Surface Characteristics of Segmental Concrete Pavements Acceptable to Wheelchair Users

David R. Smith,[1] Eric Sinagra[2] and Jonathan Duvall[3]

[1] Technical Director, Interlocking Concrete Pavement Institute, 14801 Murdock Street, Suite 230, Chantilly, Virginia 20151 USA

[2] CEO, Pathway Accessibility Solutions, Inc., 1401 Forbes Avenue, Suite 303, Pittsburgh, Pennsylvania 15219 USA

[3] Co-founder Pathway Accessibiltity Solutions, Inc., 1401 Forbes Avenue, Suite 303, Pittsburgh, Pennsylvania 15219 USA

Correspondence e-mail address: dsmith@icpi.org

Abstract

The United States Access Board is the federal government agency that develops standards and guideliness for accessibility. These standards apply to buildings and the public right-of-way. Research funded by the Access Board investigated acceptable surface roughness for sidewalk pavements for wheelchair users. The technology to measure surface roughness computes vertical displacement over a given horizontal distance (roughness index) is called Pathway Measurement Technology (PathMeT). This was developed by the University of Pittsburgh. PathMeT development was supported by the Interlocking Concrete Pavement Institute and Brick Industry Association. The use of the measurement technology was formalized into an ASTM standard. The University of Pittsburgh roughness criteria using this measurement method has been published by the US Access Board to assess accessibility of sidewalks by wheelchair users. This paper provides data measured on segmental concrete pavements by PathMeT around three cities in the Eastern United States, The data defines accessible segmental concrete pavement surfaces, marginial ones, and those that would potentially deny access to wheelchair users based on a high roughness index. Surface roughness information can be included in municipal sidewalk pavement management and maintenance programs, as currently done for roadways.

Key Words: segmental pavement roughness; wheelchair accessibility on segmental pavements; sidewalk pavement management

Introduction

Over three million people in the United States use wheelchairs. They are part of approximately 15% of the population that has a temporary or permanent physical disability. All rely on sidewalks as a primary travel way. Since 2000, national legislation in the United States known as the American with Disabilities Act (ADA) require that sidewalks and other surfaces in the public right-of-way (owned by federal, state and municipal goverments) be accessible to disabled persons. Accessibility is defined through design guidelines published by the Access Board for accessible surfaces and routes. These are as follows:

Table 1. United States Access Board accessibility requirements for surfaces and pavements.

Parameter	Requirement
Sidewalk or Path Width	Minimum 91.5 cm
Openings	Maximum 13 mm
Obstacles in Path	
Up to 6 mm	No action needed
6 mm to 13 mm	Use bevel with maximum 1:2 slope ~26°)
Over 13 mm	Use Ramp
Ramp Slopes	
1:12 to 1:16 (5° to 3.5°)	Maximum 0.75 m high, 9 m long
1:16 to 1:20 (3.5° to 2.8°)	Maximum 0.75 m high, 12 m long
Cross Slope	1:50 (~1°)

The above guidelines do not account for surface roughness which can impact wheelchair user comfort. Rough sidewalks can cause wheelchair users neck and back pain, thereby making some sidewalks inaccessible.

Past Research

Design guidelines were proposed in 2000 by the Access Board that excluded segmental paving from the traveled portion of sidewalks in an onstentsible effort to make them accessible by wheelchair users. The concrete and clay brick paving industries responded by funding research on the relationship between surface characteristics and vibrations. This research was done in 2002 [1] and 2004 [2] by the University of Pittsburgh (Pennsylvania) Human Environmental Research Laboratories. This work involved measuring whole body vibrations with accelerometers on the foot rest and on the seat of manual and powered wheelchairs.

Manual and powered wheelchair users traversed concrete and clay paving units with a range of chamfers and joint widths in 90 and 45 degree herringbone patterns, as well as on jointed, cast-in-place concrete sidewalks (see Figure 1). Manual wheelchairs traversing 90 degree herringbone pavers with 0 and 2 mm wide chamfers exhibited lower vibrations than from a cast-in-place concrete sidewalk. Figure 2 illustrates chamfer width. With higher weights and wider pneumatic tires, powered wheelchars on pavers with a 90 degree herringbone pattern and no chamfers exhibited less vibrations at the seat than cast-in-place concrete surface. Pavers in a 90 degree herringbone with 0, 2 and 4 mm wide chamfers produced less vibrations in the wheelchair footrest than the cast-in-place concrete surface. Not surprisingly, the 90 degree herringbone pavers with the widest chamfers at 8 mm generated the highest vibrations. Large joints spaced every 1.2 meters in the cast-in-place concrete surface explains why it generated higher vibrations than on some segmental pavement surfaces.



Figure 1. Pavements tested for vibrations in manual and powered wheelchairs in 2002 and 2004 by the University of Pittsburgh.

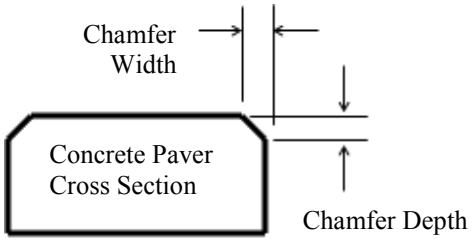


Figure 2. Chamfer width illustrated

A second vibration study was conducted in 2004 on some of the same surfaces in the previous study, plus additional paver surfaces. In the second study, wheelchair users traversed over the cast-in-place concrete, pavers in 90 degree herringbone with 0, 2 and 8 mm wide chamfers, and pavers in a 45 degree herringbone with with 0 and 4 mm wide chamfers. Vibration levels were compared to that in ISO 2631 *Mechanical Vibration and Shock -- Evaluation of Human Exposure to Whole-Body Vibration*. This standard includes vibration limits for human bodies over eight hours. It evaluates vibration in the workplace e.g., for truck drivers and helicopter pilots.

The second study provided additional information on wheelchair users subjection to vibrations. The results indicated that powered wheelchars moving at 1 m/s over pavers in 90 degree herringbone pattern with 8 mm chamfers and 45 degree herringbone with 4 mm wide chamfers generated vibrations that exceeded the ISO 2631

limit for 8-hour exposure. When traveling a 2 m/s, the ISO 2631 vibration exposure limits were exceeded in less than three hours of continuous driving on all surfaces. Wheelchair users do not typically drive for three hours without stopping. However, some do move about for 8 hours and experience vibrations.

To obtain a clearer view of vibration exposure of manual wheelchair users over an 8 hour day, Garcia, et al. [3] attached vibration data loggers, wheel encoders and seat occupancy sensors to the user's wheelchair. Vibrations were recorded for two weeks on wheelchair users traversing their community and at events. All study participants received vibration levels at the seat surface within or over the health caution zone set by the ISO 2631 standard.

Development of Surface Roughness Acceptance Criteria for Wheelchair Users

Further research was conducted by the University of Pittsburgh for the US Access Board in 2013 to develop a clearer relationship between surface roughness and wheelchair user comfort [4][5]. Measuring surface roughness was considered a suitable surrogate for measuring seat and footrest vibrations, and followed the rationale in vehicular pavement roughness assessment. The research used laboratory and field measurements of manual and power wheelchair users to develop a roughness index expressed as vertical change divided by traveled horizontal distance.

Simultaneous to this research, the clay and concrete segmental paving industries funded the University of Pittsburgh to develop a prototypical, custom-built surface measurement device [6]. Named pathway measurement tool or PathMeT, the initial device used an instrumented power wheelchair frame with an encoder and a laser distance sensor aimed perpendicular to the ground. The laser recorded distances and elevation changes every 1 mm. This measurement resolution was needed due to 3-5 mm joint widths as well as chamfer widths in segmental concrete pavements. Actually, the laser measured with an accuracy of less than 1 mm traveling at 1 m/s. The PathMeT prototype went through several design iterations for eventually being used for the research described in this paper.

In addition to developing a prototype device, a national standard was developed by the University of Pittsburgh and approved by the American Society of Testing and Materials International (ASTM) on how to collect and process data using PathMeT or similar roughness measurement equipment. This effort resulted in publication of ASTM E3028 *Standard Practice for Computing Wheelchair Pathway Roughness Index as Related to Comfort, Passability, and Whole Body Vibrations from Longitudinal Profile Measurements* [7]. This practice develops a Wheelchair Pathway Roughness Index (WPRI). According to this ASTM standard, a WPRI is "an index computed from a longitudinal profile measurement using a standard 70 mm (2.5 in.) diameter wheel with no deformation and no affects from speed. The index represents the total vertical deflection of that wheel as it travels over a surface….WPRI is reported in either millimeters per meter (mm/m) or inches per foot (in./ft)."

The international roughness index (IRI) measurement for vehicles per ASTM E1926 *Standard Practice for Computing International Roughness Index of Roads from Longitudinal Profile Measurements* was instructive. Like ASTM E1926, PathMeT measures and sums the vertical deviations of the surface profile over a given horizontal distance. Unlike road vehicles, wheelchairs have distinctly different wheels (and suspensions), typically small wheels on the front and larger wheels on the rear. Wheel diameter, tires size and paver joint widths were expected to vary. To overcome these variations, a "standard wheel" of 70 mm diameter was selected for the research. A U.S. Transportation Research Board paper by Duvall et al. [4] provides a thorough explanation on filtering roughness data to equalize variations in wheel sizes to the standard wheel after taking laboratory and field roughness measurements.

Beside presenting laboratory and field roughness data, his paper provides rationale for roughness index not exceeding 50 mm per 1 m measured over distances of 30 m along an accessible route such as a sidewalk. For distances less than 3 m, a proposed roughness threshold is 100 mm per 1 m. The U.S. Access Board recognized these indexes [8]. It remains to be seen if the Board publishes guidelines on roughness indexes initially as non-mandatory advisory Information. If done, this may lead to the guidelines becoming an enforceable accessibility design criteria in future years.

Field Measurements

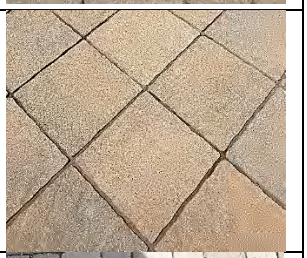
Field surveys using PathMeT were completed to better understand the relationship among surface roughness and concrete paver shapes, patterns, joint and chamfer widths that conform or do not conform to the above-noted acceptance guidelines. Surveys were conducted on interlocking concrete pavements (ICP), permeable interlocking concrete pavements (PICP) and segmental concrete paving slabs in Pittsburgh, Pennsylvania (36 measurements), northern Virginia near Washington, DC (38 measurements), and in the Philadephia, Pennsylvania area (29 measurements). The data was collected in 2017 and 2018 by Pathway Accessibility Solutions, Inc. (pathVu), specializing in data collection and analysis of roughness information for use in sidewalk asset management systems. PathVu used an improved design of the PathMeT device originally developed by the University of Pittsburgh which conformed to the requirements of ASTM E3028.

Tables 2, 3 and 4 visually characterize the surfaces and present the data collected. Tthese tables do not include the entire set of roughness data from 103 sites. The tables present characteristics of all surfaces. The age of and base materials under the surfaces were not established since obtaining this data was outside the scope and budget for this study. All sites are in climate zones subject to freezing. However, all measurements were taken in non-freezing temperatures.

Interlocking concrete pavement (ICP) or permeable interlocking concrete pavement (PICP) means paving units that conform to those in ASTM C936 *Standard Specification for Solid Interlocking Concrete Paving Units*. The term ‘slab’ indicates larger paving units that conform to ASTM C1782 *Standard Specification for Segmental Concrete Paving Slabs*. Most of the surfaces had no special surface texture whereas a few surfaces consisted of tumbled units or those with verigated surfaces. The laying pattern and the orientation shown under the Surface Illustrations column in the tables also indicates the direction of travel of the PathMeT device. Based on suggested thresholds by Duvall et al., [5] a WPRI less than 50 mm/m over 100 m is considered an accessible surface by wheelchair users.

Table 2. Characteristic WPRI data for segmental concrete pavements in Pittsburgh

Location, Pavement Type, Pattern, Notes	Average Joint width, mm	Average Chamfer width, mm	WPRI	Surface Illustration
Pittsburgh ICP 90 degree herringbone	2.7	0	16.4	
Pittsburgh ICP Parquet	2.6	6.9	17.5	
Pittsburgh ICP Running bond Slightly textured Surface	3.5	0	22	

Pittsburgh ICP & Slabs Random pattern Tumbled surface	3.3	0	24.7	
Pittsburgh Slabs Stack bond Textured surface	11.7	0	24.7	
Pittsburgh ICP Running bond Textured surface	2.9	5.2	25	
Pittsburgh Slabs Random Textured surface	3.1	0	25.7	
Pittsburgh Stone Running bond Textured surface	19.7	2.2	58.2	
Pittsburgh ICP Random No texture	5.7	0	65.7	

Pittsburgh PICP 90 degree herringbone No texture	43.2	6.2	68.3	
Pittsburgh ICP Running bond No texture	1.7	5.5	78	

Table 3 provides excerpts from 38 sites measured in Virginia near Washington, DC. Most of the surfaces are PICP.

Table 3. Characteristic WPRI data for segmental concrete pavements in nothern Virginia.

Location, Pavement Type, Pattern, Notes	**Average Joint width, mm**	**Average Chamfer width, mm**	**WPRI**	**Surface Illustration**
Virginia (16)	10.3	0	27	
Virginia (14)	10.3	0	32.8	
Virginia (15)	10.5	0	36.1	

Virginia PICP 45 degree herringbone No texture (less joints) (3)	2.7	5.8	28	
Virginia PICP 45 degree herringbone No texture (more joints) (2)	2.2	5.1	55.7	
Virginia PICP L-shaped 45 degree Herringbon No texture (33)	5.0	4.4	30.9	
Virginia PICP L-shaped 90 degree Herringbon No texture (1)	6.1	4.5	31.9	
Virginia Slabs and pavers Random Pattern Textured surface (11)	7.8	5.7	37.1	
Virginia PICP 45 degree herringbone No texture (19)	2.6	0	34.8	

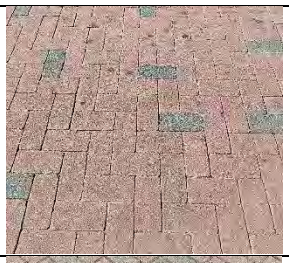
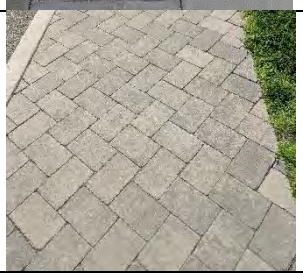
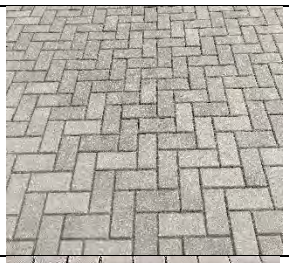
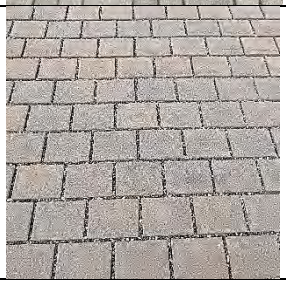
Virginia PICP 45 degree herringbone No texture (18)	3.9	0	34.9	
Virginia PICP 45 degree herringbone No texture (31)	3.3	7.7	75.9	

Table 4.Characteristic WPRI data for segmental concrete pavements in Philadelphia.

Location, Pavement Type, Pattern, Notes	**Average Joint width, mm**	**Average Chamfer width, mm**	**WPRI**	**Surface Illustration**
Philadelphia ICP Running bond No texture (8)	1.7	5.3	18.5	
Philadelphia ICP 90 degree herringbone No texture (2)	2.5	3.1	25.5	
Philadelphia Slabs Random pattern No texture (1)	3.9	N/A	30.0	
Philadelphia ICP 45 degree herringbone No texture (21)	3.7	2.3	30.6	

Philadelphia ICP Running bond Tumbled texture (19)	5.8	3.7	32.3	
Philadelphia ICP K-pattern & running bond No texture (16)	2.3	5.6	36.1	
Philadelphia ICP Running bond No texture (22)	2.3	7.5	42.1	
Philadelphia PICP Stack bond No texture (26)	15.2	5.2	44.7	
Philadelphia PICP Running bond No texture (26)	14.2	4.6	48.8	

Philadelphia ICP 90 degree herringbone No texture (5)	2.5	5.7	48.9	
Philadelphia PICP Running bond No texture (18)	15.3	5.3	57.9	

Discussion

All data was subject to regression analyses to help identify trends in data groupings. The data was divided into ICP and PICP surfaces and WPRI analyzed as influenced by average joint width and chamfer width. The results are shown in Figures 3 through 6. A least squares (thin dotted) line is included in each as well as a thicker horizontal dashed line indicating the 50 mm/m over 30 m roughness criteria for accessibility.

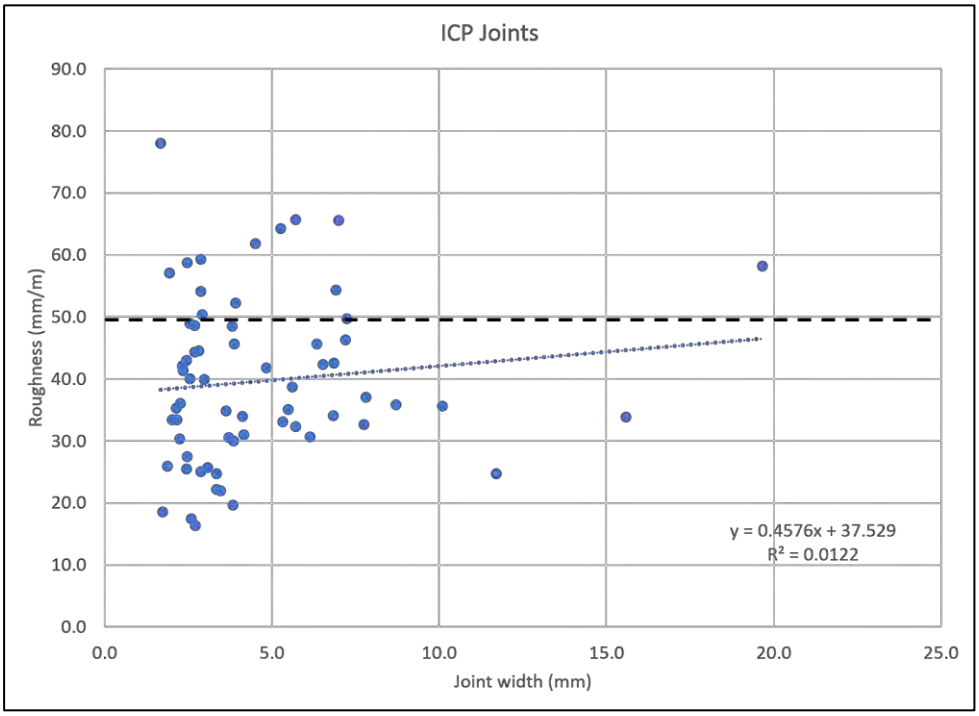


Figure 3. WPRI as a function of average ICP joint widths

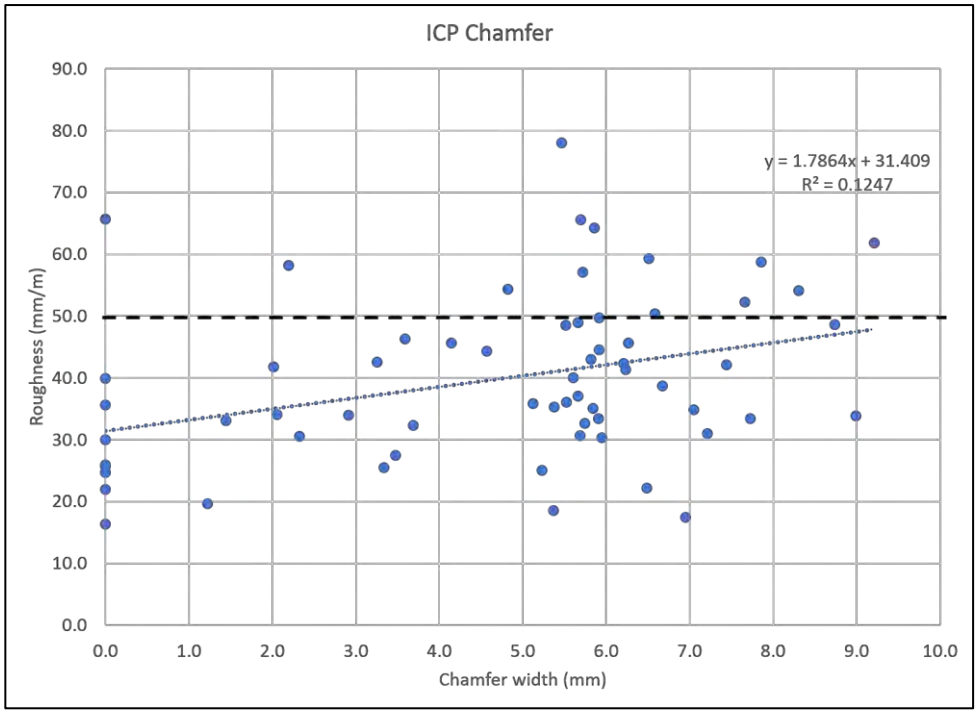


Figure 4. WPRI as a function of average ICP paving unit chamfer widths

The data in Figures 3 and 4 suggest that with ICP, joint and chamfer widths less than 5 mm can help ensure a wheelchair user-friendly WPRI less of than 50 mm/m.

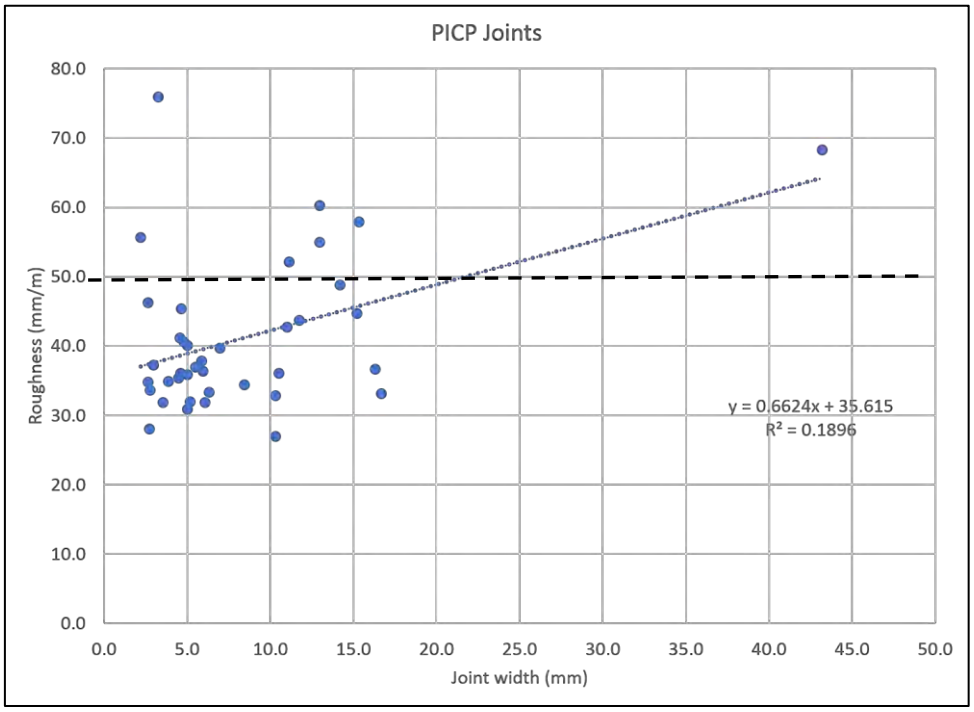


Figure 5. WPRI as a function of average PICP joint widths

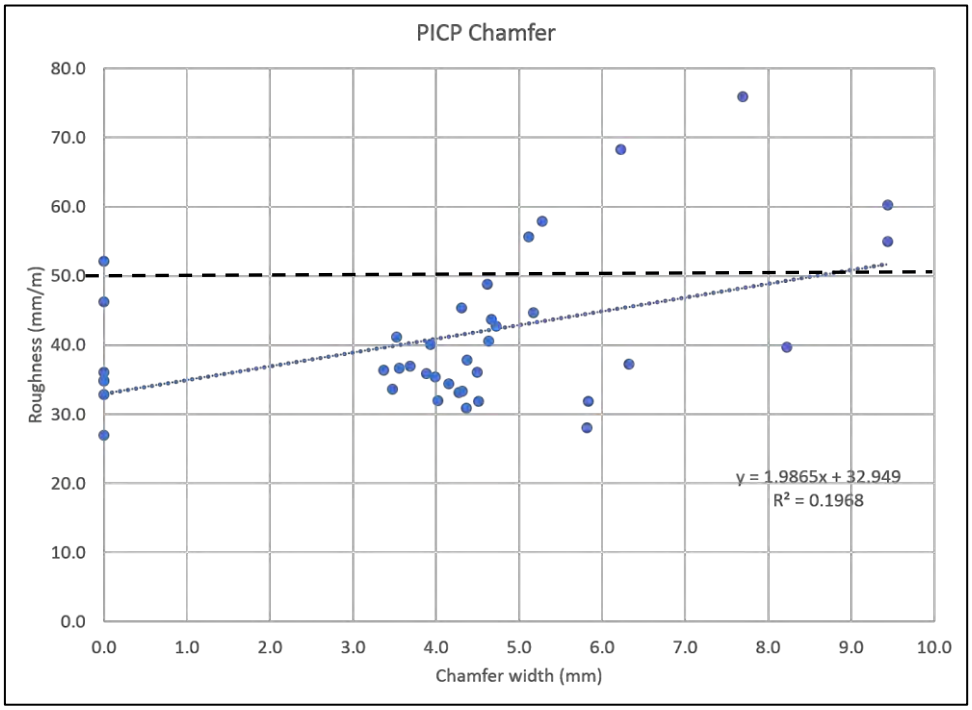


Figure 6. WPRI as a function of average PICP chamfer widths

The data in Figures 5 and 6 suggest that with PICP, joint widths 10 mm or smaller and chamfer widths 4 mm or smaller or can help ensure a wheelchair user-friendly WPRI less of than 50 mm/m over 30 m. Data within joint and chamfer widths suggested from Figures 3 through 6 but above 50 mm/m roughness may be influenced by surface profile uneveness.

Conclusions

The WPRI results and observations from the data on joint and chamfer widths suggest agreement with conclusions by Cooper in references 4 and 5. He measured accelerations in wheelchair seats and footrests rather than roughness of the pavement surface. A key consideration remains attention to limiting chamfer and joint widths.

The length of all WPRI measurements with PathMet is not specified. According to the proposed roughness criteria, all surfaces would be under the WPRI of 100 mm/m over 3 m. Figures 3 through 6 demonstrate that only some paver surfaces would be under a WPRI of 50 mm/m over 30 m. While the correlations from regressions between WPRI compared to joint and chamfer widths are almost non-existent, the clustering of the WPRI data suggests limits on joint widths and chamfer widths for non-permeable and permeable surfaces. These widths could be incorporated into industry guidelines that provide accessible (i.e., minimal or no discomfort and pain) surfaces for wheelchair users. In addition, concrete paver manufacturers could develop (or might already have) paving unIts branded as “wheelchair-user friendly,” those that conform to the chamfer widths and joint widths susggested by this study.

Future studies might examine WPRI changes over time as a function of maintenance (or lack of) as well different base materials, construction practices including compaction/density and climate. This data could be incorporated into an existing ASTM standard for assessing the condition of interlocking concrete pavements, ASTM E2840 *Standard Practice for Pavement Condition Index Surveys for Interlocking Concrete Roads and Parking Lots*. This might require development of a condition index for pedestrian pavements that includes wheelchair accessibility via a roughness index.

Additional roughness studies on other segmental paving surfaces such as clay brick, stone, porcelain and wood decks could help determine configurations that present accessible surfaces to wheelchair users. Finally, data should be compared to WPRIs on conventional asphalt and concrete pavements of various ages, conditions,

maintenance levels and climates, as these two surfaces degrade over time and can present inaccessible surfaces to wheelchair users. Roughness data could be included in ASTM D6433 *Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys*. Again, this might require development of a condition index for pedestrian pavements that includes wheelchair accessibility.

References

[1] Cooper, R.A., Wolf, E., Fitzgerald, S.G., Dobson, A., Ammer, W. and Smith, D.R., "Interaction of Wheelchairs and Segmental Pavement Surfaces," in *Proceedings* of the 7th International Conference on Concrete Block Paving, Sun City, South Africa, 2003. http://www.sept.org/techpapers/1280.pdf

[2] Cooper, R.A., Wolf, E., Fitzgerald, S. G., Dobson, A., Ammer, W., Boninger, M. L. and Cooper R. *Evaluation of Selected Sidewalk Pavement Surfaces*, 2004, Departments of Rehabilitation Science & Technology, Physical Medicine & Rehabilitation, and Bioengineering, University of Pittsburgh.

[3] Garcia-Mendez, Y, et al. 2012, Dynamic stiffness and transmissibility of commercially available wheelchair cushions using a laboratory test method, *Journal of Rehabilitation Research & Development* 49.1 (2012): 7+. Academic OneFile. Web. 5 June 2012.

[4] Duvall, J., Sinagra, E., Stuckey, D., Cooper, R. Pearlman, J., 2013, "Development of Surface Roughness Standards for Pathways used by Wheelchairs," Human Engineering Research Laboratories, University of Pittsburgh, *Transportation Research Record: Journal of the Transportation Research Board*, 2387, Transportation Research Board of the National Academies, Washington, DC, pp. 149-156, DOI: 10.3141/2387-17.

[5] Jonathan Duvall, J., Sinagra, E, Cooper, R. and Pearlman, J., 2016, Proposed pedestrian pathway roughness thresholds to ensure safety and comfort for wheelchair users, *Assistive Technology*, 28:4, 209-215, https://www.tandfonline.com/doi/full/10.1080/10400435.2016.1150364.

[6] Pearlman, J., Sinagra, E. and Duvall, J., *Development, Testing, and Data Collection of a Pathway Measurement Tool (PathMeT)*, 2014, University of Pittsburgh, Human Engineering Research Laboratories, Pittsburgh, Pennsylvania, USA.

[7] ASTM E3028 Standard Practice for Computing Wheelchair Pathway Roughness Index as Related to Comfort, Passability, and Whole Body Vibrations from Longitudinal Profile Measurements, 2016, *ASTM Annual Book of Standards*, Vol. 04.03, ASTM International, Conshohocken, Pennsylvania, USA.

[8] United States Access Board, *Development of Surface Roughness Standards for Pathways Used by Wheelchairs Users*, Washington, DC, 2013, www.access-board.gov/attachments/article/1680/surface-roughness.pdf.