial smoothness is the intersection of the three circles, or the smoothness “sweet spot.”

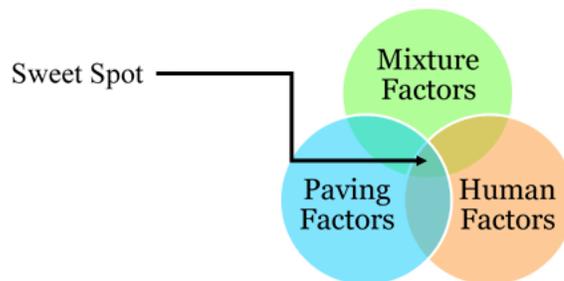


Figure 1. Graphical representation of the interdependence of factors affecting initial smoothness and the sweet spot

Taking the illustration in Figure 1 further, consider a hypothetical project where the mixture materials are highly nonuniform, resulting in frequent changes to mixture workability, and the project conditions dictate a noncontiguous paving sequence, resulting in short paving runs (Figure 2).

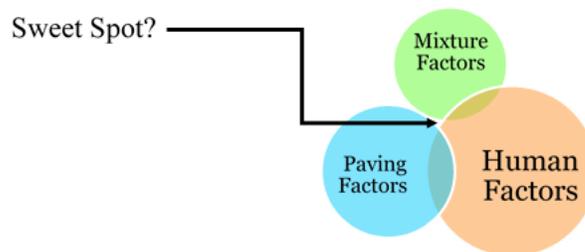


Figure 2. Mixture factors and paving factors that render finding the smoothness sweet spot impossible for a hypothetical project

In this scenario, it may not be possible to achieve the desired level of smoothness without making some adjustments to the concrete mixture and/or the project details (paving sequence).

Given the same hypothetical project portrayed in Figure 2, an adjustment to mixture materials and/or processes and a change in project personnel to a crew with more experience and better training could enhance the contractor’s ability to find (and maximize) the smoothness sweet spot (Figure 3).

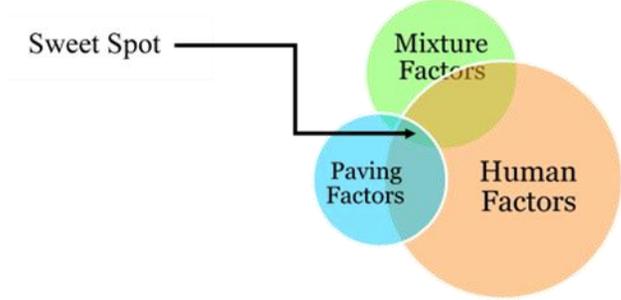


Figure 3. Adjusted mixture factors and human factors that enhance the smoothness sweet spot

The examples in Figures 1 through 3 are provided to illustrate how the contractor’s ability to achieve smoothness is impacted by many factors. Real-world situations are rarely resolved easily and may require multiple adjustments to materials, equipment, and construction processes to achieve the desired results.

SPECIFICATIONS AND DESIGN

While the focus of these guidelines is on achieving satisfactory initial smoothness for concrete pavements, a basic understanding of the specifications that address initial smoothness is important. Similarly, the potential impact of design features on the ability to achieve satisfactory initial smoothness needs to be understood.

Specifications for Initial Smoothness

Smoothness specifications vary by agency, and these differences may or may not be founded on sound engineering principles. In some cases, the evolution of an agency's smoothness specification may be the result of negative experiences (e.g., paying a smoothness incentive for a result objectively deemed to be undeserving of an incentive). These local differences in smoothness specifications can lead to confusion, contradictions, and/or unintended consequences.

At a minimum, a comprehensive smoothness specification should include the features summarized below.

Use of the International Roughness Index (IRI) and Inertial Profiler for Profile Measurement

The IRI is a more objective measure of ride quality or how a vehicle responds to the pavement profile than a straightedge or profilograph. Inertial profilers provide the best representation of the actual pavement profile for the interpretation of ride quality. Pavement profile measurement requirements should include the following:

- Equipment and certification requirements
- Hardware and software settings
- Operator certification requirements
- Timing of measurements (e.g., timing after pavement placement and time of day)
- Reporting requirements

Options for Various Project Types (e.g., Urban/Rural, Low Speed/High Speed, Lane Additions, Overlays)

Lower-speed and/or urban pavement smoothness requirements may not need to be as stringent as those of high-speed facilities. Smoothness requirements may need to be relaxed for lane additions (paving next to existing pavement) and concrete overlays where there is little control over the smoothness of the underlying surface.

IRI Thresholds for Incentive, Full Pay, and Disincentive

Ideally, incentive and disincentive pay adjustments should be based on sound engineering principles (life-cycle cost, public benefit, etc.)

Localized Roughness Provisions

Areas of localized roughness (ALRs) are isolated locations that disproportionately contribute to overall roughness. ALRs are typically identified using a continuous IRI report with a 25 ft base length.

Corrective Action Requirements

The IRI threshold for which corrective action is required and the type of corrective action permitted (e.g., diamond grinding, removal and replacement) should be defined.

Delineation of Leave-Outs

Areas not to be included in smoothness measurements and pay adjustments should be clearly identified. These typically include bridge approach slabs (and bridge decks unless separate requirements are provided), end-of-day headers, intersections, drainage inlets, and other areas where the contractor must match the elevation of a fixed object.

Additional Requirements for Specific Pavement Types

Certain pavement types may have additional requirements, such as in the following examples:

- For jointed concrete pavements, measurements may be required at certain times of day to account for the effects of slab curling/warping.
- For longitudinally tined concrete pavements, wide footprint sensors may be required for the profiler.

For further information, a companion model specification for determining the initial smoothness of concrete pavements is being published by the National Concrete Pavement Technology (CP Tech) Center.

Design Features that Influence Initial Smoothness

Roadways are designed to accommodate multiple criteria: safety, drainage, right-of-way constraints, and more. It is not feasible nor is it cost-effective to optimize a design for initial smoothness. Therefore, it is critical to understand how certain design features can adversely impact the initial smoothness of concrete pavements. Beyond just understanding these features'

potential impacts on initial smoothness, the frequency and nature of certain design features for a given project should be reviewed and serve as the basis for determining the appropriate expectations for initial smoothness results. In other words, smoothness specifications for any project should be adjusted to account for project-specific constraints that are beyond the control of the contractor.

There may be situations where this approach of tempering the initial smoothness specification to match project conditions is deemed inappropriate. For example, a reconstruction project on a high-priority urban interstate may be required to achieve a certain IRI value, but at the same time the project may involve limited work windows (nights and/or weekends), highly fragmented areas of work, or other constraints that limit the potential to achieve the desired IRI. For projects of this type, where the desired initial smoothness cannot be compromised but is likely unattainable due to design features, a pay item for diamond grinding should be included in the contract.

Design features that have an adverse effect on the contractor's ability to achieve a given level of initial smoothness include those summarized below.

Vertical Curves

Sharp vertical curves with less than 200 ft between tangent profile sections may not give the paver adequate distance (time) to achieve stasis as the paver adjusts to changes in profile grade.

Superelevation Transitions

Changes in cross-slope impact the concrete head carried by the paver, which in turn result in higher IRI values behind the paver. Crowned pavements also require an adjustment to the paving mold through superelevation transitions, which also introduces roughness behind the paver. To mitigate the effects of cross-slope transitions, the design length should be as long as practical while still achieving safety and drainage objectives.

Paving Sequence

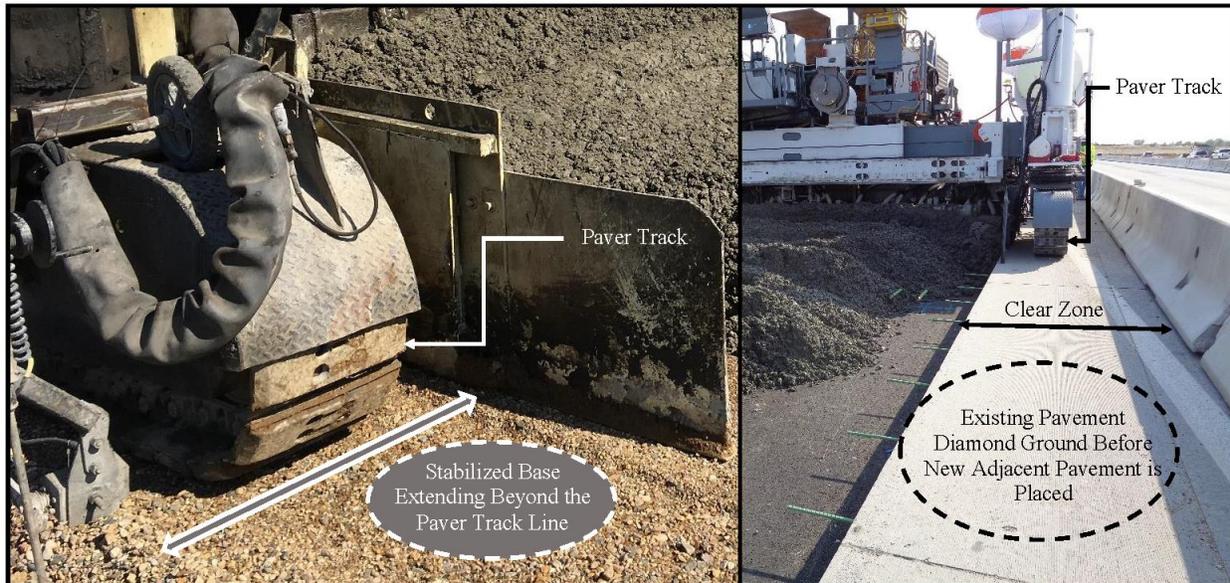
Maintenance of traffic objectives on urban projects often limits the areas available for paving, resulting in noncontiguous, short paving runs. Slipform paving operations typically need some distance (100 ft to 200 ft) to achieve a level of stability where the paver has been adjusted and the mixture is uniform. The ability to meet a stringent IRI specification on short runs (less than 0.2 miles) is more difficult than on longer paving runs because of adjustments that are necessary at daily startup. The initial roughness on short runs, which may be limited to the first 100 ft of pavement placed, can result in an elevated IRI for the first 0.1-mile segment, even when the remainder of the segment is at or below the specified IRI.

Blockouts

Similar to short paving runs, blockouts for in-pavement structures increase the difficulty of achieving a specified smoothness requirement. Tenth-mile segments that include blockouts often have elevated initial IRI results.

Matching New Pavement to Existing Lanes

The initial smoothness of a concrete pavement that abuts an existing roadway is highly influenced by the profile of the existing pavement that is being matched. This roughness that is mirrored from the existing pavement occurs primarily on the side of the paver nearest the existing pavement, but it can also extend across the width of the paver. Smoothness specification requirements for widened sections should be adjusted for the IRI of the existing pavement to be matched. Alternatively, the design may be modified to include diamond grinding of the existing pavement to an acceptable IRI before being matched with new concrete pavement (Figure 4).



The Transtec Group, Inc.

Figure 4. Example of matching existing pavement, design of adequate clearance for slipform paving equipment, and stabilized base for paver track line

Equipment Clearance and Paver Track Line

All concrete pavers are propelled by tracks that are located outside of the footprint of the pavement being placed. Wherever practical, designs should include a minimum clearance of 3.0 ft between the edge of the pavement and any lateral obstructions that would prohibit slipform placement. The stabilized base should be extended beyond the width of the pavement within this 3.0 ft clear zone (Figure 4). Narrower track lines of 2.0 ft can be accommodated with certain

slipform paver models, but initial smoothness values may suffer compared to heavy-duty mainline pavers.

This summary of design features that affect initial smoothness is intended to provide a basic understanding of specific project features that may impact the relative difficulty of achieving a specified level of smoothness. It is necessary to recognize that engineering judgment must be exercised on how to best optimize the design for smoothness. The economic impacts of all design options should be evaluated before a final design is arrived at. In some cases, minor adjustments to the design can result in cost-effective solutions that improve the probability of achieving a desired level of initial smoothness. In other cases, the design and maintenance-of-traffic scenarios may dictate that the smoothness specification be modified or that diamond grinding be included as a contract pay item in recognition of the constructability issues specific to that project.

CONSTRUCTING SMOOTH CONCRETE PAVEMENTS

Materials and Mixtures

Performance engineered mixtures are the newest standard for developing concrete mixtures that are optimized for long service life. Concrete durability should be the first objective in designing a mixture for concrete pavement. This does not imply that smoothness is not important; rather, it acknowledges that a concrete mixture that yields excellent initial smoothness results but lacks the ability to withstand environmental and loading factors has missed the mark. In fact, a pavement system that is failing due to durability issues will exhibit rapidly escalating roughness, negating any benefits from good initial smoothness. However, when developing and placing durable concrete mixtures, the guidelines for PEM best practices and initial pavement smoothness are not mutually exclusive but can be complementary.

Highlights of current PEM initiatives include the following:

- Specifying and measuring properties that are related to performance.
- Emphasizing testing at the mixture prequalification stage and at the time of concrete delivery.
- Reducing concrete variability.
- Early identification and correction of mixture deficiencies.

The scope of this document is to improve the initial smoothness of concrete pavements, and therefore only the elements of PEM that most influence smoothness are discussed in detail. Excellent resources are available that provide comprehensive guidance on PEMs, including but not limited to the following:

- The National CP Tech Center's web page for PEM resources:
<https://cptechcenter.org/performance-engineered-mixtures-pem/>
- *Performance Engineered Mixtures for Contractors* (Taylor 2018):
https://intrans.iastate.edu/app/uploads/2018/11/PEM_for_contractors_tb.pdf

From a smoothness perspective, workability is the primary PEM property that is most applicable. While not explicitly stated, finishability is implied within the overall definition of workability. For the purposes of these guidelines, finishability is a subjective characteristic that can be described best as the relative ease/difficulty of filling surface voids behind the slipform paver using hand finishing and/or mechanical finishing methods.

Workability

Combined Gradation

Over the years, many methods have been used for determining the aggregate proportions of concrete mixtures used for slipform paving. The approaches range from application of arbitrary

percentages of each individual aggregate to optimized methods based on empirical results of laboratory and field trials. One of the most promising approaches, however, is the adoption of the Tarantula Curve (T-Curve) as the best practice for proportioning aggregates for slipformed concrete pavement mixtures.

A summary of the T-Curve approach is provided in this section. Comprehensive details regarding the development and implementation of the T-Curve (Ley et al. 2012) can be found at the following locations:

- Development and Field Evaluation of the Tarantula Curve:
<http://www.tarantulacurve.com/publications.html>.
- Video tutorials on implementing the Tarantula Curve and troubleshooting mixtures:
https://www.youtube.com/playlist?list=PLRq6Z9d0kCT_A5z_xwSMlt5ta2mGSMpEb.

Summary of the Tarantula Curve Method for Optimizing Aggregate Proportions. It must be understood that optimizing aggregates for a concrete mixture, in most cases, is an exercise in determining the best compromise between many, sometimes opposing, factors. The relative importance of these factors can vary by project and performance/specified objectives, and therefore there is no standard combined gradation that is ideal for all cases. Some of these factors include the following:

- Economics.
- Sustainability.
- Utilization of locally available materials.
- Durability of the mixture.
- Workability of the mixture.
- Other performance objectives.

The T-Curve provides a relatively wide band of combined gradations that will yield acceptable results with respect to workability (response to vibration) for slipformed mixtures.

Percent Retained on Individual Sieves. Individual aggregate gradations are mathematically combined to calculate the percent retained on each individual sieve to evaluate the composite aggregate. An example of this method is provided in Table 1.

Table 1. Sample combined gradation

Sieve	Percent Passing Coarse #1	Percent Passing Coarse #2	Percent Passing Fine #1	Combined % Retained	Combined % Retained on Each Sieve	Combined % Passing
2½"	100%	100%	100%	0%	0%	100%
2"	100%	100%	100%	0%	0%	100%
1½"	100%	100%	100%	0%	0%	100%
1"	96%	100%	100%	2%	2%	98%
¾"	79%	100%	100%	10%	8%	90%
½"	41%	99%	100%	27%	18%	73%
⅜"	22%	71%	100%	39%	12%	61%
#4	5%	8%	99%	55%	16%	45%
#8	1%	6%	86%	63%	8%	37%
#16	1%	4%	67%	71%	8%	29%
#30	1%	2%	44%	81%	10%	19%
#50	1%	1%	21%	91%	10%	9%
#100	1%	1%	5%	97%	7%	3%
#200	0.4%	0.3%	1.5%	99.2%	1.8%	0.9%

Aggregate ratios: Coarse #1 = 46.00%, Coarse #2 = 12.00%, Fine #1 = 42.00%, Combined = 100.00%
 Dark shading = 26% Coarse Sand
 Medium shading = Overlap between Coarse Sand and Fine Sand Categories
 Light shading = 28% Fine Sand

Coarse Sand. The T-Curve defines coarse sand as the sum of the percent retained on the #8, #16, and #30 sieves. This value is related to the cohesion properties (segregation and edge slump) of the mixture. This value should be equal to or greater than 15%.

Fine Sand. The T-Curve defines fine sand as the sum of the percent retained on the #30, #50, #100, and #200 sieves. This value is primarily related to the finishability (surface voids) of the mixture. This value should be between 24% and 34%.

Example Tarantula Curve. The combined percents retained on each sieve from Table 1 are plotted in Figure 5. Note that the goal is to keep the percent retained for each sieve in between the “tarantula-shaped” dashed red lines in the plot.

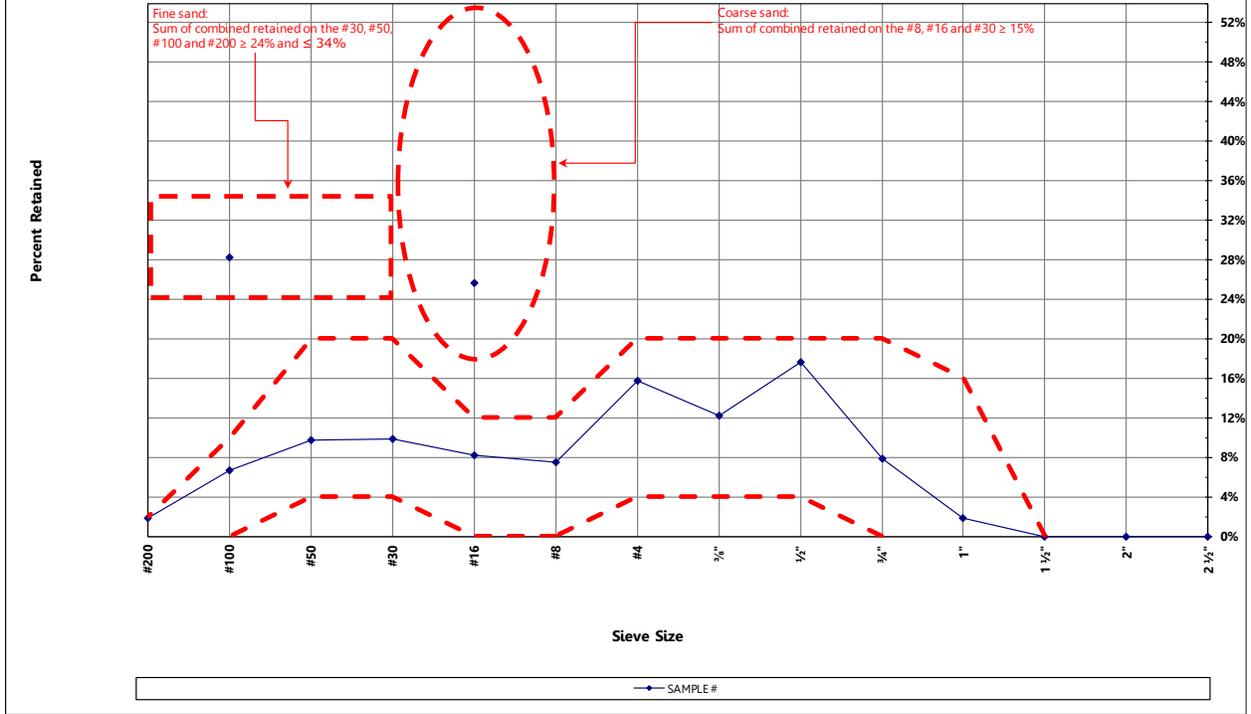


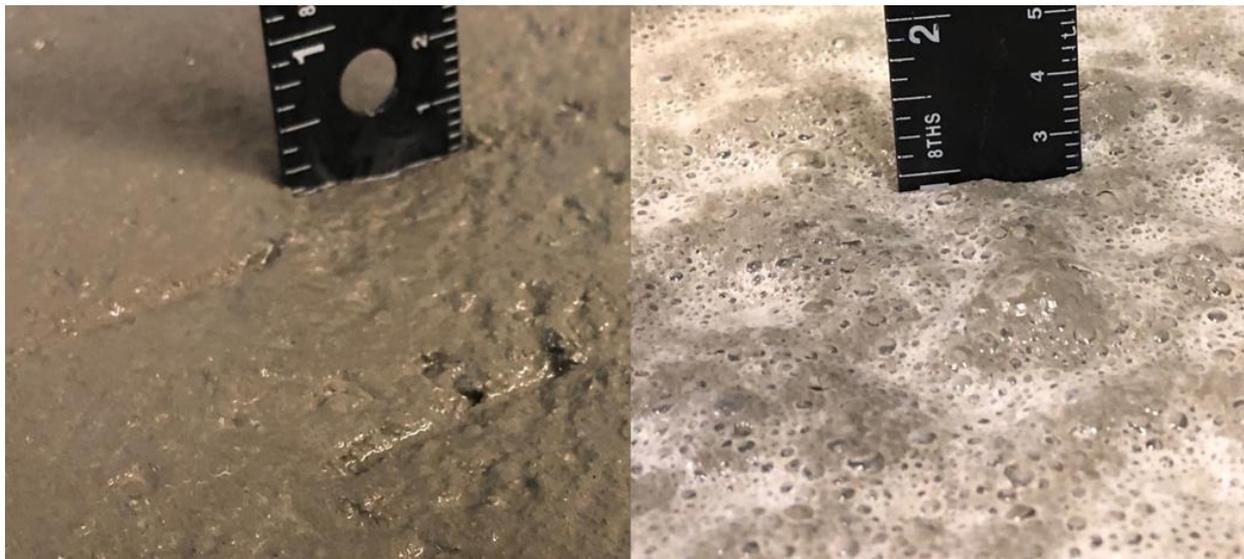
Figure 5. Plot of a tarantula curve

Optimization of mixture workability for slipform paving requires laboratory trials at the anticipated mixture temperature during placement using the T-Curve and varying the paste volume to arrive at a mixture that meets all specified criteria. Field adjustments to the mixture are most commonly based on visual examination of the slab directly behind the slipform paver (which can detect excessive voids, excessive slurry, edge slump, and edge instability). These field adjustments may include subtraction/addition of water (not to exceed the maximum water/cementitious materials [w/cm] ratio of the approved mixture design), adjustment of admixture dosages, minor reportioning of aggregates, and heating or cooling the mixture.

Paste Content

Paste is comprised of portland cement, supplementary cementitious materials, water, admixtures, and air (entrapped and entrained). In general terms, the volume of paste in a mixture should be greater than the volume of voids between the aggregates but not exceed the point where durability is compromised due to shrinkage and/or increased permeability. On a volume basis, the ratio of paste to voids between the aggregate particles should be approximately 1.5:1. A rule of thumb to gauge whether the paste volume is appropriate is to vibrate a sample of concrete in a 6 in. diameter cylinder mold or pressure air content bucket for several minutes. When measured

with a steel ruler after vibration, the thickness of mortar at the surface of the sample should not exceed 0.25 in. (Figure 6) (Taylor 2018).



National CP Tech Center

Figure 6. Two mortar thickness depths at the top of a vibrated sample: approximately 0.25 in. (left) and approximately 1.00 in. (right)

Repeated trial-and-error mixture samples may be necessary using the Box Test, VKelly Test, or both in conjunction with the vibrated cylinder mold method to arrive at an optimum paste content. Further details on the Box Test and VKelly Test are provided in the following section, Response to Vibration and Edge Stability.

Because optimum paste content is related to the volume of voids in the aggregates, it may be impossible to find a paste content that provides a workable yet durable mixture for the chosen aggregate blend. Adjusting the aggregate blend or choosing different aggregates may be necessary to develop a mixture that meets the desired requirements for both workability and durability. Field adjustments from the approved mixture proportions should be limited to minor adjustments ($\pm 3\%$) of the ratio of aggregates to water content. Therefore, it is critical that the approved mixture proportions allow for field adjustment of the water content without exceeding the maximum specified w/cm ratio.

Response to Vibration and Edge Stability

A standard slump test does not provide adequate feedback regarding a mixture's workability to determine whether the mixture will be appropriate for slipform placement. Therefore, the Box Test and/or VKelly Test should be used in the laboratory to assess the dynamic behavior of a mixture under vibration. It may take multiple iterations in the laboratory assessing combined gradation (T-Curve) and paste content with these test methods to arrive at a mixture that will yield the durability, surface finish, and edge stability that are both desired and specified. These

tests should be repeated in the field during the mixture verification stage (plant startup) to confirm that the production mixture has the same properties as the laboratory results for the approved mixture.

A summary of these test methods and guidelines for interpreting them are provided in this section as well as in *Integrated Materials and Construction Practices for Concrete Pavement* (Taylor et al. 2019). Comprehensive resources on these tests can be found on the National CP Tech Center’s website at <https://cptechcenter.org/> and on Oklahoma State University’s Tarantula Curve webpage at <http://www.tarantulacurve.com/>.

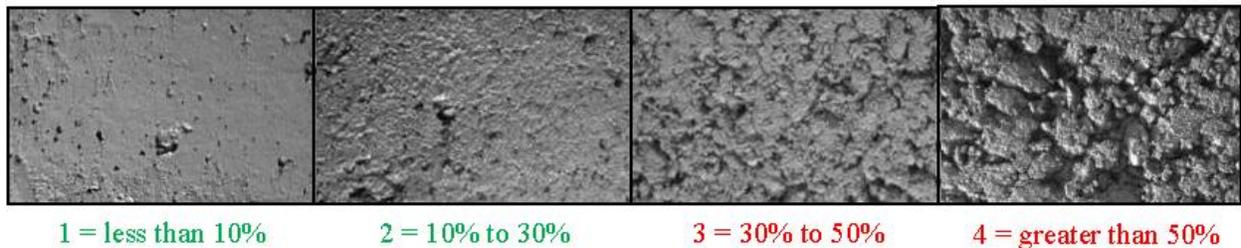
Box Test. The Box Test involves vibrating a concrete sample in a 1 ft³ mold for 6 seconds at 12,000 vibrations per minute (vpm). The sides of the mold are immediately removed, and the sample is examined for edge slump and consolidation (Figure 7).



National CP Tech Center

Figure 7. Box test specimen after stripping the mold

Edge slump greater than 0.25 in. indicates that the mixture may not be appropriate for slipform placement. Consolidation is subjectively rated against a visual standard (Figure 8).



National CP Tech Center

Figure 8. Visual rating of Box Test surface voids

A surface void score greater than 2 indicates that the mixture may not be appropriate for slipform placement.

VKelly Test. The VKelly Test is an adaptation of the Kelly Ball Test, where vibration is added to the mixture and an objective assessment of the mixture’s response to the vibration is obtained. The Kelly Ball is vibrated at 8,000 vpm for 36 seconds, and the penetration depth is recorded every 6 seconds (Figure 9).



National CP Tech Center

Figure 9. VKelly testing apparatus

The penetration data are plotted, and a linear regression analysis is performed to determine the slope of the line (Figure 10).

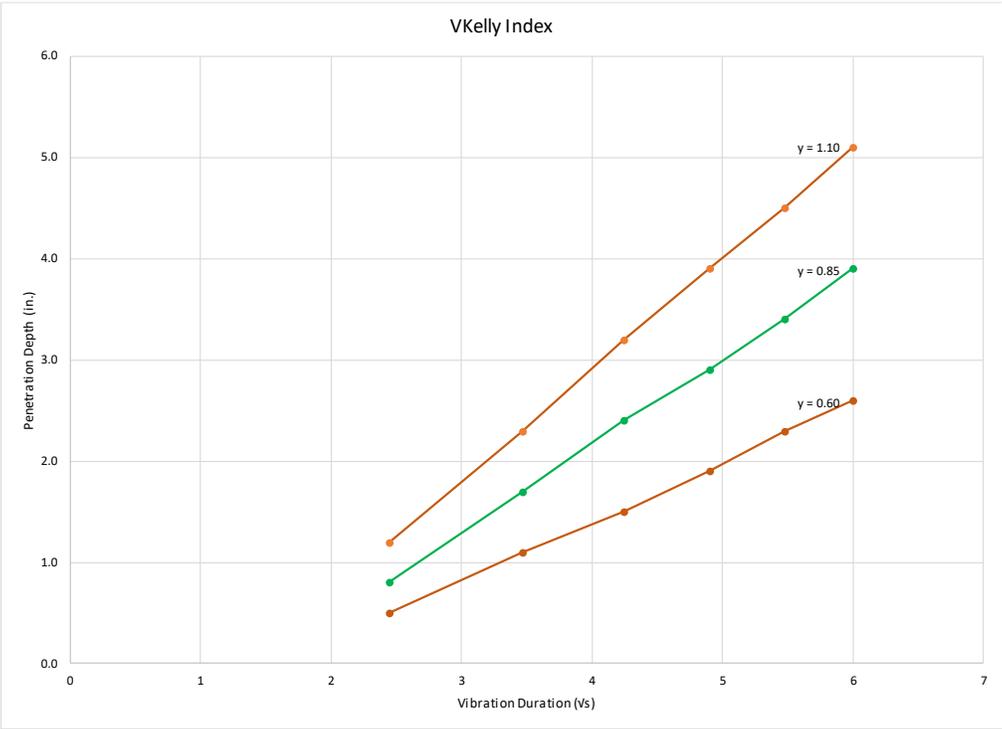


Figure 10. VKelly indices of 0.60 to 1.10

The VKelly index is the slope of this plotted line. Current experience indicates that a VKelly index between 0.6 in./ \sqrt{s} and 1.1 in./ \sqrt{s} is appropriate for mixtures that will be slipformed.

Concrete Plant Production

With respect to constructing smooth concrete pavements, the concrete plant had two primary objectives:

1. Supply uniform concrete to the paving operation.
2. Produce and deliver the concrete at a rate that will allow the paving operations to maintain a consistent speed with minimal paver stops (i.e., consistent delivery). Trucking of raw materials and fresh concrete should be matched to plant production rates. In some cases, the availability of qualified truck drivers may be the limiting factor in concrete production.

Concrete Uniformity

Assuming the approved mixture proportions have been verified to meet all durability requirements, uniform workability is the fresh concrete property that has the largest impact on initial smoothness. Concrete uniformity can be divided into two categories:

- *Within Batches* – Each batch of concrete should be thoroughly mixed so that workability properties are consistent throughout the delivered load.
- *Between Batches* – After mixture adjustments have been made to achieve the desired workability properties behind the paver, each load of concrete throughout the day should be consistent.

Within-batch uniformity can be controlled by properly maintaining the mixer and ensuring that the mixing time is adequate to produce a homogeneous mixture. Between-batch uniformity is more difficult to achieve. The primary factors affecting between-batch uniformity and recommendations for improving between-batch uniformity are shown in Table 2.

Table 2. Concrete production factors that influence the uniformity of workability between batches

Factors	Recommendations
Mixture proportions	Calibrate scales and water meters regularly to ensure that mixture proportions are within specified tolerances.
	Maintain stockpiles at a moisture content above saturated surface dry (SSD).
	Draw aggregates from areas of the stockpiles that have known moisture contents.
Total water content	Update moisture compensation values in the plant control system to match the aggregate stockpile moistures. Moisture content testing of the aggregate stockpiles and adjustment of the moisture compensation values should be performed at least twice per day and more frequently if nonuniformity is observed.
	Reject aggregates that do not meet job mix formula tolerances.
Aggregate gradation	Observe proper stockpiling techniques to minimize segregation. Blending of individual aggregate stockpiles may improve uniformity and mitigate moisture variability.
Air content	Monitor air content at the plant and adjust admixture dosages as needed.
Segregation of the mixture during transport	Maintain the haul route in a manner that minimizes excessively rough sections, which can segregate the concrete mixture in non-agitating trucks.

Consistent Delivery of Concrete Mixture

Many different types of trucks can be used to deliver concrete to the paving operation. The type of truck/trailer used should be compatible with project haul road conditions as well as the dumping and spreading operation. It should be noted that transit mix (drum) trucks generally take significantly longer to empty their loads in front of the paver than other types of trucks/trailers. Therefore, they may not be desirable for high-volume mainline paving applications.

More important than the type of truck used is the ability to deliver a steady supply of concrete to the paving operation so that the paver can maintain a consistent speed and minimize the number of stops per day. This is accomplished by having an adequate number of trucks available for concrete delivery. The number of trucks required to keep the paver moving at a consistent speed is a function of the plant production rate (cubic yards per hour), the total cycle time for transporting the concrete and returning to the plant, and the width and thickness of the pavement being placed. Plant production rate and the width and thickness of the pavement can be considered constants for a given day's paving. However, cycle times can be variable, and project personnel should consider the following when estimating the number of trucks required:

- Round trip distance
- Average speed of haul units, considering urban routes with multiple stops and traffic impacts, soft and muddy conditions, etc.
- Time needed for wash out of trucks to keep beds clean.
- Availability of truck drivers and limits on driver hours
- Breakdowns that remove trucks from service

Paving Equipment Setup

After being transported to a project, most mainline slipform pavers will need to be reassembled before paving can begin. Every paver should be reassembled and set up according to the manufacturer's recommendations for that specific model of paver.

This section of the guidelines provides generic advice for paver setup that is meant to supplement and in no way supersede any manufacturer's recommendations. Therefore, this information should be used as a checklist to ensure that the paver setup is optimized for achieving the desired initial smoothness.

Paving Mold

- ✓ Check that the paving mold is clean and free from defects.
- ✓ Check with a stringline and adjust to be true and straight with respect to the design crown/cross-slope(s).
- ✓ Verify that paving width is correct for the design typical section.

Vibrators

- ✓ Verify that all vibrators are operating.
- ✓ Set initial frequencies. Final adjustments should be made at the start of paving while all paver systems are operating and the vibrators are under load.
- ✓ Set to the desired height and angle.
- ✓ Install physical stops on the hydraulic cylinders to prevent the vibrators from contacting the dowel baskets, tie bar baskets, and/or continuous steel reinforcement.

Tie Bar Inserter(s) – Centerline and/or Pavement Edge

- ✓ Check that the centerline tie bar inserter is located in the correct position relative to the designed longitudinal joint.
- ✓ Check that the control system is programmed for correct spacing and the minimum distance from the transverse joints.
- ✓ Dry run all tie bar inserters.

Dowel Bar Inserter (DBI)

- ✓ Verify that dowel spacings are correct.
- ✓ Check that the control system is programmed for correct spacing.
- ✓ Dry run the DBI to confirm that it is operating correctly.
- ✓ Check trueness and set the oscillating correcting beam to an appropriate frequency.

Steering and Elevation Control (Stringline or Three-Dimensional (3D) Machine Control)

- ✓ Verify that all sensors and/or systems are operating correctly.
- ✓ Verify that leg barrel movement is smooth and that the leg barrels return to a “zero” position after movement.
- ✓ Set the paver to grade using the stringline or 3D model and adjust the paving mold to be as flat as practical from front to back (longitudinal) relative to the design profile of the roadway. Some lead/draft may be necessary when paving begins, but the initial setup should be flat.
- ✓ Dry run the paver on the stringline or 3D model to verify that steering and grade control are operating correctly and that the stringline or 3D model follows the geometric design requirements (thickness, alignment, and crown/cross-slope).

Trailing Finishing Pan

- ✓ Check that the trailing finishing pan is clean and free from defects.
- ✓ Check with a stringline and adjust to be true and straight with respect to the design crown/cross-slope(s).
- ✓ Adjust to be free floating on the surface of the fresh concrete. Avoid walking on the trailing finishing pan when paving.

Final Finisher (if Used)

- ✓ Adjust the mechanical finisher so that it does not dig or tear the surface of the pavement.
- ✓ Adjust the controls to limit final finisher operation to the desired width and verify that direction reversals are smooth.

Texture and Cure

- ✓ Inspect all burlap, turf, and broom drags; replace as necessary.
- ✓ Verify that all drags are installed soundly and will result in texture that is parallel to the centerline of the pavement.
- ✓ Ensure that the misting spraybar and/or hose(s) for wetting drags are operating correctly and will not result in excess water being applied to the pavement surface.
- ✓ Inspect and clean all tines; replace any tines that are bent or have mortar buildup.
- ✓ Verify that tine spacing is in accordance with the specification.
- ✓ Clean all curing compound spray nozzles.

- ✓ Dry run the texture/cure machine to verify that the steering, elevation, and spray systems are operating correctly.

Dry Run

- ✓ Make all final adjustments at least one working shift before paving will commence.
- ✓ Repeat dry runs after all adjustments to confirm that all systems are working correctly.
- ✓ Verify that all paving equipment has enough fuel to complete the first day's paving.

Construction Practices to Achieve Initial Smoothness

Concrete paving is a complicated process. To a casual observer, it can look easy when all inputs and processes are in control, but nothing could be further from the truth. It takes focused effort from everyone involved to construct a durable, high-quality concrete pavement. As described in the Background section of these guidelines, multiple variables can affect the ability to achieve the desired smoothness in terms of finding and maximizing the smoothness sweet spot (Figure 11).

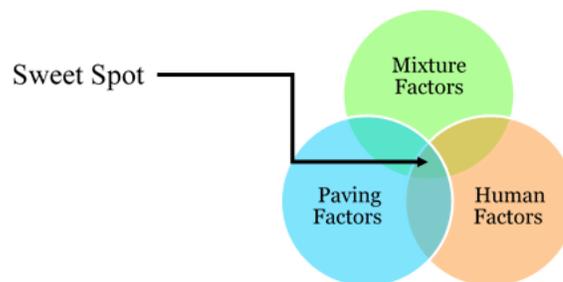


Figure 11. Multiple sets of variables that impact the quality and smoothness of a concrete pavement

To achieve satisfactory levels of initial smoothness, the design and specifications must be tailored to specific project conditions, the mixture must be durable and uniform, and all personnel involved must understand how their actions impact pavement smoothness. When looking at the interactions among the three sets of factors in Figure 11 (mixture, human, and paving), it is clear that there is no way to isolate only one or two of them and consistently find the smoothness sweet spot. The three sets of factors are interdependent and must be simultaneously and continuously adjusted for changing materials, weather, and project conditions.

The Materials and Mixture section of these guidelines provided recommendations for developing a concrete mixture that will be both durable and have the workability properties to meet smoothness specifications. Recommendations were also provided for producing and delivering a steady supply of uniform concrete to the paving operations. In summary, allowable mixture adjustments that may be made during paving include the following:

- Subtraction/addition of water (keeping within the w/cm tolerance of the approved mixture design)
- Adjustment of admixture dosages
- Minor reportioning of aggregates
- Heating or cooling of the mixture

The focus of this section of the guidelines is on specific construction practices and process adjustments that will enhance the probability of improving the initial smoothness of concrete pavements. Before specific practices are addressed, note the following general principles that should be adhered to when adjusting the paving process:

1. *Make measured and methodical adjustments, one at a time.* Do not use a “shotgun” approach (i.e., adjusting multiple factors at once), which can lead to misleading conclusions about the effectiveness of individual changes. There are too many variables that can affect concrete pavement smoothness to discern which of the multiple changes may have had a positive or negative impact on smoothness or whether they partially cancelled each other out.
2. *Be data-driven.* All conclusions regarding the effectiveness of process adjustments for improving smoothness should be based on the analyses of profile data (real-time or hardened) that have been properly collected.
3. *Keep records.* Maintain a meticulous log of process adjustments and events that have the potential to impact pavement smoothness measurements. This log can be handwritten or in digital format. At a minimum, it should include time, station, and description of the process adjustment or event that may have had an impact on smoothness results. Events that are commonly tracked in this type of log for concrete paving projects include stringline disturbances, 3D machine control issues, paver stops, changes in concrete workability, paver track line issues, superelevation transitions, vertical curves, etc. The information in this log should be incorporated into the analyses of profile data to assist in making sound conclusions about the effectiveness of process adjustments and to document events that negatively impacted smoothness results.

Subgrade and Subbase Preparation

Improving initial concrete pavement smoothness begins at the pavement foundation. Regardless of the specified measure of compaction, what is desired is a stable working platform that is resistant to deformation from construction traffic. Additionally, the base layer directly beneath the concrete pavement should ideally be trimmed or fine-graded to ± 0.01 ft of design grade. A pavement foundation meeting these criteria (stable and finished to grade) improves the uniformity of concrete pavement thickness. This has a positive impact on the ability of the paver operator to maintain a consistent level of concrete head in the paver’s grout box (Figure 12), which in turn leads to improved smoothness results.



The Transtec Group, Inc.

Figure 12. Maintaining the concrete head in the grout box

Conversely, a base course that deforms under construction traffic and/or is not fine-graded to a tight enough tolerance leads to variability in the concrete head because constant adjustments to the dumping and spreading operations are necessary. This constant variability in the concrete head and adjustments to the spreading operation result in a cycle of alternating low and high levels of concrete head, which can be reflected as roughness in the pavement profile.

Paver Track Line

A stable working platform must extend beyond the edges of the pavement and base courses. A stable, non-yielding paver track line reduces both the amplitude and frequency of the leg barrel movements necessary to maintain the paver mold at the prescribed grade. The track lines should also be maintained throughout paving, keeping them clear of stray piles of concrete or subbase material. Even though modern slipform pavers are capable of overcoming deviations in the track line profile, this roughness may still be reflected in the concrete pavement profile to some degree. Minimizing the amount of leg barrel movement by constructing a properly graded, stable track line enhances the odds of improving the initial smoothness of a concrete pavement (Figure 13).



The Transtec Group, Inc.

Figure 13. Properly graded and stable paver track line

Stringline Pins (When Used)

Beyond the paver track line, when a stringline is used for steering and elevation control, it can also be impacted by instability in the pavement foundation. This stringline, which is the basis for controlling the pavement alignment and profile, is supported by pins that are anchored into the pavement foundation (Figure 14). A pavement foundation that yields and pumps can displace the stringline pins, resulting in pavement roughness.



The Transtec Group, Inc.

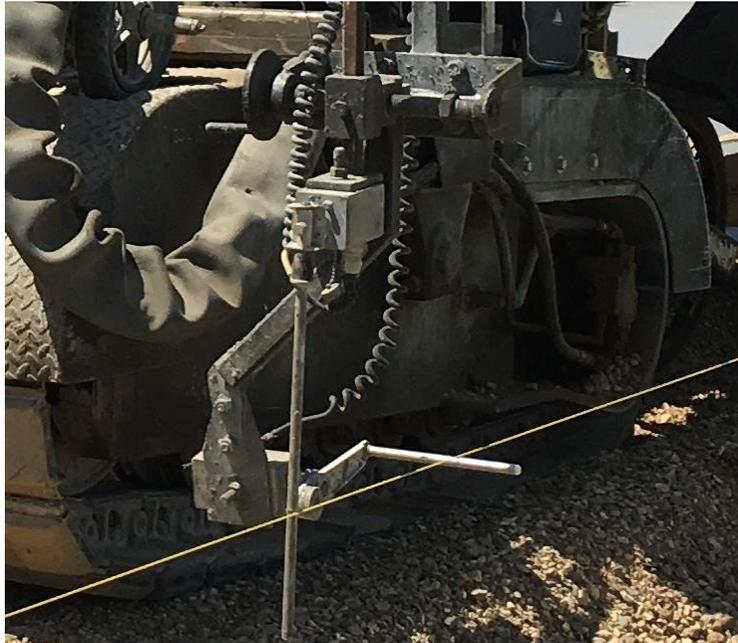
Figure 14. Stringline pins anchored in an unstable pavement foundation

Stringline

When a stringline is used to control the paver's alignment and elevation, initial pavement smoothness is highly sensitive to the smoothness of the stringline. Different types of stringline (poly, cable core, wire, etc.) may be used so long as they can be tensioned to practically eliminate stringline sag between pins. Properly setting and adjusting the stringline requires strict attention to detail. The steps involved in the stringline process are summarized as follows:

- Conduct a survey to provide graded paving hubs for alignment and elevation.
- Space the stringline pins at no greater than 25 ft center-to-center.
- Tension the stringline using a winch. Check and re-tension the stringline that has been in place for more than five days.
- Hang a known mass from the stringline midway between the anchor and tension points and measure the deflection caused by the suspended mass. Tension each segment of stringline so that the deflection is uniform for all segments.
- Set the stringline to the surveyed grade.
- Using the stringlines set to the surveyed grade, verify at each set of pins that the minimum concrete pavement thickness will be constructed.
- Raise the stringline where the base course is high (i.e., where less than the design thickness of the concrete pavement will be constructed).
- “Eyeball” the stringline and adjust for smoothness.

The sensor that follows the stringline and controls the paver hydraulic system uses an adjustable spring that keeps the sensor in contact with the stringline (Figure 15).



The Transtec Group, Inc.

Figure 15. Paver sensor in contact with the stringline

If this spring is not adjusted properly to the tension of the stringline, the sensor wand may lift the string between pins, resulting in pavement roughness. This can be checked during paving by measuring from a flat surface beneath the stringline ahead of the paver and remeasuring as the sensor wand passes by this same location. Adjustments should be made to stringline tension and/or the sensor spring to mitigate any stringline sag and/or lifting.

Stringless Controls

3D machine control for slipform concrete pavers (Figure 16) has been widely implemented across the US.



The Transtec Group, Inc.

Figure 16. Stringless 3D machine control for a slipform paver

Eliminating stringlines from concrete paving projects has numerous logistical advantages. With respect to pavement smoothness, there is a theoretical advantage because the chord effect of stringline pins is no longer present. However, that does not guarantee that using 3D machine controls will result in better smoothness than using stringline controls.

Based on field observations and profile data collected from multiple projects that used 3D machine control during the *Implementation Support for Second Strategic Highway Research Program (SHRP2) Renewal R06E: Real-Time Smoothness Measurements on Portland Cement Concrete Pavements During Construction* project (Fick et al. 2018), the following items should be monitored for their impact on pavement smoothness:

- Distance between the robotic total station and the paver. Figure 17 shows an example of how allowing the distance between the total station and paver to become too great impacted pavement smoothness, as measured by an RTS system during paving.
- Line of sight issues between the robotic total station and the prism mounted on the paver. These issues may involve the following:
 - Construction equipment
 - Direct sunlight on the prism
 - Heavy fog and mist
 - Excessive dust
- High winds causing movement to the robotic total station and/or the prism mounted on the paver.
- 3D system errors (radio, software, hardware, wiring, batteries, etc.).

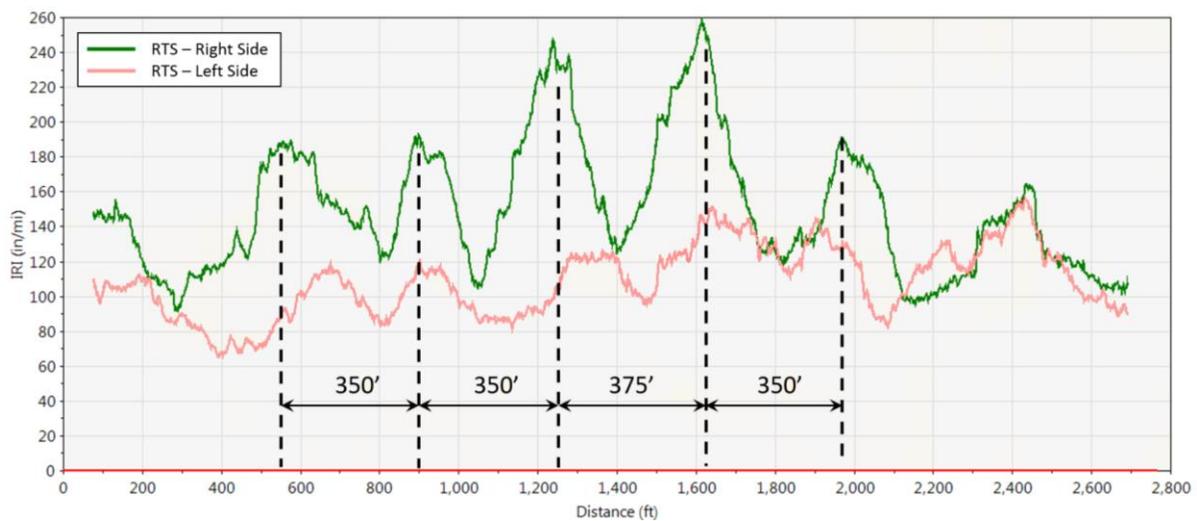


Figure 17. Real-time profile data illustrating fluctuation of IRI corresponding to distance from the paver to the robotic total station

Currently, limited resources and guidance are available that provide best practices for using 3D machine control with concrete pavers. Therefore, the system manufacturer’s procedures should be adhered to. Tools are available for calculating the IRI of the 3D model before paving, and using these tools is highly recommended to identify any issues with the model before paving begins.

3D machine control technology is a valuable construction tool that holds promise for improving concrete pavement smoothness. This potential improvement will be realized as contractors gain more experience with building 3D models and best practices are documented for concrete paving operations.

Spreading Concrete and Concrete Head

Whether trucks are dumping concrete directly ahead of the paver or a concrete placer/spreader is used, the objectives are to keep the paver moving at a consistent speed and maintain a uniform head of concrete in the grout box. Communication between the paver operator and the personnel involved in the dumping/spreading operation is vital. Changes in concrete head should be reacted to as quickly as possible, which is easier to accomplish when the paver is following closely behind the spreader (Figure 18).



The Transtec Group, Inc.

Figure 18. Close spacing between the concrete spreader and paver to allow quick response to changes in concrete head

However, there is a risk of slowing or stopping the paver if it is following too closely to the spreading operation. The paver operator should adjust the speed and following distance to find the best compromise between reacting to changes in concrete head and minimizing paver stops.

Concrete overlays that are designed to correct all surface irregularities (cross-slope, profile variability, etc.) without any milling or a separation layer can present a significant challenge for maintaining a consistent concrete head. The need for quick and effective communication between the paver operator and dumping/spreading operation is especially critical for overlay projects of this type.

Running out of concrete in the paver (i.e., losing all concrete head in the grout box) will result in pavement roughness and likely lead to localized durability issues and should not be tolerated. Process adjustments must be made to prevent this from occurring.

Paver Speed

Under ideal conditions, the paver would operate for an entire shift at a consistent speed without stopping. This is not realistic, but finding a consistent speed that results in minimal stops allows for the entire paving operation to find a rhythm. When a consistent rhythm is found, pavement smoothness typically improves. When using an RTS system to monitor smoothness behind the paver, this semi-continuous paving rhythm also makes it easier to identify whether intentional process changes have had a negative or positive impact on pavement smoothness results.

There is debate about whether slowing the paver down yields better smoothness results than stopping the paver. The answer to this has question has not been definitively quantified, but based on limited data and anecdotal evidence, it appears that stopping the paver does result in better overall smoothness results than drastically slowing the paver down. However, the effects of stopping versus slowing down can depend upon both the paver and how much the paver is slowing down. Contractors should systematically evaluate whether stopping is better than slowing down for their specific paver through field experimentation.

Vibrator Frequency and Height

The primary function of concrete vibrators is to consolidate the concrete. They should be operated at a frequency (vpm) that provides full consolidation without inducing segregation or reducing the entrained air content of the mixture. Vibrators' direct impact on smoothness has not been documented, although experience indicates that they do influence pavement smoothness. The use of a vibrator monitor is highly recommended to accurately monitor and control vibrator frequencies.

Increasing vibrator frequency above the maximum specified limit should not be used to compensate for a mixture that does not finish well or has excessive voids. Mixture adjustments should be made to avoid over-vibration. Higher-than-normal vibrator frequencies may be necessary when the paver speed is increased for thinner concrete overlay pavements. Vibrator frequency may be lowered when paving over a stiff subbase that reflects more vibrator energy.

Adjusting vibrator frequency, height, and/or angle to improve pavement smoothness is something that each contractor can experiment with. Each adjustment should be made independently, and profile data should then be analyzed daily to evaluate the impact of the adjustments. If improvements in smoothness are shown to be related to vibrator frequency, it should be noted that these are likely to be mixture specific and sensitive to the paver's speed. In other words, these same vibrator frequencies may not have an equivalent impact on pavement smoothness for a different mixture or a different paver speed.

Paver Attitude (Lead/Draft)

As described in the checklist under Paving Equipment Setup, the paver should be set up so that the mold is flat relative to the design profile of the roadway. It is fairly common for the front of

the paving mold to be set slightly higher than the rear of the paving mold, a practice referred to as lead or draft. This practice can help fill some surface voids, but when the lead/draft is excessive, concrete will “boil” out of the back of the paving mold, leaving a bulge that then relaxes (Figure 19).

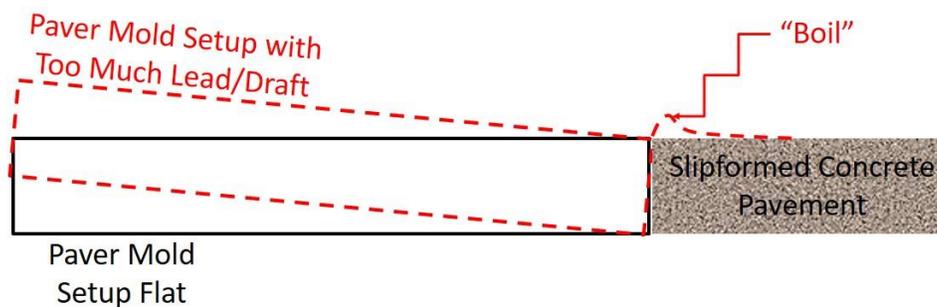


Figure 19. Effect of paving with too much lead/draft

Based on limited profile data, keeping the paving mold as flat as practical leads to improved initial smoothness results. Regardless of whether stringline or 3D paving controls are used, one person on the crew should be responsible for adjusting the lead/draft, and those adjustments should be logged so that the paver can be adjusted back to flat without having to determine the adjustments that were made after the start of paving. In general, lead/draft should be reduced when paving uphill and increased slightly when paving downhill.

DBI Roll Height and Oscillating Correcting Beam (OCB)

Similar to the grout box, the DBI carries a head of concrete “roll” to fill in the voids left after the load transfer dowels are inserted. The OCB then puts a final finish on the pavement. To improve smoothness results, the roll carried ahead of the OCB should be maintained as uniform as possible.

The OCB should be straight and true and properly adjusted to the crown/cross-slope(s) of the design typical section. The oscillating frequency can be adjusted and the profile results evaluated to determine the impact of the adjustments on pavement smoothness.

Hydraulic Response

The paving mold on a slipform paver is maintained at the prescribed grade by movement of the leg barrels. The magnitude of the leg barrel movement necessary to hold the paving mold at grade is dictated by input from the stringline sensors or 3D control system. The speed with which the leg barrels react to that input is adjustable for both types of control systems. The paver can be set up to react quickly or sluggishly by changing the sensitivity settings. The optimal sensitivity settings for a given project should be related to the relative smoothness of the paver track line. Smooth track lines warrant higher sensitivity settings (resulting in quicker leg barrel reactions) than rough track lines (for which slower leg barrel reactions yield the best performance).

Real-time smoothness results have shown significant improvements to initial smoothness when sensitivity is adjusted appropriately. An example IRI profile from a recent project that illustrates the impact of sensitivity adjustments is shown in Figure 20.

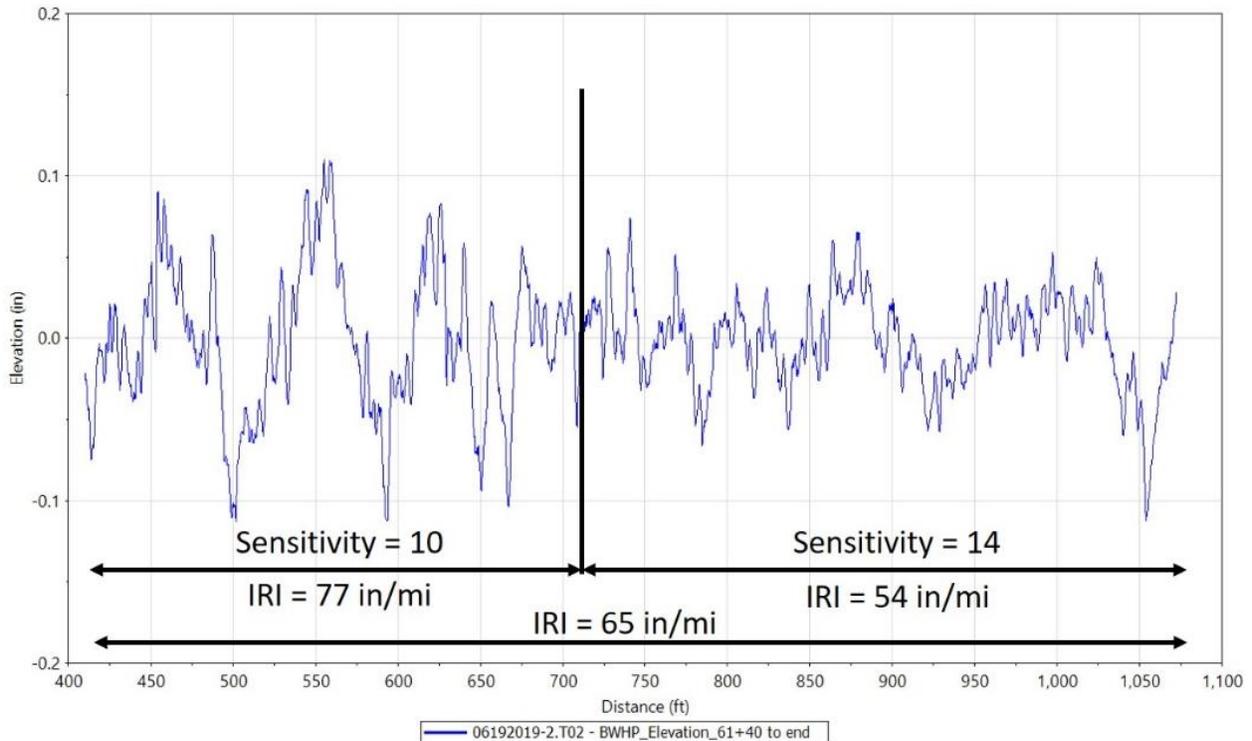


Figure 20. Improved IRI results from sensitivity adjustment

Hand Finishing

Although there are rare exceptions, hand finishing behind the slipform paver is the current practice in the US. The combination of tools used and their order of use varies widely by contractor and region. These decisions are partially driven by the mixture’s response to vibration, the setup of the paver, and contractor preference. The results provided in *Real-Time Smoothness Measurements on Portland Cement Concrete Pavements During Construction* (Fick et al. 2018) show that hand finishing does improve the initial smoothness of concrete pavements. A summary of these results and two example charts showing improved profiles after hand finishing (Figures 21 and 22) are provided here as evidence that hand finishing reduces localized roughness and improves short-baselength continuous IRI results.

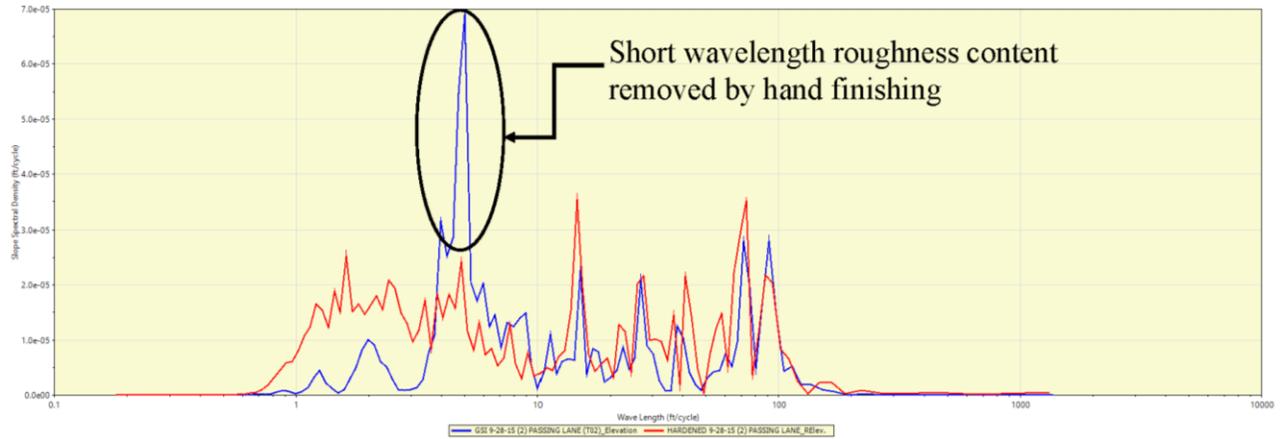


Figure 21. Comparison of power spectral density (PSD) data for real-time (blue) and hardened (red) profiles demonstrating that hand finishing removes roughness at the 5 ft wavelength

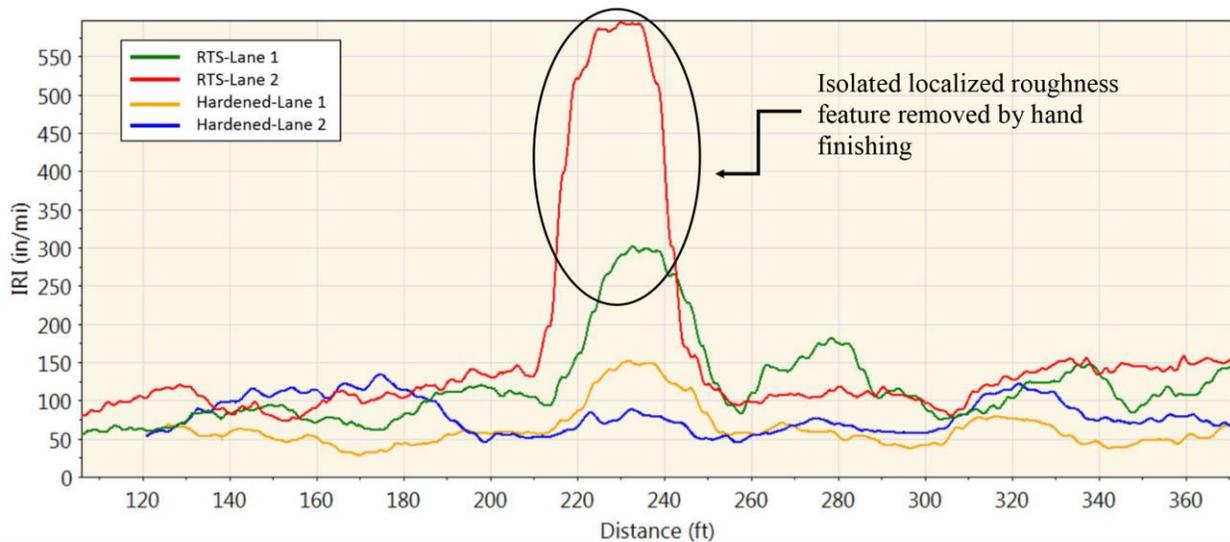


Figure 22. Example of localized roughness removed by hand finishing

Fick et al. (2018) states the following regarding the effects of hand finishing:

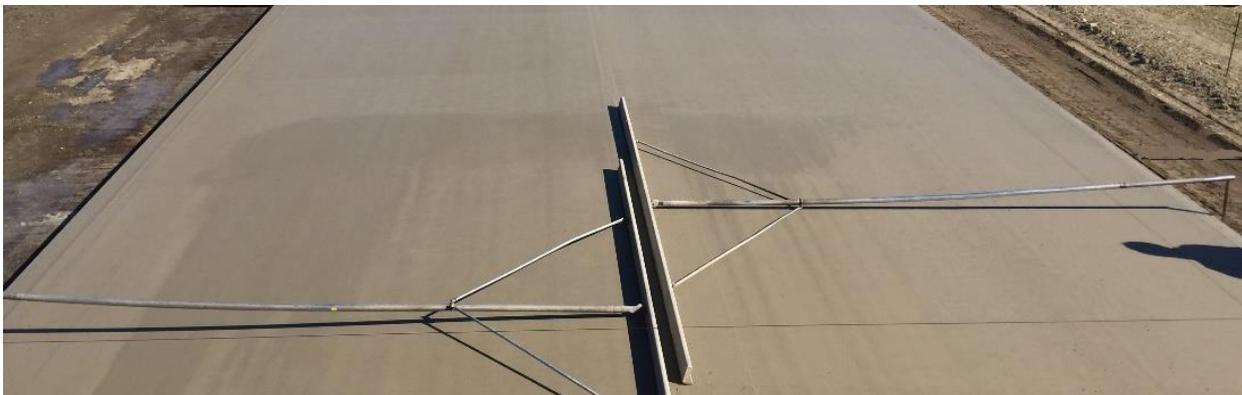
If one accepts that real-time profilers accurately measure the profile directly behind the paver and then considers all of the potential changes to the early-age pavement profile that could occur between the real-time IRI measurement and the hardened IRI measurement, finishing (hand finishing or auto-float) is the only item that could potentially lower the IRI.

Based on the observations and analyses performed throughout the equipment loans, proper hand finishing can improve the initial smoothness of concrete paving. A contractor can compare real-time and hardened profile data to confirm that the hand finishing techniques being used by their crew are effective. However, because there are

so many factors that have the potential to increase the hardened IRI, the same comparison cannot be used to determine if the finishing techniques are introducing roughness into the profile. (Fick et al. 2018)

The following recommendations for hand finishing techniques to improve concrete pavement smoothness are based on observation and comparison of real-time and hardened profile data:

- If a float is needed to fill surface voids, it should be used transversely ahead of a straightedge and be at least 8 ft in length.
- In all cases, a straightedge with a minimum length of 16 ft should be used transversely (Figure 23). The straightedge should be centered over load transfer devices and advanced to overlap a minimum of 4 ft for each pass.



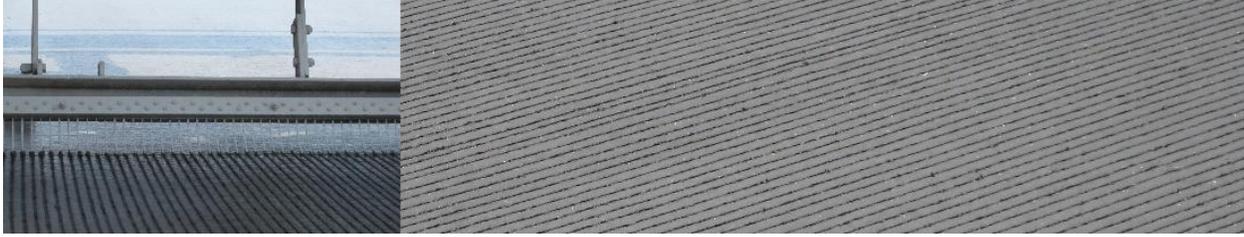
The Transtec Group, Inc.

Figure 23. Hand finishing with two 16 ft straightedges

Final Texture

The potential impacts of pavement macrotexture on smoothness are primarily known through anecdotal evidence. One study performed by the Minnesota Department of Transportation (MnDOT) on broom-textured concrete pavement showed that an inertial profiler measured different IRI values for textured versus non-textured pavements (Izevbekhai and Ahn 2017). These differences in IRI were most sensitive to the time of measurement and type of laser used. In theory, however, the tire envelopment moving average filter applied when computing IRI should filter out the short-wavelength roughness from pavement texture.

Regardless of the effects of texture on IRI, best practices for imparting macrotexture to a concrete pavement should be used. These practices are fully described in *How to Reduce Tire-Pavement Noise: Better Practices for Constructing and Texturing Concrete Pavement Surfaces* (Rasmussen et al. 2012). Although this resource is focused on tire-pavement noise, the practices described for constructing uniform macrotexture (Figure 24) are applicable to reducing any impact that macrotexture may have on IRI or the measurement of IRI.



The Transtec Group, Inc.

Figure 24. Uniform macrotexture as a result of good construction practices

In order to construct uniform macrotexture, project controls should be implemented to accomplish the following on a daily basis:

- Inspect all burlap, turf, and broom drags; replace as necessary.
- Verify that all drags are installed soundly and will result in texture that is parallel to the centerline of the pavement.
- Ensure that the misting spraybar and/or hose(s) for wetting drags are operating correctly and will not result in excess water being applied to the pavement surface.
- Inspect and clean all tines; replace any tines that are bent or have mortar buildup.

Curing

Curing compound is applied to a concrete pavement at an early age primarily to minimize moisture loss, which, if not prevented, leads to moisture warping, early-age cracking, durability issues, and many other undesirable performance issues. A secondary effect of applying white-pigmented curing compound is the reflectance of solar radiation, which reduces the early-age temperature of the concrete as it develops strength. This temperature reduction can reduce the magnitude of temperature curling as well.

Both moisture warping and temperature curling have been shown to have significant effects on jointed concrete pavement smoothness (Merritt et al. 2015). Therefore, proper application of curing compound can be an important step in improving the initial smoothness of concrete pavements.

The following practices should be implemented to ensure that curing compound is applied correctly:

- Clean all spray nozzles daily.
- Use the specified curing compound.
- Keep the curing compound well agitated.
- Completely cover the pavement with curing compound (Figure 25).



National CP Tech Center

Figure 25. Full and complete coverage of curing compound, which can reduce curling and warping

SMOOTHNESS MEASUREMENTS

Many methods and indices have been used over the years to quantify pavement smoothness. While straightedges and profilographs have been the predominant methods used for concrete pavements, the proliferation of inertial profiler technology has led to IRI becoming widely adopted in the US as the primary metric for pavement smoothness acceptance and pavement management systems. For comprehensive information regarding IRI, readers can consult the Pavement Tools Consortium (n.d.) Pavement Interactive webpage on Roughness: <https://www.pavementinteractive.org/reference-desk/pavement-management/pavement-evaluation/roughness/>.

Complementary to all recommendations discussed in these guidelines regarding the impact of design, specifications, mixture, equipment, and construction processes on initial smoothness is the need to obtain quality pavement profile data for the calculation of IRI. This chapter provides a description of real-time and hardened smoothness measurements, key issues related to collecting quality smoothness data, and references for additional information.

Real-Time Smoothness Measurements

Description

Measuring concrete pavement smoothness in real-time, during paving, enables the contractor to quickly evaluate the effects of material and process adjustments on smoothness results. An RTS system allows the contractor to gauge whether an adjustment has had a positive or negative effect on pavement smoothness almost immediately instead of after hardened profile data are collected 18 to 36 hours later. RTS systems are not appropriate for acceptance measurements, nor are they a replacement for inertial profilers as a quality control (QC) tool. As a QC tool, they are best used in conjunction with a lightweight inertial profiler so that real-time and hardened IRI results are considered when evaluating efforts aimed at improving initial pavement smoothness.

RTS devices have been proven to provide measurements adequate for QC feedback and are commercially available for mounting to virtually any slipform paver (Figure 26).



Ames Engineering (left) and GOMACO (right)

Figure 26. RTS devices installed on slipform pavers

Key Points for Using RTS Devices

The following list, from *Implementation Support for Second Strategic Highway Research Program (SHRP2) Renewal R06E: Real-Time Smoothness Measurements on Portland Cement Concrete Pavements During Construction* (Fick et al. 2018), summarizes lessons learned and guidance for implementation of RTS for contractors:

1. Is there any clear relationship or correlation between RTS and hardened profile data and smoothness indices?
 - With regard to IRI, there is no definitive relationship between real-time versus hardened smoothness values that can be applied to all projects.
 - In general, real-time IRI will be higher (rougher) than hardened data, but not by a fixed amount. And the higher the real-time IRI values, the greater the difference between the real-time and hardened IRI values. ... [R]eal-time numbers have ranged from less than 2 in./mi to over 95 in./mi higher than the hardened numbers.
 - The relationship will be project specific and will need to be established during the first few days of a paving project in order for the contractor to use the real-time data to adjust paving processes.

2. Which features show up in real-time profiles but not in hardened profiles and vice versa?
 - Very good agreement exists between the real-time and hardened profiles, assuming the DMIs [distance measuring instruments] are properly calibrated. Similar trends in the profile can be observed when comparing real-time and hardened profiles after high-pass filtering of the profile data.
 - Real-time profiles will generally contain a greater amount of shorter wavelength content than hardened profiles. This is due to finishing processes (straightedge and float) applied to the pavement slab behind the RTS profilers, which remove much of this shorter wavelength content.
 - Real-time profilers generally pick up long-wavelength content (greater than 80 ft) that is not necessarily relevant to ride quality and not likely caused by any processes related to

the paving operation. Further investigation of the source of this long-wavelength content, and what relevance it may have to paving processes, is needed.

3. What artifacts of the pavement or paving process are picked up in the RTS data such that corrections/adjustments can be made?
 - Real-time profilers pick up the effects from dowel basket rebound, which show up as dominant spectral content at the joint (dowel basket) spacing. This joint-related spectral content [is] not as dominant and, in most cases, [has not been] observed in projects that utilized dowel bar inserters. In most cases, dowel basket effects are less dominant in the hardened profiles, likely due to the finishing processes that remove many of these disturbances at the dowel baskets.
 - Stringline effects (stringline sag or chord effects) are picked up in both the real-time and hardened profile data. This is likely due to the inability of the finishing processes to remove this longer (25 to 50 ft) wavelength content.
 - Although dowel basket rebound and stringline sag effects may be dominant content in a spectral analysis, this does not mean that these factors adversely affect smoothness numbers. Dominant spectral content should always be evaluated in context of the overall smoothness numbers.
 - Spacing of concrete loads can also be picked up in real-time and hardened profile data. Load spacing content may be due to slight variations in the concrete mixture, which cause the paver to respond in such a manner as to leave a feature in the pavement profile, or this content may simply be due to the paver's response to varying heads of fresh concrete in front of the paver. Similar to stringline effects, PSD content at the load spacing interval should always be evaluated in context of the overall smoothness numbers

Additional RTS References

The following additional resources are available on the National CP Tech Center's Real-Time Smoothness webpage at <https://cptechcenter.org/real-time-smoothness/>:

- *Real-Time Smoothness Quick Reference Index* (Fick and Merritt 2018a)
- *Real-Time Smoothness Pocket Reference* (Fick and Merritt 2018b)
- *Real-Time Smoothness Measurements on Portland Cement Concrete Pavements During Construction* (Fick et al. 2018)

Hardened Pavement Smoothness Measurements

Timely collection of hardened pavement profile data is critical for assessing the impacts of various project features and paving processes on pavement smoothness. Ideally, hardened profile data should be collected after each day of paving so that, if necessary, adjustments can be made to the next day's paving. If an RTS system is also being used, it is critical to compare the RTS and hardened pavement results to develop a correlation between the two. This allows the contractor to have at least a general idea of the hardened pavement smoothness results based on the RTS numbers during paving.

The use of inertial profilers for collecting pavement profile data has been standard practice in the US for many years. While there have been issues with the repeatability of profile data using single-point lasers on longitudinally tined concrete, most modern inertial profilers use wide-spot or line lasers, eliminating this issue. Lightweight inertial profilers have become very affordable and allow measurement of the hardened pavement profile the day after paving, providing critical feedback for subsequent days of paving.

Key issues related to collecting early-age profile data and evaluating IRI include the following:

- The pavement surface should be clear of foreign objects and debris (saw slurry, rocks, dirt, etc.) that may artificially impact IRI.
- For jointed concrete pavements, changes in IRI may be observed when profiling at different times of day as a result of temperature curling and/or moisture warping. While some agencies have adopted time-of-day profiling requirements to address this issue, there is still no established standard method to account for potential differences in IRI at different times of day.

A valuable resource that provides additional information on collecting profile data and computing IRI is *The Little Book of Profiling* (Sayers and Karamihas 1998).

Profile Data Analysis

The Federal Highway Administration's (FHWA's) ProVAL software is a nationally accepted tool for analyzing profile data and is referenced in most state highway agency (SHA) specifications. It is a free software tool that can be downloaded from <http://www.roadprofile.com/>.

Some of the key analysis modules within the ProVAL software that are useful for analysis of both hardened and real-time pavement profile data include the following:

- *Ride Quality (RQ)* – This analysis module allows the user to compute various roughness indices (IRI, Mean Roughness Index, Half-Car Roughness Index, Ride Number) using three reporting options: overall roughness (a single value for the entire profile), fixed-interval roughness (e.g., 0.1-mile segment analysis), and continuous roughness (typically used to identify ALR).
- *Smoothness Assurance Module (SAM)* – This analysis module allows for simultaneous analysis of fixed-interval (e.g., 0.1-mile segment) and localized roughness as well as a side-by-side comparison of roughness (e.g., IRI) data and raw pavement profile data to help identify features (e.g., bumps and dips) in the profile that are contributing to roughness. SAM also provides a grinding simulation tool that generates a fully customizable grinding plan to

allow the user to evaluate the effects of diamond grinding on the smoothness results before any actual grinding on the pavement.

- *Power Spectral Density (PSD)* – This analysis module helps identify dominant content (i.e., repeating patterns) in the profile data caused by pavement features or paving processes that may be contributing to roughness.

REFERENCES

- Amos, D. 2006. *Pavement Smoothness and Fuel Efficiency: An Analysis of the Economic Dimensions of the Missouri Smooth Road Initiative*. Missouri Department of Transportation, Jefferson City, MO.
- Carey, W. N., Jr. and P. E. Irick. 1960. *The Pavement Serviceability-Performance Concept*. HRB Bulletin 250. Highway Research Board, Washington, DC.
<http://onlinepubs.trb.org/Onlinepubs/hrbulletin/250/250-003.pdf>.
- Chatti, K. 2010. Effect of Pavement Conditions on Rolling Resistance and Fuel Consumption. Pavement Life Cycle Assessment Workshop, May 5–7, Davis, CA.
http://www.ucprc.ucdavis.edu/P-LCA/pdf/08_rollingresistance_web.pdf.
- Fick, G. and D. Merritt. 2018a. *Real-Time Smoothness Quick Reference Index*. National Concrete Pavement Technology Center, Iowa State University, Ames, IA.
https://intrans.iastate.edu/app/uploads/sites/7/2018/10/RTS_quick_reference_index.pdf.
- Fick, G. and D. Merritt. 2018b. *Real-Time Smoothness Pocket Reference*. National Concrete Pavement Technology Center, Iowa State University, Ames, IA.
https://intrans.iastate.edu/app/uploads/sites/7/2018/10/RTS_pocket_reference_11x8.5.pdf.
- Fick, G., D. Merritt, P. Taylor, T. Hanke, H. Torres, and R. Rasmussen. 2018. *Implementation Support for Second Strategic Highway Research Program (SHRP2) Renewal R06E: Real-Time Smoothness Measurements on Portland Cement Concrete Pavements During Construction*. National Concrete Pavement Technology Center, Iowa State University, Ames, IA. https://intrans.iastate.edu/app/uploads/sites/7/2018/10/real-time_smoothness_implementation_asstc_summary_w_cvr.pdf.
- Izevbekhai, B. I. and H. J. Ahn. 2017. *Line Laser and Triple Laser Quantification of the Difference in International Roughness Index between Textured and Non-Textured Strips*. Minnesota Department of Transportation, St. Paul, MN.
- Ley, T., D. Cook, and G. Fick. 2012. *Concrete Pavement Mixture Design and Analysis (MDA): Effect of Aggregate Systems on Concrete Properties*. National Concrete Pavement Technology Center, Iowa State University, Ames, IA.
https://intrans.iastate.edu/app/uploads/2018/03/mda_aggregates_w_cvr-1.pdf.
- Merritt, D. K., G. K. Chang, H. N. Torres, K. Mohanraj, and R. O. Rasmussen. 2015. *Evaluating the Effects of Concrete Pavement Curling and Warping on Ride Quality*. Colorado Department of Transportation, Denver, CO.
- Oklahoma State University. n.d. Tarantula Curve. <http://www.tarantulacurve.com/>.
- Pavement Tools Consortium. n.d. Pavement Interactive: Roughness.
<https://www.pavementinteractive.org/reference-desk/pavement-management/pavement-evaluation/roughness/>.
- Rasmussen, R. O., P. D. Wiegand, G. J. Fick, and D. S. Harrington. 2012. *How to Reduce Tire-Pavement Noise: Better Practices for Constructing and Texturing Concrete Pavement Surfaces*. National Concrete Pavement Technology Center, Iowa State University, Ames, IA. https://intrans.iastate.edu/app/uploads/2018/08/How_to_Reduce_Tire-Pavement_Noise_final.pdf.
- Sayers, M. W. and S. M. Karamihas. 1998. *The Little Book of Profiling: Basic Information about Measuring and Interpreting Road Profiles*. University of Michigan, Ann Arbor, MI.

- Taylor, P. 2018. *Performance of Engineered Mixtures for Contractors*. Tech Brief. National Concrete Pavement Technology Center, Iowa State University, Ames, IA.
- Taylor, P., T. Van Dam, L. Sutter, and G. Fick. 2019. *Integrated Materials and Construction Practices for Concrete Pavement: A State-of-the-Practice Manual*. Second Edition. National Concrete Pavement Technology Center, Iowa State University, Ames, IA. https://intrans.iastate.edu/app/uploads/2019/05/IMCP_manual.pdf.

National Concrete Pavement
Technology Center

