WWE

MEMORANDUM

To: Morgan Lynch, P.E., CFM
Mile High Flood District

From: Wright Water Engineers, Inc.
Jane Clary, Andrew Earles, P.E., Ph.D. and Katie Knight, E.I.T.

Date: March 17, 2021

Re: Review of Permeable Interlocking Concrete Pavement (PICP) Design and Effect on Outflow Pollutant Concentrations

INTRODUCTION

Wright Water Engineers (WWE) has prepared this memorandum to summarize targeted research related to Permeable Interlocking Concrete Pavement (PICP) design for Mile High Flood District (MHFD) as part of the update to Chapter 4 of the MHFD Criteria Manual Volume 3. Fact Sheet T-10 in Chapter 4 describes the design procedure and criteria for constructing permeable pavements. Presently, the Fact Sheet specifies that the underdrain of the permeable pavement should be placed underneath a 6-inch layer of sand surrounded by CDOT Class B or C filter material (sand layer) in order to provide adequate pollutant removal (Figure 1). However, practitioners have expressed concern that the use of a sand filter layer in permeable pavement systems can cause structural issues due to spreading. The purpose of this memorandum is to synthesize findings from national studies that examined the pollutant removal effectiveness of PICP under various design criteria in order to determine whether a sand filter layer is necessary for adequate pollutant removal. Additionally, this memorandum compares the Volume 3 permeable pavement system specifications to the criteria manuals of other municipalities and agencies, as well as guidance from the Interlocking Concrete Pavement Institute and from ASCE in *Permeable Pavements* (Eisenberg et al. 2015).

Performance Evaluation Review

Table 1 lists 10 studies that include 13 PICP monitoring sites that WWE reviewed for this memorandum. Most of these studies were retrieved from the International Stormwater BMP Database, supplemented by a few recent publications. For purposes of this memorandum, porous concrete and pervious asphalt were excluded, given that PICP tends to perform better than porous concrete and pervious asphalt designs.

Figure 1. Permeable Pavement Section with Underdrain from MHFD Criteria Manual Volume 3 Chapter 4 BMP Fact Sheet T-10

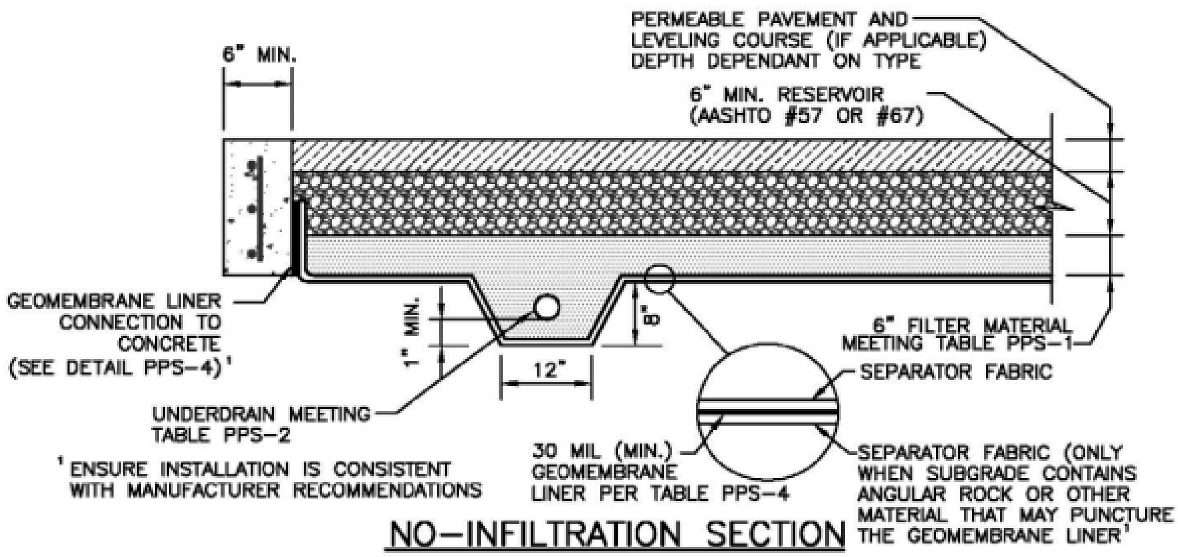


Table 2 summarizes key design characteristics for the PICP installations in the studies. The only two studies that included a sand filter layer were one MHFD site in Denver (Piza, 2011) and one of the sites in Fort Collins on Walnut Street (NES 2009). Both of these studies generally followed current MHFD guidance. An older PICP study conducted by Ben Urbonas from 1994 to 2004 in Lakewood for MHFD is also included in the data set, but this installation preceded the sand filter layer design. The Fort Collins study is particularly interesting because the Walnut Street site followed MHFD guidance, whereas the Mountain Avenue site followed guidance similar to ASCE (2015). Brattebo (2003) did not describe the specific thickness of aggregate layers beneath the PICP, but instead referred to the standard specifications of the relevant criteria manual for the study location.

Table 1. Summary of Studies and Reports Reviewed

Study/Report Title	Authors	Project Location	Year Published
Stormwater Quality Monitoring Report: Porous Asphalt at Denver Wastewater Management Building	Piza, H., Eisel, C.	Denver, CO, USA	2011
Preliminary Findings of the UDFCD BMP Field Studies, UDFCD 2004 Annual Seminar	Urbonas, B.	Lakewood, CO, USA	2004
Evaluation of Four Permeable Pavement Sites in Eastern North Carolina for Runoff Reduction and Water Quality Impacts*[1]	Bean, E.Z., Hunt, W.F., and Bidelspach, D.A.,	North Carolina, USA	2007
A Field Study to Evaluate Permeable Pavement Surface Infiltration Rates, Runoff Quality, and Exfiltrate Quality*	Bean., E.Z.	Maryland, USA and North Carolina, USA	2005
Long-term Stormwater Quantity and Quality Performance of Permeable Pavement Systems	Brattebo, B.O., and Booth, D.B.	Renton, Washington, USA	2003
IMAX: Low Impact Development Infrastructure Performance and Risk Assessment*[2]	Credit Valley Conservation (CVC)	Mississauga, Ontario, Canada	2016
Urban Runoff Mitigation by Permeable Pavement System over Impermeable Soils	Fassman, E.A., and Blackbourn, S.	Auckland, New Zealand	2010
The Utility Plans for Bohemian Office Building* (Walnut Street & Mountain Avenue)	Northern Engineering Services (NES)[3]	Fort Collins, Colorado, USA	2009
Stormwater-Quality Performance of Lined Permeable Pavement Systems	Selbig, W.R., Buer, N., and Danz., M.E.	Madison, Wisconsin, USA	2019
Seasonal Variability in Stormwater Quality Treatment of Permeable Pavements Situated Over Heavy Clay in a Cold Climate	Winston, R.J., Davidson-Bennett, K.M., Buccier, K.M., and Hunt, W.F.	Willoughby Hills, Ohio, USA	2016

*At least one study location included in the study does not correspond to a reference location or measurement of influent pollutant concentrations.

[1]Includes two PICP study locations identified as Bean (2007a) and Bean (2007b) in the text.

[2]Includes three different PICP study configurations labeled as CVC (2016a), CVC (2016b), and CVC (2016c) in the text.

[3]Design drawings by NES (2009) were used for original review of these installations. An interpretive report was also completed by Colorado State University researchers: *Analysis and Evaluation of Stormwater Quality and Quantity Performance for Three Permeable Pavement Systems in Fort Collins, Colorado* (Gruber, Olson and Roesner 2012).

Table 2. Summary of Permeable Pavement System Configurations

Study	Bedding Course		Base Course Layer 1		Base Course Layer 2		Under-drain	Geo-textile
	Thickness (cm)	Aggregate	Thickness (cm)	Aggregate	Thickness (cm)	Aggregate		
Piza (2011) (Denver PICP)	5	No. 8 stone	18	No. 67 stone	15	ASTM C-33 Sand	Y[2]	Y
Urbonas (2004) (Lakewood)	5	ASTM C-33 Sand	20	No. 67 stone	Not Used	Not Used	Y[3]	Y
Bean (2007a&b) [Gold & Swan]	8	No. 72 stone	20	No. 57 stone	Not Used	Not Used	N[4]	N
Bean (2005) [Cary]	5	No. 78 stone	25	No. 57 stone	Not Used	Not Used	Y	Y
Brattebo (2003)[1]	5	No. 8 stone	10	No. 57 stone	15	No. 2 stone	Y	N
CVC (2016) (IX-5)	5	No. 8 stone	42.5	No. 57 stone	Not Used	Not Used	Y	Y
CVC (2016 (IX-5)	5	No. 8 stone	42.5	No. 57 stone	Not Used	Not Used	Y	Y
CVC (2016 (IX-7)	5	No. 8 stone	42.5	No. 57 stone	Not Used	Not Used	Y	Y
Fassman (2010)	NA	No. 8 stone	15	No. 67 stone	23	No. 2 stone	Y	Y
Selbig (2019)	5	No. 9 stone	10	No. 57 stone	30	No. 2 stone	Y	Y
Winston (2016)	5	No. 89 stone	15	No. 57 stone	30	No. 2 stone	Y	N
NES (2009) [Walnut]	5	No. 8 stone	18	No. 67, No. 8 or No. 4 stone	15	ASTM C-33 Sand	Y	Y
NES (2009) [Mountain]	5	No. 8 stone	10	No. 57 stone	30	No. 2 stone	Y	Y

[1]Describes subgrade from criteria manual. The study does not specify subgrade installation specs other than cite the relevant design criteria manual.
[2] Underdrain below sand filter layer is surrounded by No. 67 aggregate.
[3] Underdrain is surrounded by aggregate from Base Course Layer 1.
[4]A PVC pipe was installed for sample collection, but it is not an underdrain for the system.

As shown in Table 2, the common features of PICP system configurations for all studies include a layer of interlocking pavers on top of bedding course (5-8 cm thick), and either one or two layers of stone aggregate base course (combined 20-40 cm thick) beneath the bedding course. Urbonas (2004), Bean (2005), Bean (2007a&b), and CVC (2016a-c) utilized a single layer of base course material; all other studies utilized at least two layers of base course material (Table 2). When an underdrain was included, it was located in the lowest layer of base course aggregate. Approximately 70% of the studies use geotextiles to separate the lowest base course layer from underlying native soils.

The most notable difference between the PICP system configuration described in the Fact Sheet T-10 compared to those described in the studies is the size of the aggregate material used as the second base layer and surrounding the underdrain. Fact Sheet T-10 specifies the use of CDOT Class B or Class C filter material (previously ASTM C-33 sand, as used in Piza [2011] and NES [2009] at Walnut Street) as the lower layer surrounding the underdrain.

Pollutants selected for performance comparison in this memorandum include total suspended solids (TSS), copper (Cu), lead (Pb), zinc (Zn), total phosphorous (TP) and nitrate (NO_3^-). Median concentrations for the studies and constituents are summarized in Table 3, with selected pollutants summarized graphically in Figures 2 through 5. Often, permeable pavements studies utilize an adjacent reference site for comparison (with reference outflow essentially representing inflow to the test site to evaluate performance). The outflow from permeable pavement sites is collected from underdrains.

Prior to data interpretation, other observations pertinent to comparison of performance among studies based on review of reports associated with the studies include:

- Credit Valley Conservation (2016) in Ontario monitored several BMPs at an IMAX parking lot. Site IX-7 performed poorly and was considered anomalous in the performance report. The authors hypothesized that this location may have been affected by a snow dump or storage area, or maintenance that differed from the other two CVC sites on the IMAX property.
- Winston (2016) monitored several PICP installations and noted that the median values of TSS concentrations were influenced by a “maturation period” at the beginning of the study, where large TSS concentrations in the outflow from the permeable pavement system were observed, presumably caused by effluent capturing dust from quarrying and crushing of aggregate.
- The two studies PICP studies monitored by MHFD in this summary include an older design that had only one base course layer (Urbonas 2004) and a newer design that included the sand filter layer (Piza 2011). Comparison of these sites is complicated by the fact that the reference outflow for the Piza (2011) Denver Wastewater Building site was much dirtier than that at the Lakewood site studied by Urbonas (2004). This difference is expected to partially explain the median effluent concentrations being lower at the older Lakewood site. From a percent removal perspective, the newer design has the appearance of performing better due to dirtier influent enabling calculation of a higher percent removal. (This also

illustrates the importance of having some type of reference outflow monitored as part of the study design.)

Table 3. Summary of PICP Water Quality Performance for Selected Constituents

Study	Median Concentrations										Percent Reduction for Paired Studies				
Analyte	TSS (mg/L)		Zn, T (ug/L)		Cu, T (ug/L)		TP (mg/L)		NOx (mg/L)		TSS (mg/L)	Zn, T (mg/L)	Cu, T (ug/L)	TP (mg/L)	NOx (mg/L)
Sample Type	In	Out	In	Out	In	Out	In	Out	In	Out					
Piza (2011a) [Den]	185.0	56.0	125.0	46.3	26.0	18.9	0.37	0.29	0.53	1.85	70%	63%	28%	22%	-248%
Urbonas (2004) [Lake]	23.5	11.5	50.0	25.0	7.0	9.0	0.10	0.10	0.93	1.11	51%	50%	-29%	1%	-19%
Fassman (2010)	83.9	39.0	105.5	12.2	12.0	5.4	NA	NA	NA	NA	54%	88%	55%	NA	NA
Bean (2007a) [Gold]	12.0	8.3	63.0	8.0	12.5	5.0	0.13	0.05	0.24	0.37	31%	87%	60%	62%	-55%
Brattebo (2003)	NA	NA	21.0	9.0	9.2	1.0	NA	NA	NA	NA	NA	57%	89%	NA	NA
Winston (2016)	12.0	97.0	21.0	13.0	3.8	4.4	0.05	0.04	0.38	0.63	-708%	38%	-17%	20%	-66%
Winston (2016)	12.0	154.0	21.0	16.0	3.8	5.4	0.05	0.05	0.38	0.46	-1183%	24%	-44%	0%	-21%
Selbig (2019)	76.0	50.0	55.0	31.0	9.1	9.8	0.20	0.18	NA	NA	34%	44%	-8%	10%	NA
NES (2009a) [Walnut]		10.0		17.3		10.4		0.15		1.94					
NES (2009b) [Mtn]		16.0		18.4		19.4		0.07		1.69					
Bean (2005) [Cary]		10.5		NA		NA		0.27		1.40					
Bean (2007b) [Swan]		NA		NA		NA		0.06		0.18					
CVC (2016a) [IX-5]		23.0		27.0		8.6		0.04		0.67					
CVC (2016a) [IX-6]		16.0		24.9		8.0		0.06		0.76					
CVC (2016a) [IX-7]		100.5		26.0		12.5		0.06		0.74					

Key observations based on review of Table 3 and Figures 2 through 5 below include:

- TSS: Excluding the Winston (2016) sites, all of the paired studies removed TSS relative to reference outflow concentrations. For the Fort Collins studies that enable a comparison of designs following MHFD criteria with a sand filter layer versus the ASCE (2015) design, TSS results were comparably low. Additionally, the two studies with the sand filter layer (Piza 2011 and NES [Walnut] 2009b) were within the range of median TSS outflow concentrations observed at other sites. Seven of the sites had median effluent concentrations below a comparison benchmark of 30 mg/L TSS, despite six of them not having a sand filter layer.

- Zinc: All of the paired studies showed reductions in total zinc concentrations, with half of the studies removing more than 50 percent of the zinc. The highest median effluent zinc concentration is at the Piza (2011) site with a sand filter layer. Again, the two study designs in Fort Collins were comparable. Influent concentrations for zinc varied substantially, limiting conclusions that can be drawn among outflow concentrations achieved by individual BMPs. Outflow concentrations for total zinc are below hardness-based stream standards for dissolved zinc that would be expected for the Front Range. (Many of the influent concentrations are also below dissolved zinc stream standards.)

- Copper: Half of the paired studies showed reductions in median total copper concentrations, with some sites already having very low copper concentrations in the inflow. The two studies with sand filter layers had effluent concentrations within ranges observed at other studies without sand filter layers. Several studies showed increases in total copper, but these were at sites with already low influent concentrations.

- Total Phosphorus: Limited reductions in total phosphorous concentrations were present for most studies with paired study designs. Additionally, 10 studies had outflow total phosphorus concentrations below Colorado's interim warm water quality standard of 0.17 mg/L. Studies with the sand filter layer did not perform better than studies without the layer; instead, the Piza (2011) site had the highest total phosphorus effluent concentration relative to all of the studies and was one of three sites exceeding the warm water total phosphorus standard of 0.17 mg/L. Additionally, for the paired Fort Collins studies, the Walnut Street design with the sand filter layer had median total phosphorus twice the concentration of the Mountain Avenue site without the sand filter layer.

- Nitrate: Although nitrate was included in this analysis because nutrients are a potential permit-related issue under Regulation 85 for stormwater MS4 permit holders, nitrate is generally low in urban stormwater runoff from paved land uses relative to other land uses and wastewater plant discharges. Despite increases in nitrate at several sites, nitrate outflow is well below a stream standard of 10 mg/L in these studies and the median nitrate effluent values from permeable pavement are also below Colorado's interim value of 2.01 mg/L total nitrogen. (Figure not shown for nitrate.)

Based on these observations, the performance studies reviewed for the two sites with the sand filter layer do not show better outflow water quality than sites without the sand filter layer. These data suggest that it would be appropriate for MHFD to reconsider whether inclusion of a sand filter layer is warranted from a water quality perspective.

Figure 2. Median Total Suspended Solid Concentrations

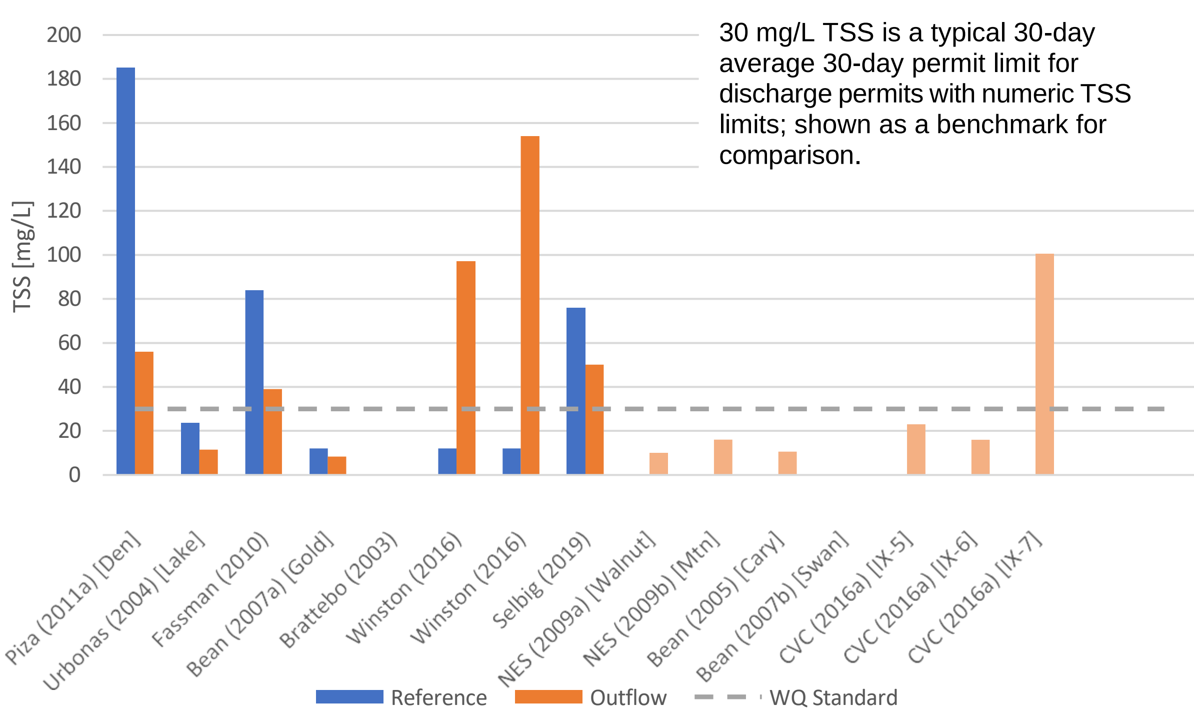


Figure 3. Median Total Phosphorus Concentrations

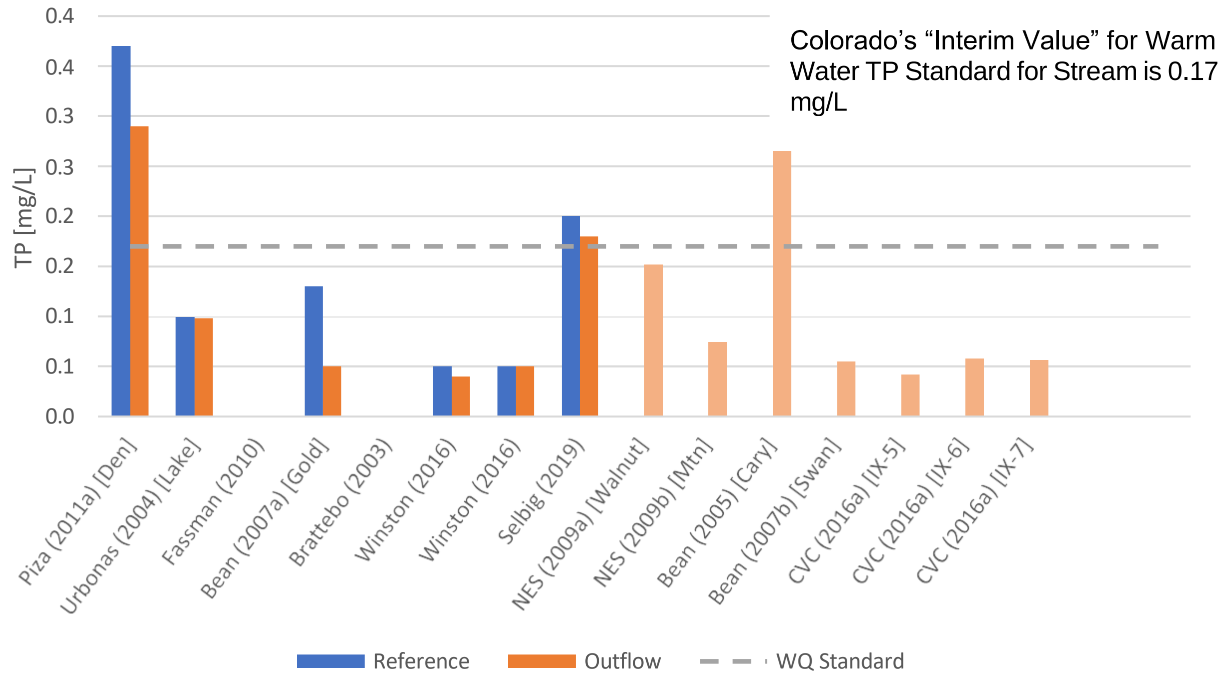


Figure 4. Median Total Zinc Concentrations

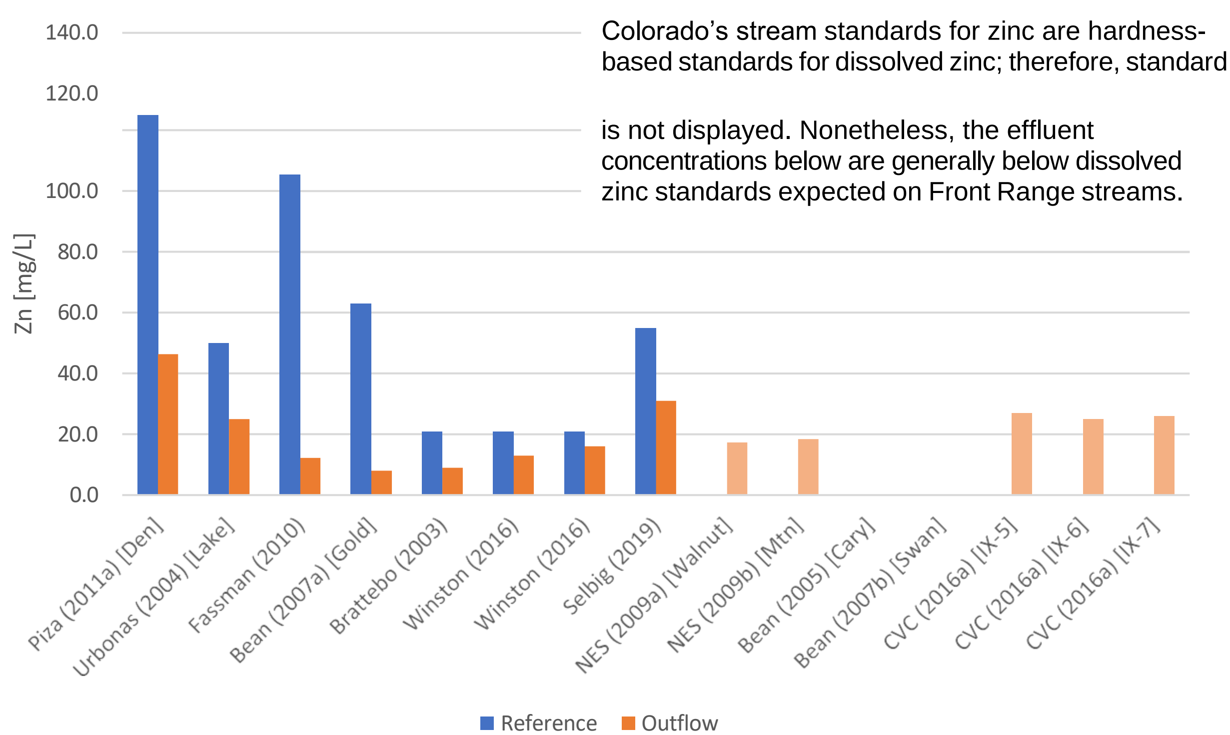
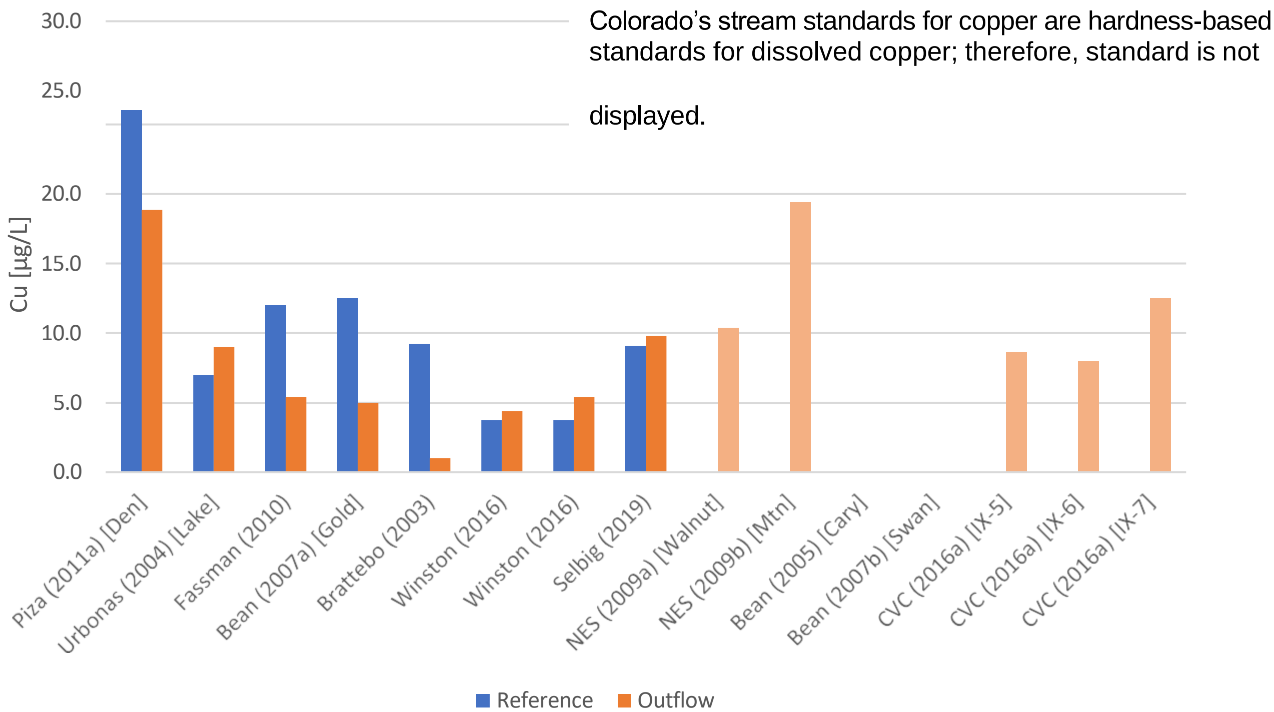


Figure 5. Median Total Copper Concentrations



Comparison of MHFD Criteria to Other Criteria Manuals

As shown in Table 4 below, MHFD's inclusion of a sand media as the lowest base layer in permeable pavement differs from currently applicable national guidance by ASCE and ICPI, as well from other criteria developed for other large cities, with the exception of the City of Houston and the County of San Diego. The County of San Diego includes an optional sand layer below the base course, but when an underdrain is included in the design, it is placed in the aggregate base course above the sand layer. Although the City of Fort Collins historically followed MHFD's criteria that included a sand filter layer, its 2017 design criteria do not include this layer. This change is based in part of the findings of the previously discussed comparative study on Walnut Street and Mountain Avenue, which found comparable water quality performance of the two designs. Because of structural concerns and greater installation quality control challenges with the sand filter layer, Fort Collins removed the sand filter layer and now uses the design shown in Attachment 1 to this memorandum. Fort Collins reports that they have been pleased with this new design, and further noted that a critical area of improvement has been a requirement of inspection by the city as each layer of the pavement is installed, following the checklist in Attachment 2.

Table 5 compares Fact Sheet T-10 to the Interlocking Concrete Pavement Institute's design guidance (https://icpi.org/permeable-interlocking-concrete-pavement-drawings) and ASCE's guidance *Permeable Pavement Systems* (ASCE 2015), further illustrating differences between MHFD's currently recommended design relative to ICPI and ASCE. ICPI does not include a sand layer in its design. ASCE (2015) does not include a sand layer in its standard design (Figure 6); instead, it identifies use of a sand layer as "optional." When the sand filter layer is considered, the configuration of the layers is different than in Fact Sheet T-10, as shown below in Figure 7. In this case, the filter course of sand is below the first choker course and includes a second choker course beneath it, above the reservoir layer.

Table 4. Summary of Criteria Manual Specifications for Acceptable Aggregate Sizes for the Lowest Base Layer of Permeable Pavement System Configurations

Criteria Manual	Acceptable Aggregate Size for Lowest Base Layer							
	No. 2	No. 3	No. 4	No. 5	No. 57	No. 67	ASTM C-33 Sand or CDOT Class B or C Filter Material	Underdrain Comment
MHFD							X	CDOT Class B or C Filter Material around underdrain
Interlocking Concrete Pavement Institute					X			No. 57 stone around underdrain
ASCE 2015 Permeable Pavement (for PICP)	X	X						No. 2 or 3 Stone around underdrain
City of Fort Collins					X	X		No. 57 or No. 67 Stone around underdrain
WA State Department of Ecology	X							No. 2 Stone around underdrain
City of Portland			X					Not described
County of San Diego			X				X	No. 4 Stone around underdrain, above sand layer, if included
New York State				X				No. 5 Stone around underdrain
City of Houston	X				X		X	Not described
San Jose	X				X			No. 57 Stone around underdrain
City of Austin	X							Not described
City of San Francisco		X						No. 3 Stone around underdrain
City of Birmingham	X				X			No. 57 stone around underdrain

Table 5. Comparison of Fact Sheet T-10 to ICPI and ASCE 2015 PICP Design Criteria

	MHFD	ICPI	ASCE 2015		
Layer	**PICP&PA**	**PICP**	**PICP**	**PA**	**PC**
Bedding/ Leveling	No. 8 Stone	No. 8 Stone	No. 8 Stone (or manufacturer's spec)	Not Required	Not Required
Choker (Base)	(not specified separately from reservoir layer)	No. 57 Stone	No. 57 Stone	No. 57 Stone (optional)	No. 57 Stone (optional)
Reservoir (Sub-base)	No. 57 or No. 67	No. 2 Stone (No. 3 or 4 allowed)	No. 2 or 3 Stone	No. 2 or 3 Stone	No. 2, 3 or 57 Stone
Filter Layer	CDOT Class B or C (previously ASTM C-33 Sand)	Not included	Filter layer not included at the underdrain layer. Optional as a layer above Reservoir. When used, a second choker course is provided.		
Underdrain	No. 57 or 67	No. 57 Stone			

Figure 6. ICPI Permeable Pavement with Partial Infiltration to Subgrade
(Source: ICPI Drawing ICPI-69, https://icpi.org/permeable-interlocking-concrete-pavement-drawings)

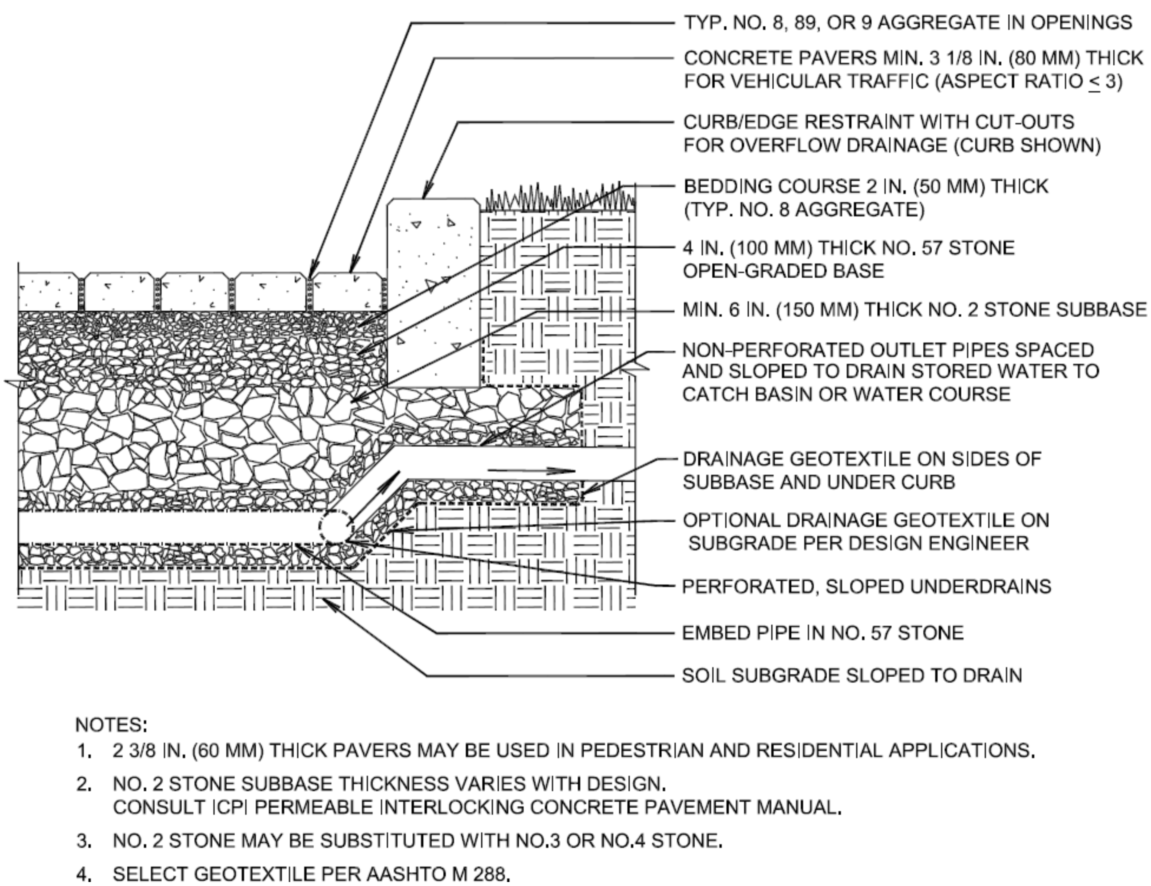


Figure 7. ASCE 2015 Permeable Pavement Partial-infiltration Design

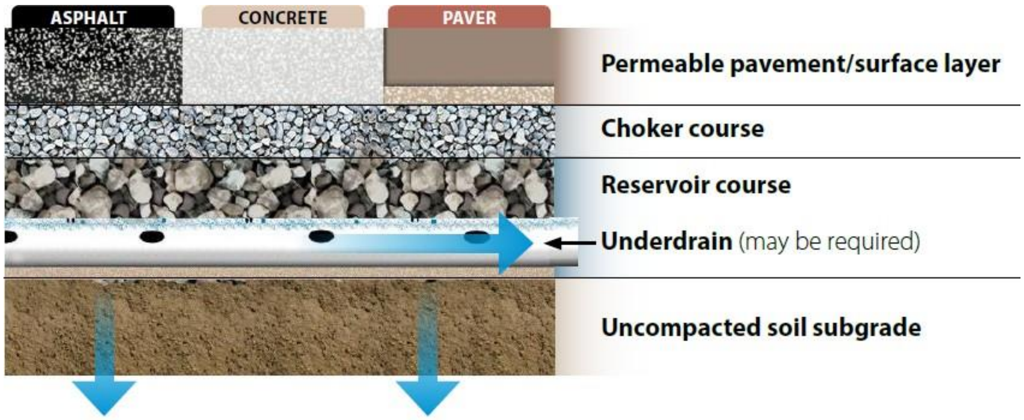


Figure 1-6
Partial-infiltration design—Underdrain, no liner
Source: © VHB

Figure 8. ASCE 2015 Permeable Pavement Design with Optional Sand Filter Course

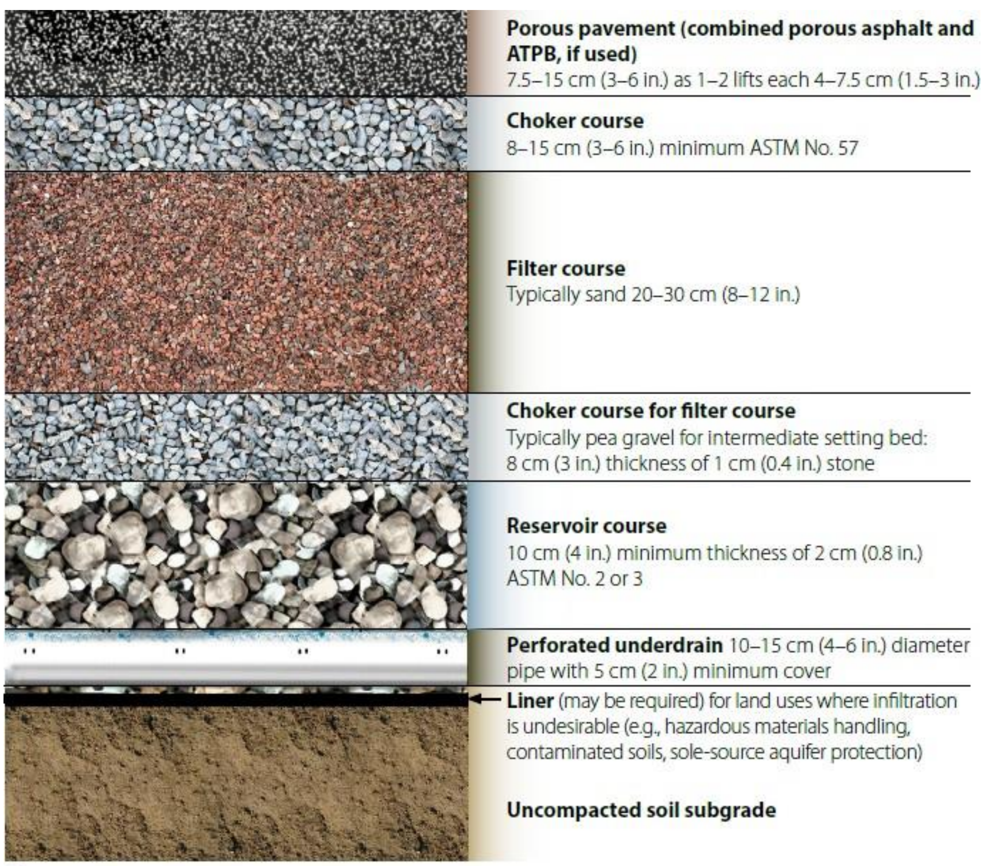


Figure 2-12
Porous asphalt section with filter course and capillary barrier for frost protection
Source: UNH Stormwater Center as modified by VHB

Although ASCE (2015) suggests that there are additional water quality and hydrologic benefits of the sand filter layer, they also state the following concerns:

> *The filter course serves two important functions both for water quality as a filtration mechanism and for pavement structure as a load bearing element. Because of its functions, the filter course is a common quality control concern. If the filter course is over compacted, internal drainage will be affected resulting from a poorly drained aggregate subbase. This has the potential to affect the system longevity in cold climates by increasing susceptibility to frost heave. Conversely, an under-compacted filter course will result in a reduced load bearing capacity contributing to a reduction in pavement strength and durability. The construction and installation of a filter course is an important point to employ construction quality assurance… A project that decides to forgo the quality control is better served using a standard subbase, and omitting the filter course as the same concerns for infiltration capacity and compaction do not exist.*

KEY TAKEAWAYS AND CONCLUSIONS

Based on the analysis described in this memo, the key findings pertinent to the update to Fact Sheet T-10 include:

- PICP installations following the MHFD criteria in Fact Sheet T-10 including a sand filter layer did not show better water quality performance than other studies that utilized a coarser base course layer material. The City of Fort Collins' comparative study is particularly relevant to this finding and supported Fort Collins's decision to remove the sand filter layer from their design criteria.

- The majority of criteria manuals from municipalities and institutions across the nation do not include a layer of aggregate smaller than No. 57 stone as the lowest base course layer of permeable pavement systems. No criteria manual reviewed that specified the use of an underdrain included a base layer of aggregate smaller than No. 57 stone.

- Standard designs recommended by ICPI and ASCE are typically layered with a bedding course of No. 8 aggregate, followed by a base of No. 57 stone, and a sub-base course of No. 2 stone. If an underdrain is included, ICPI includes a layer of No. 57 stone around the underdrain.

Based on the analysis in this memorandum, we recommend that MHFD consider modification of Fact Sheet T-10 to be consistent with the recommendations of ICPI and ASCE, given practitioner concerns expressed related to the structural performance of the sand filter layer. An additional finding from this research is the importance of construction observation as each layer of the system is installed. The City of Fort Collins' checklist may be helpful in deriving installation-related recommendations for Fact Sheet T-10.

As a side note, this memorandum reiterates the value of MHFD's stormwater BMP monitoring program, which provides data to enable comparison and evaluation of MHFD's design criteria that may affect BMP pollutant removal.

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ATTACHMENTS

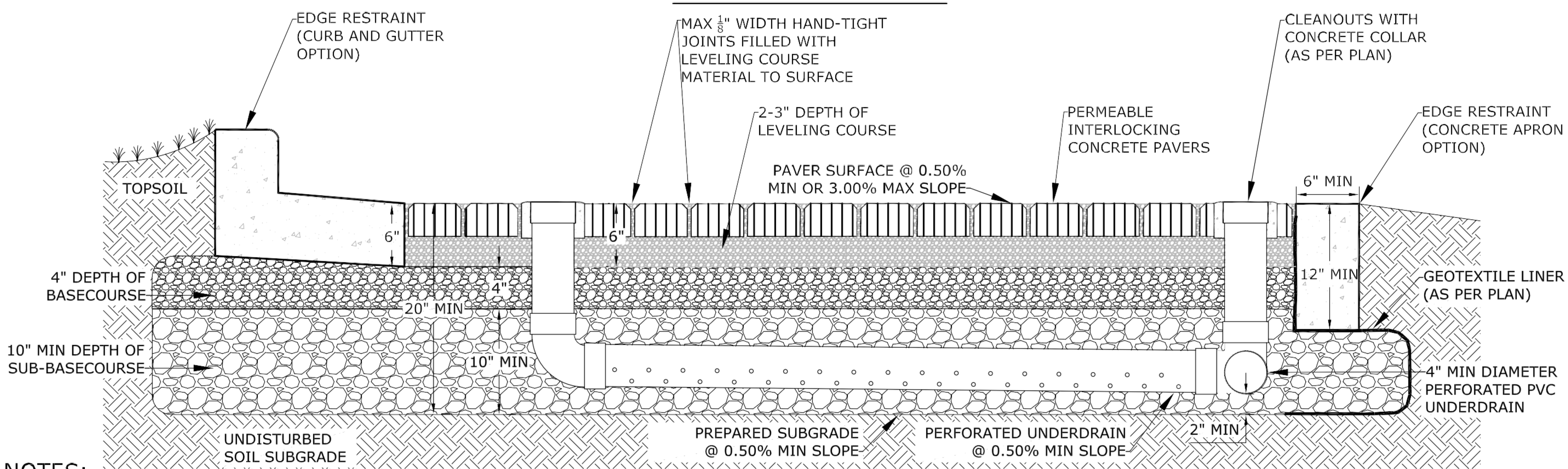
Attachment 1. City of Fort Collins PICP Design Drawing

Attachment 2. City of Fort Collins Construction Inspection Checklist

Attachment 1.

City of Fort Collins PICP Design Drawing

CROSS-SECTION DETAIL



NOTES:

1. CONTRACTOR MUST FOLLOW THE INTERLOCKING CONCRETE PAVEMENT INSTITUTE (ICPI) ASSOCIATION AND BRICK INDUSTRY ASSOCIATION CONSTRUCTION SPECIFICATIONS FOR COMPLETE INSTALLATION INFORMATION.

2. IT IS RECOMMENDED THAT A CERTIFIED PERMEABLE PAVEMENT INSTALLER PERFORM THE INSTALLATION OF THE PAVERS.

3. SUBGRADE PREPARATION:
   - 3.1. CONTRACTOR TO VERIFY THAT SUBGRADE PREPARATION, COMPACTION DENSITY AND ELEVATIONS CONFORM TO THE APPROVED DRAWINGS AND CONSTRUCTION SPECIFICATIONS.
   - 3.2. MINIMUM ALLOWABLE SUBGRADE SLOPE IS 0.5%.

4. EDGE RESTRAINTS:
   - 4.1. CONCRETE EDGE RESTRAINTS (CURB AND GUTTER OR APRON) SHALL BE INSTALLED AROUND THE PERIMETER OF THE PAVER AREA TO PROVIDE FOR PROPER EDGE RESTRAINT AND ALLOW FOR ADEQUATE SEPARATIONS BETWEEN PAVERS AND OTHER SURFACE TYPES.
   - 4.2. A CONCRETE COLLAR TO BE POURED AROUND ALL PENETRATIONS (INCLUDING CLEANOUTS) THROUGH THE PAVER SECTION .

5. GEOTEXTILE LINERS:
   - 5.5. GEOTEXTILE LINERS (PERMEABLE OR IMPERMEABLE AS PER PLAN) SHALL BE INSTALLED ALONG PERIMETER OF CROSS-SECTION OF THE PAVER AREA.
   - 5.3. GEOTEXTILE LINERS SHALL BE PLACED IN ACCORDANCE WITH MANUFACTURER'S STANDARDS AND RECOMMENDATIONS. ALL SEAMS AND OPENINGS IN THE LINER SHALL BE SEALED ACCORDING TO MANUFACTURER'S RECOMMENDATIONS AND SPECIFICATIONS.
   - 5.4. WHERE USED, IMPERMEABLE GEOMEMBRANE SHEET / LINER SHALL BE 40 MIL THICK, HIGH-DENSITY POLYETHYLENE DESIGNED SPECIFICALLY FOR FLEXIBLE GEOMEMBRANE APPLICATIONS. ADJACENT STRIPS OF IMPERMEABLE LINER SHALL OVERLAP A MINIMUM OF 18", OR PER MANUFACTURER'S SPECIFICATION.

6. AGGREGATES:
   - 6.1. ALL AGGREGATES SHALL BE ANGULAR, CRUSHED GRANITE ROCK AND SHALL BE WASHED ROCK, CLEAN OF DEBRIS AND FINES.
   - 6.2. SUB-BASECOURSE AGGREGATE SHALL BE GRADATION ASTM #2, #3, OR #4. ASTM #4 WILL NOT BE ALLOWED FOR USE WITH SUBSURFACE STORMWATER DETENTION SYSTEMS.
   - 6.3. BASECOURSE AGGREGATE SHALL BE GRADATION ASTM #57 OR #67.
   - 6.4. LEVELING COURSE SHALL BE GRADATION ASTM #8, #89 OR #9.
   - 6.5. LEVELING COURSE SHALL BE INSTALLED ALL THE WAY TO THE FINISHED GRADE SURFACE OF THE PAVERS.
   - 6.6. THE AGGREGATE SHALL BE PLACED IN 6-INCH (MAX.) LIFTS, COMPACTING EACH LIFT WITH A 10-TON, OR HEAVIER, VIBRATING STEEL DRUM ROLLER. MAKE AT LEAST FOUR PASSES WITH THE ROLLER, WITH THE INITIAL PASSES MADE WHILE VIBRATING THE ROLLER AND THE FINAL ONE TO TWO PASSES WITHOUT VIBRATION.
   - 6.7. CONTRACTOR MAY BE REQUIRED TO PROVIDE COMPACTION TESTING.

7. UNDERDRAIN:
   - 7.1. UNDERDRAIN PIPE TO BE PERFORATED OR SLOTTED.
   - 7.2. DO NOT WRAP UNDERDRAIN WITH GEOTEXTILE OR SOCK.

8. CLEANOUTS:
   - 8.1. PROVIDE CLEANOUTS (AS PER PLAN) TO ALLOW INSPECTION (BY CAMERA) OF THE UNDERDRAIN SYSTEM DURING AND AFTER CONSTRUCTION.
   - 8.2. CLEANOUTS SHALL BE PROVIDED AT EACH BEND GREATER THAN OR EQUAL TO 90° AND EVERY 100' ALONG A STRAIGHT RUN. CLEANOUT SHALL BE INSTALLED PER THE APPROVED PLANS.
   - 8.3. CLEANOUTS SHALL BE A SOLID WALL PVC STRUCTURE FOR ALL VERTICAL SECTIONS WITH FITTINGS TO CONNECT TO DISTRIBUTION AND UNDERDRAIN PIPING MATERIALS, AS REQUIRED.
   - 8.4. PROVIDE OBSERVATION PORT AT DOWNSTREAM END OF EACH PERMEABLE PAVEMENT SECTION, CONNECTED TO UNDERDRAIN WHEN PRESENT.
   - 8.5. THE CLEANOUT FRAME AND COVER SHALL BE DUCTILE IRON AND STAMPED "CLEANOUT."

9. PAVERS:
   - 9.1. CONTRACTORS MUST INSTALL A PAVER PRODUCT THAT IS APPROVED BY THE ICPI.
   - 9.2. FINISHED GRADE OF THE PAVER SURFACE TO BE EVENLY SLOPED AND FLUSH WITH THE ADJACENT EDGE RESTRAINTS.
   - 9.3. ALL PENETRATIONS THROUGH THE PAVER SURFACE, INCLUDING CLEANOUT LIDS, SHALL BE INSTALLED WITH A CONCRETE COLLAR POURED AROUND THE PERIMETER.

10. POST-INSTALLATION:
    - 10.1. LOOSE MATERIALS SHALL NOT BE STORED ON THE PERMEABLE PAVEMENT AREA.
    - 10.2. THE CONTRACTOR SHALL, AT ALL TIMES DURING AND AFTER SYSTEM INSTALLATION, PREVENT SEDIMENT, DEBRIS AND DIRT FROM ANY SOURCE FROM ENTERING THE PERMEABLE PAVEMENT SYSTEM.

PERMEABLE INTERLOCKING CONCRETE PAVERS			
City of Fort Collins — CITY OF FORT COLLINS UTILITIES P.O. BOX 580 FORT COLLINS, CO. 80522 (970) 221-6700	STORMWATER CONSTRUCTION DETAILS	APPROVED: DATE REVISED: DECEMBER 2017 DRAWN BY: HEM	DETAIL D-54

Attachment 2. City of Fort Collins Construction Inspection Checklist

Permeable Pavers

_____ Was subgrade over or under compacted?
_____ Were edge restraints installed to ensure pavers are locked tight?
_____ Was impermeable liner welded together and anchored to the edge restraint properly?
_____ Was geotextile liner entrenched properly? (No specific depths, just entrenched enough)
_____ Was underdrain perforated with holes smaller than #2 aggregate?
_____ Did the perforation in the underdrain end before the pipe entered native soils?
_____ Was underdrain installed WITHOUT wrapping?
_____ Was the underdrain correctly installed without an orifice plate at its outfall?
_____ Were cleanouts installed at any angle larger than 90 degrees and/or every 200 ft?
_____ Were all cleanout ports, manholes, inspection ports, etc. installed with a squared concrete collar?
_____ Was #2 rock clean, washed aggregate in a layer 10" deep?
_____ Was #57 rock clean, washed aggregate in a layer 4" deep?
_____ Was #89 rock clean, washed aggregate in a layer 2-3" deep and filled to within ½" of top of pavers?
_____ Was paver system compacted with a vibratory compacter?
_____ Were pavers installed with no pieces smaller than 1/3 the size of a full paver?
_____ Were there no areas greater than 3/8" difference between pavers and final grade?
_____ Were there no areas where height between adjacent pavers was greater than 1/4" (1/8" per ICPI)?
_____ Were the pavers maintained for the life of the project per the DA?
_____ Were all inlet manholes properly labelled with "No Dumping - Drains to Poudre River"?

Note: inspector is also provided with photos of various sizes of aggregate and the design drawing.