AN INVESTIGATION OF WHEELCHAIR PATHWAY ROUGHNESS INDEX OF CLAY PAVERS

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Summary of Findings:

Pathway Accessibility Solutions, Inc., concludes that many clay pavers are acceptable for use by wheelchair users who demand smooth paving surfaces when sound installation and design practices are put in place. This conclusion is a result of investigating 99 clay paver surfaces over a three-year period. Upon analysis of the findings, we conclude that:

1. Clay pavers installed in segmental pavements can be a safe choice for wheelchair users.
2. Clay paver surfaces can perform better or comparable to the standard concrete slabs or aggregate surface. This may be attributed to larger joint widths in the concrete slabs or the continuous vertical deviations in the aggregate.
3. The age of the paving installation may have little to do with the smoothness of the pavement. Instead, installation and design are key factors for success.

Executive Summary

The purpose of this report is to investigate the Wheelchair Pathway Roughness Index (WPRI) ratings of various clay paver surfaces. The goal is to clearly explain WPRI compared to the types of surfaces made with clay pavers that may be safe or unsafe for wheelchair uses.

pathVu (Pathway Accessibility Solutions, Inc.) is a small business located in Pittsburgh, PA whose mission is to enable independent mobility by creating a more accessible and livable world for all pedestrians – of any ability. In 2017, pathVu's team successfully worked toward the publication of standard ASTM E3028, *Standard Practice for Computing Wheelchair Pathway Roughness Index as Related to Comfort, Passability and Whole Body Vibrations from Longitudinal Profile Measurements*.

ASTM E3028 was a result of years of research conducted at the University of Pittsburgh and the Human Engineering Research Laboratories with funding from the U.S. Access Board, Brick Industry Association, and Interlocking Concrete Pavement Institute. This research led to the development of PathMeT, a proprietary pathway measurement tool used to characterize pathway conditions. PathMeT was used in the research that led to the development of ASTM E3028. In 2016, Duvall et al. published suggested WPRI thresholds based on ISO 2631-1 vibration exposure limits and wheelchair user ratings. Duvall et al. suggest WPRI limits of 50 mm/m for a distance of 100 meters and 100 mm/m for 3 meters. Thus, WPRI is divided into ranges of (green) 0-50 mm/m, (yellow) 50-100 mm/m, and (red) 100 mm/m or more.

From 2015 to 2018, 99 different surfaces in the Pittsburgh (6), Philadelphia (31), Dayton/Columbus (31), and Wilmington/Baltimore/DC (31) regions were surveyed to obtain WPRI values. All of the surfaces were clay paver surfaces, except four, which were used for comparison. Of the total 99 surfaces, 76 performed in the green range and 22 performed in the yellow range, while 1 performed in the red range.

The results from 99 sites show that clay pavers installed in segmental pavements can be a safe choice for wheelchair users when determining the type of pavement to install. The data shows that it is common for traditional clay paver pavements to have low WPRI, with the majority of sites tested in the green zone and remain in the green zone years after initial installation. Many clay paver surfaces that were tested performed better or comparable to the standard concrete slabs or aggregate surface. This may be attributed to larger joint widths in the concrete slabs or the continuous vertical deviations in the aggregate.

The data suggests that age of clay paver installations may not play a major role in determining WPRI as originally suspected. Based on the surfaces measured, pavement WPRI shows a minimal trend and no significant correlation to the age of pavement installation. However, further testing is needed over time to definitely characterize the effects of age and maintenance on WPRI. The data suggests that a major factor to a smooth clay paver pavement is initial installation and design.

Purpose

The purpose of this report is to investigate the Wheelchair Pathway Roughness Index (WPRI) ratings of various clay paver surfaces. The goal is to clearly explain WPRI compared to the types of surfaces made with clay pavers that may be safe or unsafe for wheelchair uses.

Background

Problem

Over three million people in the U.S. use a wheelchair as their primary means of mobility. Wheelchair users are often subjected to unhealthy levels of vibration exposure due to rough pathways[1] and are twice as likely to suffer from back and neck pain[2]. Limiting pathway roughness and vibration exposure is essential to ensure wheelchair user safety, mobility, and independence.

pathVu

pathVu (Pathway Accessibility Solutions, Inc.) is a small business located in Pittsburgh, PA whose mission is to enable independent mobility by creating a more accessible and livable world for all pedestrians – of any ability. pathVu is a spinout of the University of Pittsburgh and the Human Engineering Research Laboratories. Research at these institutions led to ASTM E3028, PathMeT, and suggested WPRI Thresholds, all described below. pathVu has an exclusive license on the PathMeT technology, which was used in the research that led to the development of ASTM E3028.

Past Research

In 2002, researchers at the University of Pittsburgh and the Human Engineering Research Laboratories investigated the vibration exposure to wheelchair users as they traversed various pathway and segmental paver surfaces[3]. Four of the segmental surfaces compared similarly to poured concrete. This research led to a study conducted by Duvall et al.[4], where vibrations and

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[1] Garcia-Mendez, Y., Pearlman, J. L., Boninger, M. L. & Cooper, R. A. (2013). Health risks of vibration exposure to wheelchair users in the community. J Spinal Cord Med, 36(4), 365-75.

[2] M. L. Boninger, R. A. Cooper, S. G. Fitzgerald, J. Lin, R. Cooper, B. Dicianno, and B. Liu, "Investigating neck pain in wheelchair users," *Am. J. Phys. Med. Rehabil.*, vol. 82, pp. 197–202, 2003.

[3] 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.

[4] Duvall, J.,Cooper, R., Sinagra, E., Stuckey, D., Brown, J., and Pearlman, J., "Development of Surface Roughness Standards for Pathways Used by Wheelchairs," in *Transportation Research Board 92nd Annual Meeting*, 2013.

subject feedback were collected from wheelchair users as they traversed various outdoor and engineered surfaces. In order to draw correlations of surface roughness to 1) Vibration exposure and 2) Wheelchair user subjective feedback, Duvall et al. developed a surface roughness measurement tool (which would become PathMeT) and profile analysis methodology (which would be the foundation of ASTM E3028).

Note: Portions of this research were funded by the U.S. Access Board, Brick Industry Association, and Interlocking Concrete Pavement Institute.

ASTM E3028

The research conducted at the University of Pittsburgh and the Human Engineering Research Laboratories led to the development of ASTM E3028. ASTM E3028[5], *Standard Practice for Computing Wheelchair Pathway Roughness Index as Related to Comfort, Passability and Whole Body Vibrations from Longitudinal Profile Measurements*, methodology was used to determine Wheelchair Pathway Roughness Index (WPRI) for this study. WPRI is "an index computed from longitudinal profile measurements 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)."

PathMeT

PathMeT is pathVu's proprietary device (patent # 10,101,454) used to collect high-quality, high-resolution pathway data. PathMeT was used in data collection and testing to develop ASTM E3028. PathMeT is a manually propelled three-wheeled device (Figure 1). PathMeT contains numerous sensors, including laser displacement measurement tool, wheel encoder, inertial measurement unit, camera, and GPS. PathMeT's laser is a single-point laser, allowing the technician to accurately collect the correct centerline and complying with ASTM E3028 requirements. The profile is collected at a millimeter resolution or better in order to collect the necessary details of the surface, including joints. Besides WPRI, PathMeT identifies tripping hazards, running slope, cross slope, and depressions.

[5] Accessible at: https://www.astm.org/Standards/E3028.htm

Figure 1: Picture of PathMeT

Suggested WPRI Thresholds

In 2016, Duvall et al.[6] investigated the effects of WPRI further. Duvall et al. considered the ISO 2631-1 standard, *Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibrations* when conducting their research. The study found that there is a direct correlation between whole-body vibrations experienced by wheelchair users and the surface WPRI. As a result, Duvall et al. used ISO 2631-1 and wheelchair user ratings to identify suggested WPRI thresholds to ensure wheelchair user comfort and safety. Duvall et al. suggests threshold limits of 100 mm/m for surface segments of 3 m and 50 mm/m for surface segments of 100 m. For surfaces of other various lengths, a 3 m and/or 100 m moving window should be used. For example, a 3-meter moving window run should be run across a 50-meter surface having a 75 mm/m WPRI, searching for localized WPRI over 100 mm/m. Similarly, a 3-meter and 100-meter moving window should be used on a 200-meter surface with 75 mm/m WPRI.

Thus, surfaces are considered in the green and allowable for any distance if the WPRI is between 0 and 50 mm/m. Surfaces are considered in the yellow and should be used with precaution for distances of 3 meters to 100 m if the WPRI is between 50 and 100 mm/m. No surfaces above 100 mm/m should be installed since they can create dangerous vibrations for wheelchair users.

Note: These suggested WPRI thresholds, although published in a peer-reviewed journal, are not officially adopted or enforced by any agency. They are only the author's and pathVu's suggested thresholds.

[6] Jonathan Duvall MS, Eric Sinagra MS, Rory Cooper PhD & Jonathan Pearlman PhD (2016) Proposed pedestrian pathway roughness thresholds to ensure safety and comfort for wheelchair users, Assistive Technology, 28:4, 209-215, DOI: 10.1080/10400435.2016.1150364

Testing Methodology

From 2015 to 2018, 99 different surfaces in the Pittsburgh (6), Philadelphia (31), Dayton/Columbus (31), and Wilmington/Baltimore/DC (31) regions were surveyed to obtain WPRI values. All of the surfaces were clay paver surfaces, except four, which were used for comparison. Two of the remaining surfaces were concrete slabs, one was aggregate, and one was cobblestone located on the road. Data collection in each location occurred in fair to warm weather, 50°F - 80°F.

The pathVu team collected the following data for each surveyed surface: one image and at least 2 data collection runs with PathMeT along, typically, different centerlines. The centerline of the surface was chosen to avoid the gap between lateral pavers. The image was taken from the perspective of the direction of travel.

For each surface, the pathVu technician followed the steps below. During PathMeT data collection, the technician would walk at a pace of approximately 1 m/s (2.2 mph). The technician would clean the pathway of any sticks, leaves, or debris before measurement if necessary. Runs with errors were discarded and not included in analysis. Figure 2 shows images of data collection with PathMeT.

Data collection procedures:

1) Take image
2) Record device serial name/number
3) Identify centerline to be collected
4) Collect at least two PathMeT data collection runs
5) Return to the office to process data

Figure 2: Picture of PathMeT Data Collection

Results

Table 1 shows the results of data collection for this project. The location, design pattern, average WPRI, clay paver type, age, setting bed, and image are shown for 22 of the 99 surfaces tested. Further, a report ID and the project surface number are provided. Appendix A shows larger HD images of the surfaces in Table 1. In this report, half bond is defined as a running bond pattern perpendicular to traffic flow, while running bond refers to parallel traffic flow. Similarly, 45 herringbone refers to a herringbone pattern that has been rotated by 45 degrees in respect to traffic flow, while 90 herringbone refers to parallel traffic flow. Data is organized by increasing WPRI. WPRI is color-coded based on the suggested thresholds by Duvall et al.: green (<50 mm/m), yellow (>=50 mm/m & <100 mm/m), red (>=100 mm/m). Of the total 99 surfaces, 76 performed in the green range and 22 performed in the yellow range, while 1 performed in the red range.

Note: This project focused on clay paver WPRI analysis. One cobblestone and three concrete surfaces are provided for comparison purposes.

Table 1: WPRI results from PathMeT data collection. 22 of 99 surfaces shown

ID	Project Surface No.	Location	Design Pattern	Avg WPRI (mm/m)	Clay Paver Type	Age (yrs)	Setting Bed	Image
1	3	College Park, MD[7]	Half Bond	15.0	Extruded	Unknown	Sand	
2	12	Dayton, OH[8]	45 Herringbone	22.1	Vaccuum Press	8	Sand	
3	16	College Park, MD[7]	Half Bond	25.3	Extruded	6	Sand	

[7] Wilmington, DE/Washington, D.C./Baltimore, MD/Northern Virginia Project. Data collection completed: October 30-31, 2017. Report date: February 6, 2018.

[8] Dayton/Columbus, OH Project. Data collection completed: June 14-15, 2016. Report date: August 22, 2016.

4	29	Wilmington, DE[7]	CIP Concrete	25.6	N/A	4	N/A	
5	7	Barrington, NJ[9]	Running Bond	31.9	Extruded	12	Sand	
6	5	Pittsburgh, PA[9]	CIP Concrete	32.5	N/A	3	N/A	
7	2	Pittsburgh, PA[10]	Running Bond	32.6	Extruded	18	Bitumen	
8	8	White Marsh, MD[7]	45 Herringbone	37.8	Extruded	2	Bitumen	
9	18	Philadelphia, PA[10]	Half Bond	41.2	Extruded	9	Sand	
10	20	Columbus, OH[8]	Running Bond	41.4	Molded	18	Bitumen	
11	15	College Park, MD[7]	Half Bond (Permeable)	44.7	Vaccuum Press	6	Open Grade Aggregat e	

[9] Philadelphia, PA/New Jersey Project. Data collection completed: October 14-15, 2015. Report date: December 8, 2015.
[10] Pittsburgh, PA Demo Project. Data collection completed: May 5, 2015. Report date: June 28, 2015.

12	5	Haddonfield, NJ[10]	45 Herringbone (Permeable)	46.6	Extruded	11	Open Grade Aggregate	
13	21	Columbus, OH[8]	Half Bond	47.5	Extruded	18	Bitumen	
14	29	Westerville, OH[8]	90 Herringbone	52.4	Extruded	4	Bitumen	
15	14	Dayton, OH[8]	45 Herringbone (Permeable)	53.6	Vaccuum Press	3	Open Grade Aggregate	
16	30	Philadelphia, PA[10]	Half Bond (Permeable)	56.7	Extruded	10	Open Grade Aggregate	
17	5	New Castle, DE[7]	45 Herringbone	59.5	Moulded	40+	Sand	
18	4	Pittsburgh, PA[9]	Exposed Aggregate Concrete	60.4	N/A	Unknown	N/A	
19	20	Alexandria, VA[7]	45 Herringbone	67.2	Moulded	6	Sand	

20	19	Columbus, OH[8]	Half Bond	80.0	Reclaimed Brick	18	Bitumen	
21	24	Philadelphia, PA[10]	45 Herringbone (Permeable)	85.5	Vaccuum Press	8	Open Grade Aggregate	
22	26	Dayton/Columbus[8]	Cobblestone	111.5	4x4 Cobblestone, Fan Pattern	Unknown	Mortar	

Table 2 shows the analysis that was performed on the data to find the average WPRI and standard deviation by pattern. Appendix B shows a sample image for each pattern type. When considering the four patterns that were surveyed the most (running bond, 90-degree herringbone, half bond, 45-degree herringbone), the order of increasing WPRI is as follows: running bond, 90-degree herringbone, half bond, 45-degree herringbone. This is consistent with what is expected since running bond has the fewest joints and 45 herringbone has the most joints. All of the pattern types had averages in the acceptable range except for the cobblestone random fan pattern. (It should be noted that this surface was not a brick/clay paver surface). Similarly, Table 3 shows the results of the 96 paver surfaces according to setting bed type. The results are ordered by increasing WPRI. On average, the sand bed setting performs significantly better than other bed types.

Table 2: Average WPRI and Standard Deviation by Pattern Type

Pattern Type	Average WPRI (mm/m)	Standard Deviation (mm/m)	Count	# <=50 mm/m	# 50-100 mm/m	# >=100 mm/m
CIP concrete	29.1	4.9	2	2	0	0
Stacked bond	31.6	0.6	2	2	0	0
Running bond	35.9	8.4	17	16	1	0
Mixed	38.7	1.1	2	2	0	0
90° Herringbone	38.8	12.6	9	7	2	0
Windmill	39.6	3.9	3	3	0	0
Half bond	42.4	14.3	17	13	4	0
45° Herringbone	43.2	10.5	37	28	9	0
Pinwheel	46.4	0	1	1	0	0
Basketweave	46.5	9.8	3	2	1	0
Aggregate Concrete	60.4	0	1	0	1	0
45° Running Bond	64.2	0	1	0	1	0
45° Stacked Bond	65.4	0	1	0	1	0
45° Stacked Herringbone	70.0	21.9	2	0	2	0
Random fan	111.5	0	1	0	0	1

Table 3: Average WPRI and Standard Deviation by Setting Bed Type

Setting Bed Type	Average WPRI (mm/m)	Standard Deviation (mm/m)	Count	# <50 mm/m	# 50-100 mm/m	# >100 mm/m
Sand	37.0	12.1	35	32	3	0
Bitumen	42.6	7.7	21	16	5	0
Dry Pack	45.1	1.8	2	2	0	0
Other/Unknown	45.2	17.3	30	22	7	1
Mortar	48.7	23.6	2	1	1	0
Open Grade Aggregate (Permeable)	51.0	7.7	6	2	4	0
Stone	61.0	22.6	3	1	2	0
Total	**42.6**	**14.1**	**99**	**76**	**22**	**1**

Further, a correlation graph (Figure 3) was developed to understand how age of a surface could affect or could be used to predict WPRI. The approximate age (years since installation) of 69 of the 99 surfaces were known and used in the analysis. The R^2 value on the graph shows a coefficient of determination of 0.0116. Based on this analysis, it appears that age does not play a major role in predicting WPRI. However, the best fit line in Figure 3 shows that there is a slight correlation that as age increases, WPRI increases as well. This correlation does not appear to be significant.

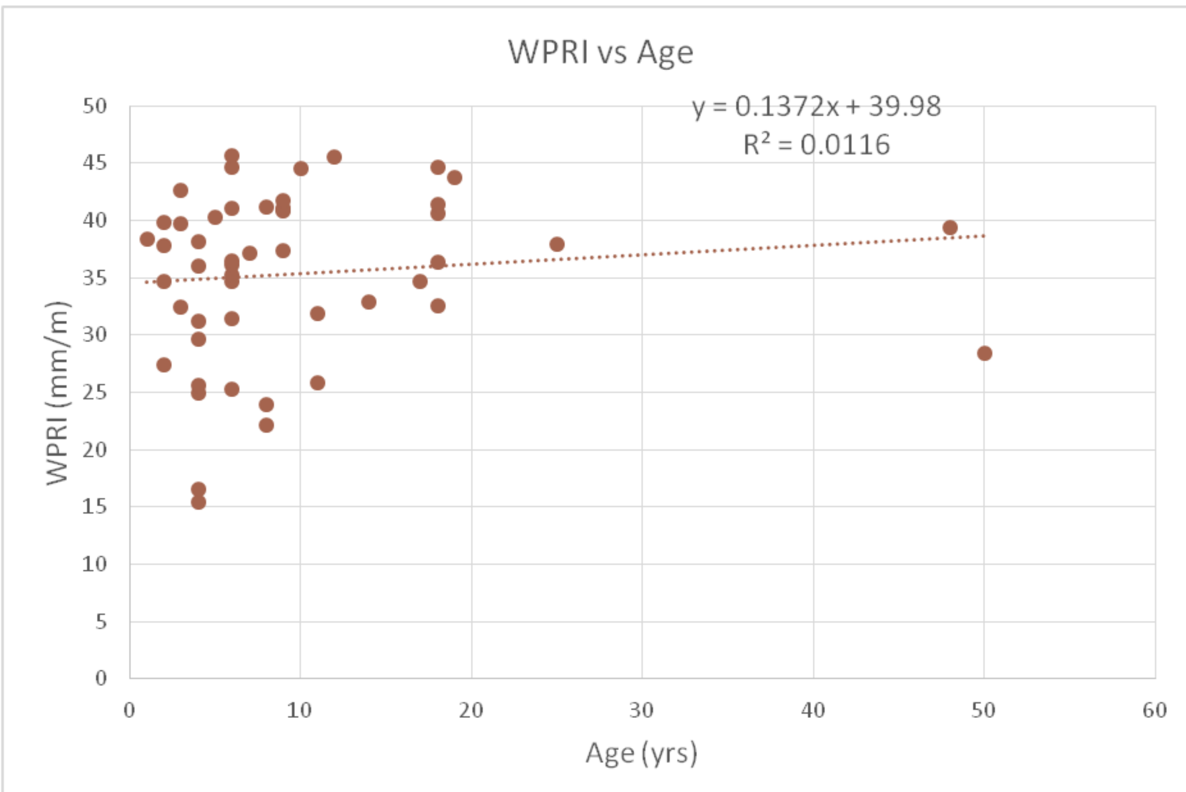


Figure 3: Graph of WPRI vs Age of Surface

Discussion

The data in this report shows that 74 of the 95 (78%) clay paver surfaces had WPRI values in the (green) acceptable range between 0 and 50 mm/m. The remaining 21 clay paver surfaces performed in the (yellow) caution range between 50 and 100 mm/m. None of the clay paver surfaces performed in the (red) range above 100 mm/m. Two of the non-paver surfaces were green, while one was in yellow, and one was in the red. Based on the suggested WPRI thresholds by Duvall et al., the 76 surfaces that performed in the green should be considered safe for wheelchair users and allowable for any distance. On the other hand, the 22 clay pavers that performed in the yellow cautioned range should be considered on a case-by-case basis. Further study is needed to determine the underlying causes of pavements scoring in the yellow range in order to give designers more guidance on specifying materials, segmental paver types, and installation methods. Based on anecdotal observations, joint size and frequency may affect surface WPRI, as many surfaces in the yellow range have wider and more frequent joints. In these cases, care should be taken to minimize WPRI, such as through: 1) A pattern change 2) Setting bed change 3) Minimizing joints and/or joint width 4) Limiting consecutive distances to 100 meters of less.

The data shows that clay pavers may be a safe choice for wheelchair users when determining which surface type to install. It is possible and common for these surfaces to create a smooth surface, with the majority of those tested performing in the green. Many clay paver surfaces that were tested performed better or comparable to the standard concrete slabs or aggregate surface. This may be attributed to larger joint widths in the concrete slabs or the continuous vertical deviations in the aggregate. In addition, the clay paver surfaces with fewer and smaller joint widths typically performed best.

Tables 2 and 3 above show the WPRI variation among surface pattern type and setting bed type. The surface and setting bed type that performed the best were running bond and sand, respectively. Although 45-degree herringbone performed towards the bottom of those surveyed, its average was still in the acceptable range. The running bond, 90-degree herringbone, half bond, and 45-degree herringbone surface types increase in WPRI, respectively. This is consistent with the hypothesis that WPRI increases as the number of joints increases. Thus, it is recommended to decrease the number of joints and joint widths in order to decrease WPRI. Similarly, setting bed type should be considered as a potential way to reduce WPRI, although multiple setting bed types perform in the acceptable zone.

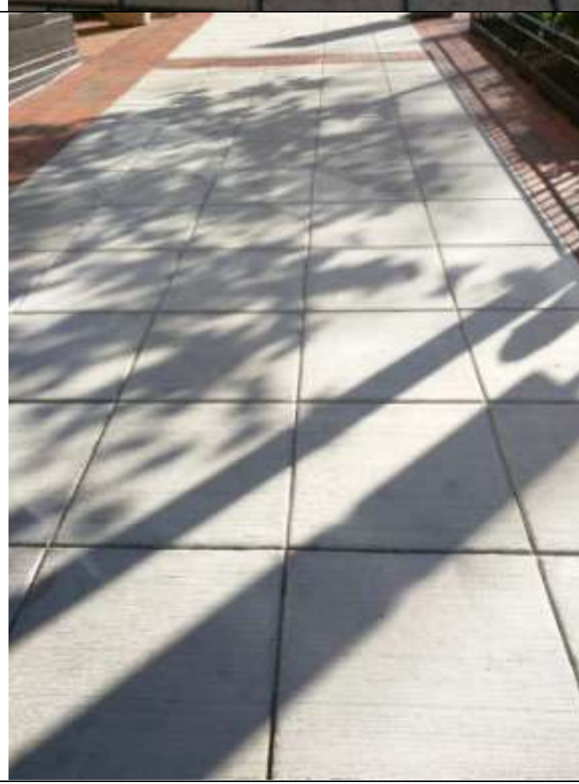
The R^2 value of Figure 3 is low, which shows that age cannot be used to predict WPRI. The best fit line in Figure 3 shows a small correlation that WPRI increases as surface age increases. This is a minimal correlation, and more research is required in order to make significant conclusions regarding WPRI and age.

Since there is no significant direct correlation between WPRI and age, alternative factors must be considered when determining what surface characteristics cause an increase in WPRI. Based on Table 2 results and the understanding of how WPRI is calculated, increased joint width and joint frequency typically increase WPRI. Furthermore, since WPRI varies among pattern type, material, age, and joint characteristics, it is believed that installation and design play a major role in limiting WPRI. It is recommended that surfaces are installed by a professional. Surfaces that are uniform are believed to result in optimal performance. Poorly maintained pathways will likely have increased WPRI, but further research is required to draw definitive conclusions.

Potential future work includes additional testing in order to discover additional factors that affect WPRI. Such testing could include testing of additional surfaces in more cities. Other options include re-testing of the surfaces in this report to understand how they change over time. All of the surfaces tested are in climates that experience snow and sub-freezing cold weather; testing in cities that are warm year-round may be beneficial. Possible factors to be tested further that could affect WPRI include, but are not limited to: age, weather deviations, location, joint width, joint frequency, surface bed, paver type, pattern, traffic type, and maintenance.

Appendix A

ID	Image
1	
2	

3		
4		

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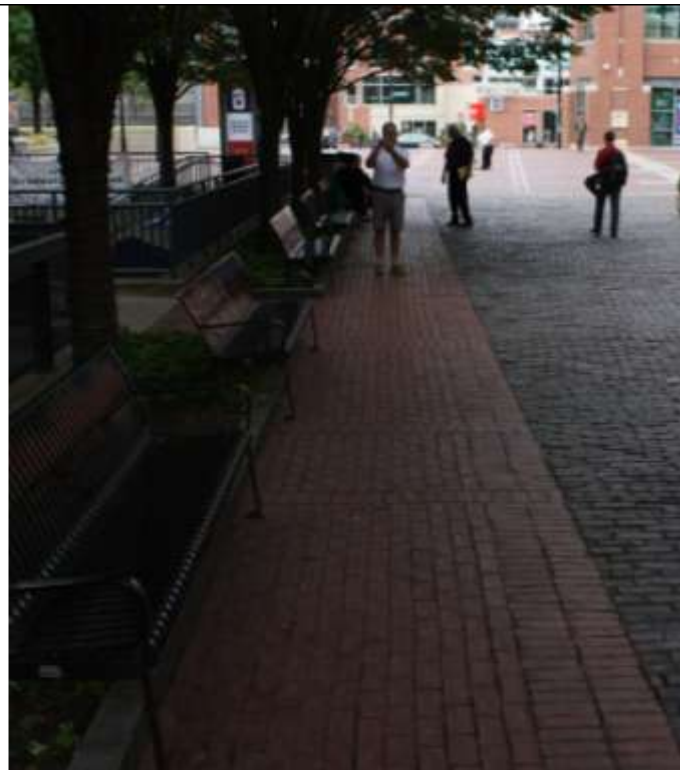
9	
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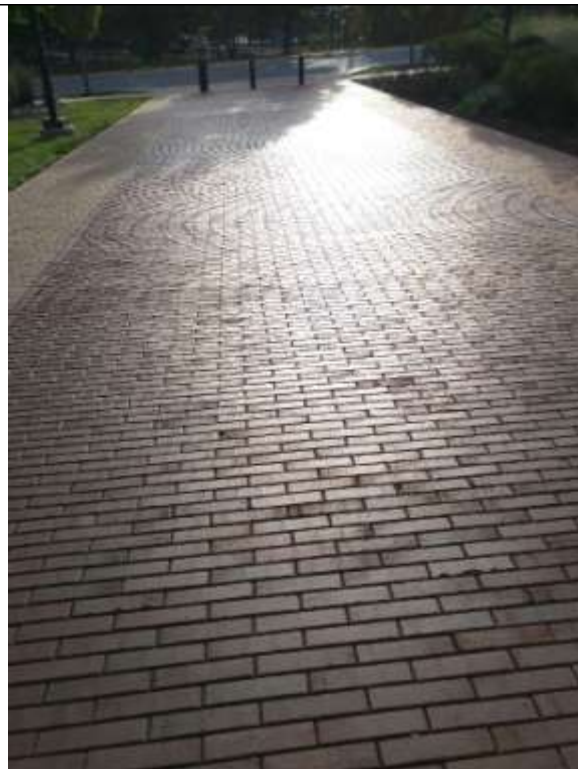
11		
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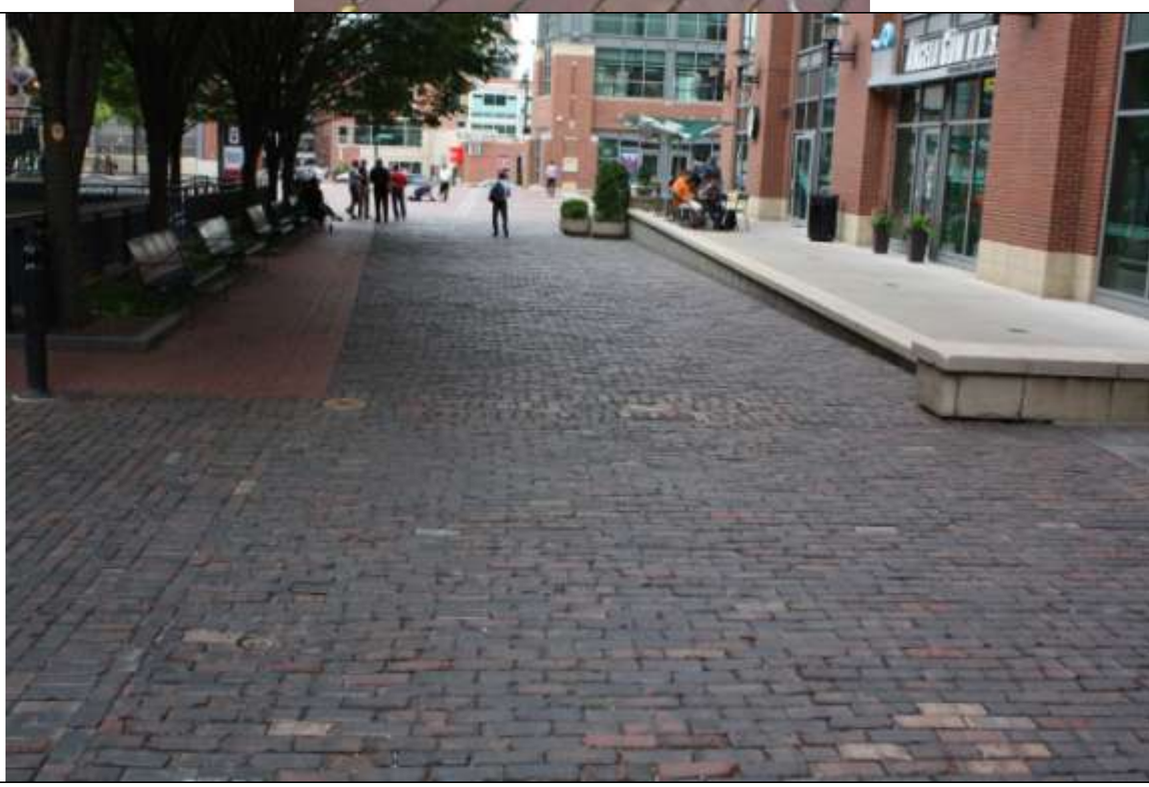
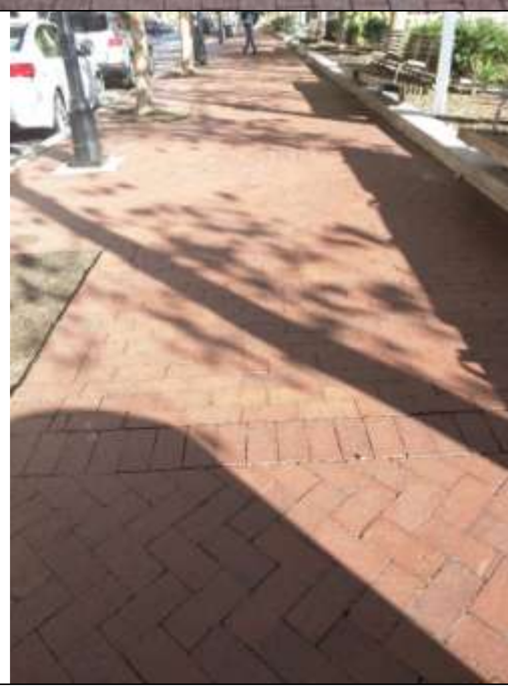
20	

21	
22	

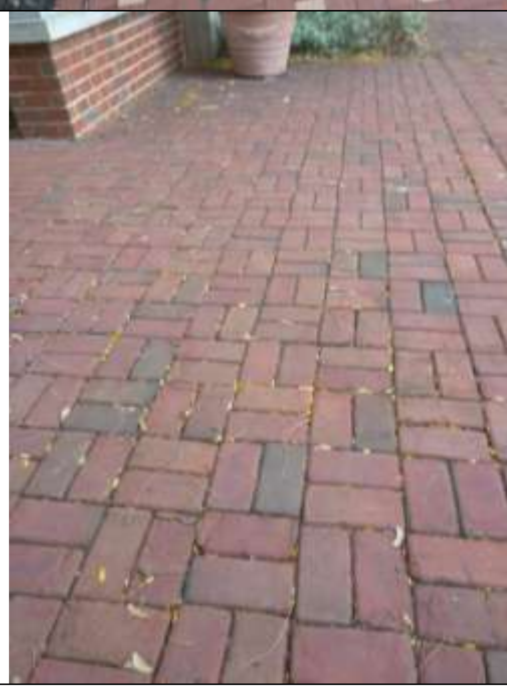
Appendix B

Pattern Type	Image
CIP Concrete	
Stacked Bond	

Running Bond	
Mixed	

90° Herringbone		
Windmill		

Half Bond	
45° Herringbone	

Pinwheel	
Basketweave	

Aggregate Concrete	
45° Running Bond	

45° Stacked Bond	
45° Stacked Herringbone	

Random Fan