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Permeable Pavement in the Northwestern United States: Pollution Source or Treatment Option?

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Abstract: Permeable pavements can be an effective stormwater mitigation technique, but there are concerns that polluted stormwater may contaminate groundwater as stormwater infiltrates through the soil beneath the pavement. This research evaluates the pollutant removal capabilities of pervious pavements using pervious cement concrete (PC) and porous asphalt concrete (PA) cylinders. Stormwater collected from an outfall was used to perform three tests. The influent and effluent were analyzed for metals, semi-volatile organic compounds (SVOCs), phosphorus, and turbidity. Average percent removal for metals were 37–63% except for zinc, which had an average export of 21% for pervious cement concrete and 52% for porous asphalt concrete. Only 10 of the SVOCs tested had an influent concentration above detection levels. Complete removal (below detection levels) was observed for benzo(a)anthracene, benzo(a)pyrene, chrysene, and indeno(1,2,3-cd) pyrene. Average removals for benzo(b)fluoranthene, benzo(g,h,i)perlyne, fluoranthene, phenanthrene, pyrene, and bis(2-ethylhexyl)phthalate were 63–96%. No significant removal was observed for total phosphorus and reactive phosphate. All contaminant concentrations were below drinking water limits except lead, which would likely be removed in the soil layer below the pavement. This study indicates permeable pavements can effectively remove stormwater contaminants and protect groundwater as a drinking water source.

Keywords: stormwater; water quality; pervious cement concrete; porous asphalt concrete

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1. Introduction

Stormwater mitigation can be challenging in urban areas, particularly in Portland, Oregon, where average annual rainfall is 36.9 inches and mostly occurs during the rainy season (October–May) with little to no rainfall in the period of June–September [1]. Many urban areas have very little permeable surfaces, resulting in significant stormwater runoff [2]. Cities must have efficient drainage systems to keep streets safe for drivers in addition to slowing runoff and reducing discharge of stormwater contaminants to protect receiving waters. Annually, 75% of weather-related crashes occur on wet pavement, resulting in 5700 deaths [3]. To increase safety, streets must drain quickly to prevent standing water on the streets. Standard drainage systems that efficiently minimize standing water can cause erosion of stream banks and beds. Increased impervious areas where stormwater is collected with a curb and gutter system and transported directly to receiving waters in a storm drain have caused a disconnect between groundwater and surface water. In addition, stormwater contaminants, including oils, fertilizers, metals, and pesticides, can negatively impact receiving waters and the aquatic ecosystem [4].

Stormwater management techniques such as green infrastructure and permeable pavements can help reconnect the hydrologic cycle, reduce flooding and erosion, and reduce contaminants in drinking water sources. Maintaining access to clean, safe drinking water is imperative for a sustainable society. The City of Portland has slowed down and treated stormwater in many areas using green stormwater infrastructure, which has also reduced the volume of stormwater going to the combined storm–sewer system by 35% [5]. These systems typically consist of soil and plants, with an underdrain in areas where infiltration rates are low. Even with an underdrain, these systems reduce peak flows and remove stormwater contaminants [6–9]. However, some neighborhoods, particularly in highly industrialized areas, do not have the space to implement green stormwater infrastructure. Permeable pavements may be a way to reduce standing water on streets as well as treat stormwater without additional space requirements and can help develop "sponge cities" [10]. Permeable pavements are similar in design to standard pavements, except the small aggregate (sand) is left out of the mix design [11]. The result is a pavement that has small, interconnected pore spaces throughout that allow stormwater to pass through. The stormwater then infiltrates into the base layer and soil beneath the pavement. There are two main types of permeable pavements that can be used on urban streets: pervious cement concrete and porous asphalt concrete. Both pervious cement concrete and porous asphalt concrete have been shown to significantly reduce standing water on streets, which reduces hydroplaning [12] and improves skid resistance [13], creating a safer surface for driving. Permeable pavements have also been shown to lower tire noise, improve nighttime visibility, and reduce heat-island effects in urban areas [14]. The U.S. Environmental Protection Agency (EPA) designates permeable pavements as "cool pavements," which are paving materials that reflect more solar energy and increase water retention compared to conventional pavements [14,15]. Recent studies have evaluated the impacts of aging on permeable pavements [16], using recycled materials as aggregate [17], and amendments to improve strength properties [18], making permeable pavement a more practical option.

Although studies have shown the benefits of permeable pavements, there is still reluctance to use them in many urban areas due to concern that contaminants in stormwater can potentially pollute soil and groundwater under permeable streets [6]. Stormwater, particularly in industrial areas, has been shown to have elevated levels of heavy metals, hydrocarbons, and other contaminants that are harmful to human and ecological health [19]. Studies have shown that it may be feasible to harvest stormwater from permeable pavements and use it as a source of potable water for buildings [20,21], with potentially 40–80% of stormwater being harvested [21], but it is imperative to determine the safety of this stormwater before implementation. Several studies have shown that permeable pavements effectively remove pollutants from stormwater [6,8,22,23] and can actually be an effective treatment method. Many studies have reported significant removal of copper, lead, and cadmium [6,8,24]. Results for zinc have been mixed; some studies have shown removal of zinc [6,24,25], whereas others have shown higher concentrations of zinc below the pavement compared to influent concentrations [6,25,26]. Significant removal of total suspended solids (TSS) has also been observed [6,25]. Metals and suspended solids are likely removed physically as the stormwater flows through the pore spaces in the pavement [27]. This is supported by studies that show lead, zinc, copper, and cadmium removal in the top 30 cm of porous asphalt concrete and pervious cement concrete [28,29]. Copper and zinc can also be removed via adsorption and complexation reactions with carbonate and hydroxide that form when pervious cement concrete is cured [24]. Studies have also shown that permeable pavements remove nutrients and hydrocarbons [6,7,25,30]. Jayasuriya et al. (2007) observed 96% total nitrogen and total phosphorus removal [6]. Pilon et al. (2019) observed 38% removal of polyaromatic hydrocarbons (PAHs) in pervious cement concrete [24]. Brattebo and Booth (2003) observed levels of lead, diesel fuel, and motor oil below detection levels under porous asphalt concrete [7]. This is similar to the observations of Charlesworth et al. (2017), who found 99.9% of motor oil was removed with porous asphalt concrete, and concentrations were well below WHO drinking water guidelines [30]. Many of the studies mentioned above were limited to common stormwater pollutants such as metals, nutrients, and motor oil. Although these studies indicate permeable pavements are effective at removing common pollutants from stormwater, additional water quality parameters, such as SVOCs, need to be tested to ensure the safety of drinking water sources or ecological receptors in receiving waters. Many SVOCs are particularly harmful to human health, and more studies are needed to ensure drinking water derived from treated stormwater is safe for consumption.

This study evaluates removal efficiencies for SVOCs, phosphorus, metals, and turbidity. Two types of permeable pavement were tested: pervious cement concrete and porous asphalt concrete. Stormwater was collected and used to conduct three tests. Influent and effluent samples were taken during each test and analyzed for contaminants that may pose a hazard for groundwater. We hypothesize that permeable pavements will decrease pollutant levels enough to meet drinking water standards and minimize risk of polluting groundwater or receiving water bodies.

2. Materials and Methods

2.1. Test Specimens

Triplicates of pervious cement concrete and porous asphalt concrete cylinders were made to evaluate water quality. For the pervious cement concrete cylinders, a mix of 76% aggregate, 19% cement, and 5% water was mixed by hand and scooped into 10.2 cm (4-inch)-diameter, 20.3 cm (8-inch)-long cylindrical molds. Aggregate gradation is shown in Table 1. The mix was compacted approximately 10% using a standard tamper, covered, and allowed to cure for seven days. The mix design and procedure for making cylinders were similar to other studies [24]. The porous asphalt concrete cylinders were made following guidelines from the National Asphalt Pavement Association, which specifies a mix of 84% aggregate, 10% mineral filler, and 6% asphalt binder [31]. Asphalt binder (PG 70-22 ER) was obtained from Lakeside Industries (Portland, OR, USA). The aggregate and asphalt binder were heated to 149 °C (300 °F), and all components were mixed in a large container before placing in an aluminum mold to make the cylinders. Both concrete and asphalt cylinders were made in one batch to ensure the consistency of the mix for the replicates. The porous asphalt concrete cylinders were the same size as the pervious cement concrete cylinders. Air voids were 28% and 34% in the pervious cement concrete and porous asphalt concrete, respectively.

Table 1. Aggregate Gradation for both Pervious Cement Concrete and Porous Asphalt Concrete.

Sieve Size	%Passing
3/4″	100
1/2″	90–100
3/8″	40–70
U.S. No. 4	0–15
U.S. No. 8	0–5

2.2. Experiments

The test setup consisted of ring stands to hold the cylinders, separatory funnels, and a container below the cylinders to collect effluent (Figure 1). Prior to testing, approximately 3 L of stormwater collected from a parking lot at the University of Portland (equivalent to 10 water quality design storms) was applied to the cylinders. The volume of a water quality design storm is 331 mL for a 10.2 cm diameter surface using the City of Portland water quality design storm of 4.1 cm (1.61 inches) [32]. The water quality design storm volume (331 mL) was applied ten times at least two days apart to wet the cylinders and allow for carbonation to develop in the pore spaces of the cylinders before testing to mimic in situ conditions [24]. For the tests, stormwater from the Columbia Slough Outfall 56C was collected, which transports stormwater from North Portland and discharges to the Columbia Slough. The outfall is part of the Oregon Department of Environmental Quality Columbia Slough Sediment Project, an effort to reduce contaminants in the Columbia Slough with the City of Portland, Multnomah County Drainage District, and private parties [33]. This outfall was selected because stormwater is collected from an industrial area in North Portland, and pollutant concentrations are typically 10 times greater than the DEQ's Columbia Slough stormwater screening levels.

Figure 1. Pervious Cement Concrete and Porous Asphalt Concrete Test Setup.

Three trials were conducted during testing. The experimental flow diagram is shown in Figure 2. During each trial, 1.25 L of stormwater was applied to each cylinder using a separatory funnel to control application rate. Although this is much more than the water quality design storm, the additional volume was needed to complete the water quality analysis. A runoff rate of 10 mL/min was applied to the cylinders. This rate is similar to that used by other studies [24] and represents a rainfall intensity for a permeable pavement road without additional run-on from upstream catchments. Tests were conducted at least two days apart to mimic rainfall patterns and allow for the cylinders to partially dry. Effluent was collected in a polypropylene container, and composite samples were collected from the container after the cylinders stopped dripping. Total phosphorus and phosphate were analyzed in accordance with Standard Methods Section 4000: Inorganic Nonmetallic Constituent [34]. The persulfate method was used to quantify total phosphorus, and the colorimetric method was used to quantify phosphate. Turbidity was quantified using a Hach turbidimeter. Arsenic, cadmium, copper, lead, zinc, and semi-volatile organics were analyzed at the City of Portland's Water Pollution Control Lab (WPCL). A list of the SVOCs analyzed is shown in Table 2. Metals were analyzed using an ICP-MS in accordance with EPA method 200.8. Semi-volatile organics were analyzed using a GCMS in accordance with EPA method 8270. All glassware and sample bottles were acid-washed and rinsed with DI water according to standard methods [34]. Samples were stored at 4 °C, preserved, and analyzed within standard holding times.

Table 2. SVOCs Analyzed in Influent and Effluent.

Contaminant
Acenaphthene
Acenaphthylene
Anthracene
Benzo(a)anthracene
Benzo(a)pyrene
Benzo(b)fluoranthene
Benzo(g,h,i)perylene
Benzo(k)fluoranthene
Chrysene
Dibenzo(a,h)anthracene
Fluoranthene
Fluorene
Indeno(1,2,3-cd)pyrene
Naphthalene
Pentachlorophenol

Table 2. *Cont.*

Contaminant
Phenanthrene
Pyrene
Butyl benzyl phthalate
Di-n-butyl phthalate
Diethyl phthalate
Dimethyl phthalate
Di-n-octyl phthalate
Bis(2-ethylhexyl) phthalate

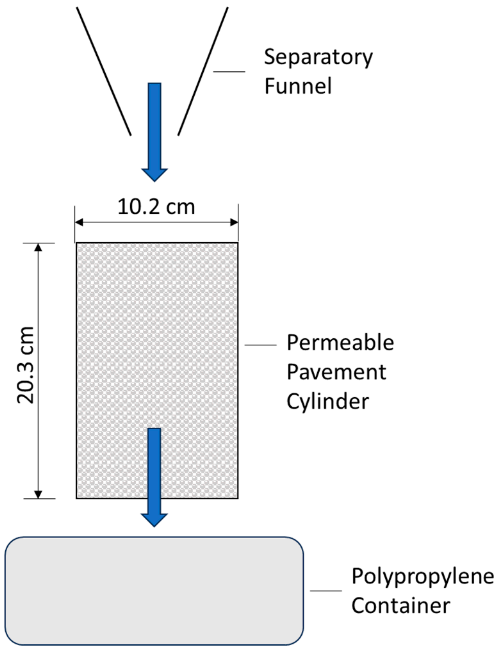

Figure 2. Pervious Cement Concrete and Porous Asphalt Concrete Test Setup.

2.3. Statistical Analysis

The average and standard deviation of the three replicates were calculated for each trial. The Kruskal–Wallis and Wilcoxon signed-rank test was used to determine whether there was a significant difference between the influent and effluent, different trials, and porous asphalt concrete and pervious cement concrete [35]. This test is commonly used for studies with small sample sizes to determine if different treatments are effective. Differences were considered significant if $p < 0.05$.

3. Results and Discussion

During each trial, all stormwater flowed through the pervious cement concrete and porous asphalt concrete at the rate applied. No ponding was observed. Although this is beneficial for removing stormwater from the street and improving safety during rain events, lower-permeability pavements may remove more pollutants given the tortuous paths and longer residence time in the pavement. Average influent turbidity was 191 NTU, and average effluent was 176 NTU. The effluent was significantly lower than the influent during trials 1 and 3 ($p = 0.03$) but statistically the same during trial 2 ($p = 0.156$). Turbidity was statistically the same in the effluent from the pervious cement concrete and porous asphalt concrete cylinders. Results are similar to other studies that showed limited removal of turbidity [25,36]. The pore spaces in permeable pavements were shown to effectively trap suspended solids, but they are not small enough to remove microscopic particles that impact the clarity of water [36].

3.1. Metals

Table 4 shows the average effluent concentrations for arsenic, cadmium, copper, lead, and zinc during each trial, and Figure 3 shows the influent and effluent concentrations for these metals. Table 3 shows the percent removal from the pervious cement concrete and porous asphalt concrete cylinders during each trial. The effluent for both pervious cement concrete and porous asphalt concrete was significantly lower than the influent for arsenic, cadmium, copper, and lead (p = 0.03–0.04). Zinc concentrations in the effluent were significantly lower than the influent during trial 1 (p = 0.03) and significantly higher than the influent during trials 2 and 3 (p = 0.03). Removal of cadmium and zinc was significantly higher in the pervious cement concrete compared to the porous asphalt concrete cylinders (p = 0.01) but statistically the same for arsenic, copper, and lead (p = 0.25–0.57).

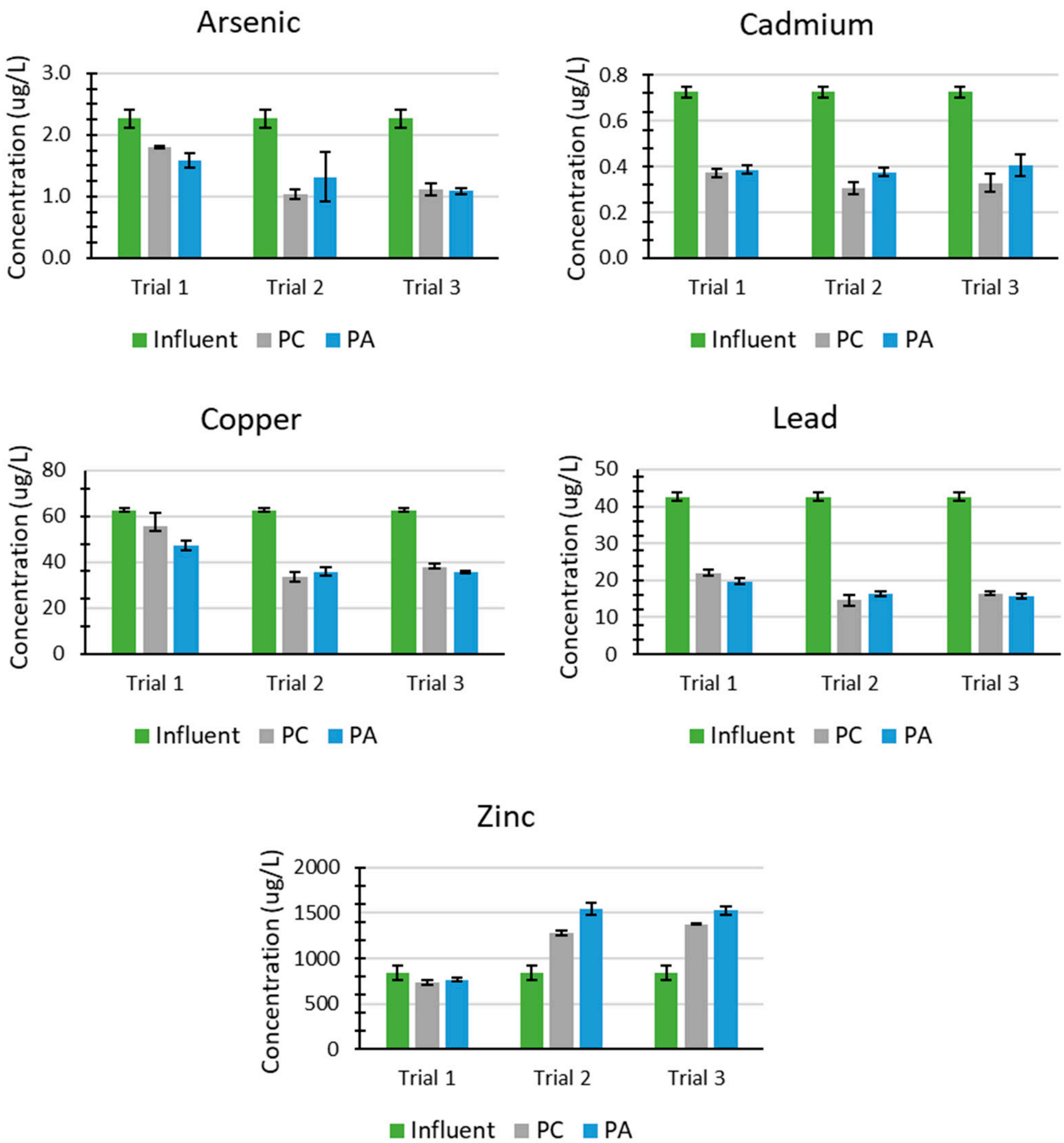

Figure 3. Influent and effluent metals concentrations during each trial. PC = pervious cement concrete, PA = porous asphalt concrete.

Table 3. Percent removal of metals for each trial. Negative values indicate export.

	% Removal					
	Pervious Cement Concrete			Porous Asphalt Concrete		
Contaminant	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 1**	**Trial 2**	**Trial 3**
Arsenic	20.1	54.5	50.6	29.8	41.7	51.9
Cadmium	48.6	58.0	54.8	46.6	48.2	43.8
Copper	10.9	46.7	40.0	24.5	42.6	42.8
Lead	48.2	65.5	61.2	53.7	61.8	62.9
Zinc	13.0	−51.8	−63.7	9.6	−83.9	−81.5

Table 4. Average effluent metals concentration during each trial with standard deviation in parentheses.

	Effluent Concentration (μg/L)					
	Pervious Concrete			Porous Asphalt		
Contaminant	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 1**	**Trial 2**	**Trial 3**
Arsenic	1.81 (0.02)	1.03 (0.08)	1.12 (0.10)	1.59 (0.11)	1.32 (0.41)	1.09 (0.04)
Cadmium	0.37 (0.02)	0.30 (0.03)	0.33 (0.04)	0.39 (0.02)	0.38 (0.02)	0.41 (0.05)
Copper	55.8 (5.83)	33.4 (2.21)	37.6 (1.97)	47.3 (2.25)	35.9 (1.89)	35.8 (0.57)
Lead	22.03 (0.83)	14.7 (1.46)	16.5 (0.44)	19.7 (0.78)	16.3 (0.71)	15.8 (0.57)
Zinc	732 (24.4)	1277 (25.2)	1377 (5.77)	761 (19.5)	1547 (64.3)	1527 (49.3)

Metals removal was similar to other studies that found metals are removed on the order of 50% [8,27], although some studies have shown higher removal rates [24,37]. The Washington Technology Assessment Protocol–Ecology (TAPE) is a protocol used to evaluate stormwater technologies in Oregon and Washington and requires 30% removal of copper and 60% removal of zinc for new stormwater technologies to be approved for use [38]. Average removal of copper was 39% for pervious cement concrete and 37% for porous asphalt concrete, which exceeds TAPE standards. However, 60% removal of zinc was not achieved; zinc was exported in both the pervious cement concrete and porous asphalt concrete. With the exception of cadmium and arsenic, removal was significantly higher during trials 2 and 3 compared to trial 1 (p = 0.03–0.04). Arsenic concentrations in the effluent were statistically the same during trials 1 and 2 (p = 0.06), but removal was significantly higher (p = 0.03) during trial 3 compared to trial 1. Cadmium concentrations in the effluent were statistically the same during all trials (p = 0.06–0.84). Higher removal during trials 2 and 3 could be due to the stormwater that remains in the cylinders between testing; slower mechanisms of removal such as complexation reactions could be occurring between tests.

Results indicate pervious cement concrete and porous asphalt concrete was not effective at removing zinc from the stormwater. Removal occurred during the first trial, but then, export occurred during trials 2 and 3. Other studies have shown 0.55–101% export of zinc [6,25,26]. This may be due to zinc saturation of the cylinders, which is then released during subsequent storm events. Further research is needed to determine why zinc is exported from permeable pavements and how it can be minimized.

3.2. Semi-Volatile Organics

Table 5 shows the average effluent concentrations of select SVOCs during each trial, and Figure 4 shows influent and effluent concentrations. Table 6 shows percent removal from the pervious cement concrete and porous asphalt concrete for each trial. The remaining SVOCs were below detection limits in both the influent and effluent during each trial. Complete removal was observed for chrysene, benzo(a)pyrene, benzo(a)anthracene, and indeno(1,2,3-cd)pyrene during all three trials; effluent concentrations were below the detection limit. Effluent concentrations were significantly lower than influent for the SVOCs that had influent concentrations above the detection limit (p = 0.03–0.04). Effluent from the pervious cement concrete and porous asphalt concrete cylinders were statistically the same (p = 0.06–0.40), and there was no difference between trials (p = 0.06–0.83).

Table 5. Average effluent SVOC concentrations for each trial, with standard deviation in parentheses. ND indicates the contaminant was below detection levels.

	Effluent Concentrations (µg/L)					
	Pervious Concrete			Porous Asphalt		
Contaminant	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 1**	**Trial 2**	**Trial 3**
Benzo(a)anthracene	ND	ND	ND	ND	ND	ND
Benzo(a)pyrene	ND	ND	ND	ND	ND	ND
Benzo(b)fluoranthene	ND	ND	ND	0.06 (0.1)	0.06 (0.1)	ND
Benzo(g,h,i)perylene	0.20 (0.03)	ND	0.06 (0.03)	0.21 (0.02)	0.18 (0.02)	ND
Chrysene	ND	ND	ND	ND	ND	ND
Fluoranthene	0.29 (0.03)	0.25 (0.02)	0.28 (0.02)	0.30 (0.01)	0.30 (0.01)	0.27 (0.01)
Indeno(1,2,3-cd) pyrene	ND	ND	ND	ND	ND	ND
Phenanthrene	0.06 (0.1)	ND	ND	0.17 (0.01)	0.18 (0.01)	ND
Pyrene	0.44 (0.05)	0.37 (0.03)	0.42 (0.03)	0.46 (0.01)	0.45 (0.01)	0.42 (0.01)
Bis(2-ethylhexyl)phthalate	5.27 (0.6)	3.77 (0.25)	4.5 (0.1)	5.23 (0.85)	4.77 (0.45)	4.43 (0.21)

Table 6. Percent removal of select semi-volatile organics for each trial.

	% Removal					
	Pervious Cement Concrete			Porous Asphalt Concrete		
Contaminant	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 1**	**Trial 2**	**Trial 3**
Benzo(a)anthracene	100	100	100	100	100	100
Benzo(a)pyrene	100	100	100	100	100	100
Benzo(b)fluoranthene	100	100	100	84.9	84.9	100
Benzo(g,h,i)perylene	60.7	100	88.7	58.0	63.3	100
Chrysene	100	100	100	100	100	100
Fluoranthene	63.7	68.4	65.0	62.4	62.4	65.4
Indeno(1,2,3-cd) pyrene	100	100	100	100	100	100
Phenanthrene	88.9	100	100	68.5	66.0	100
Pyrene	64.8	70.4	66.4	62.9	64.0	66.4
Bis(2-ethylhexyl)phthalate	59.5	71.0	65.4	59.7	63.3	65.9

Results are similar to other studies that showed removal of PAHs, diesel fuel, and motor oil from both pervious cement concrete and porous asphalt concrete [7,25,30,39]. For porous asphalt concrete, Brattebo and Booth (2003) observed complete removal of diesel fuel and motor oil [7], and Charlesworth et al. (2017) observed 99.9% removal [30]. This indicates both porous asphalt concrete and pervious cement concrete can effectively remove common organic pollutants. Removal of SVOCs may occur in the upper portion of the permeable pavement, similar to Charlesworth et al. (2017), who observed oil removal in the top 10 cm of pavement [30]. A microbial biofilm was found on the surface layer of the pavement, which likely degraded the oil. Additional studies would be needed to confirm whether biological removal is the main removal mechanism for SVOCs.

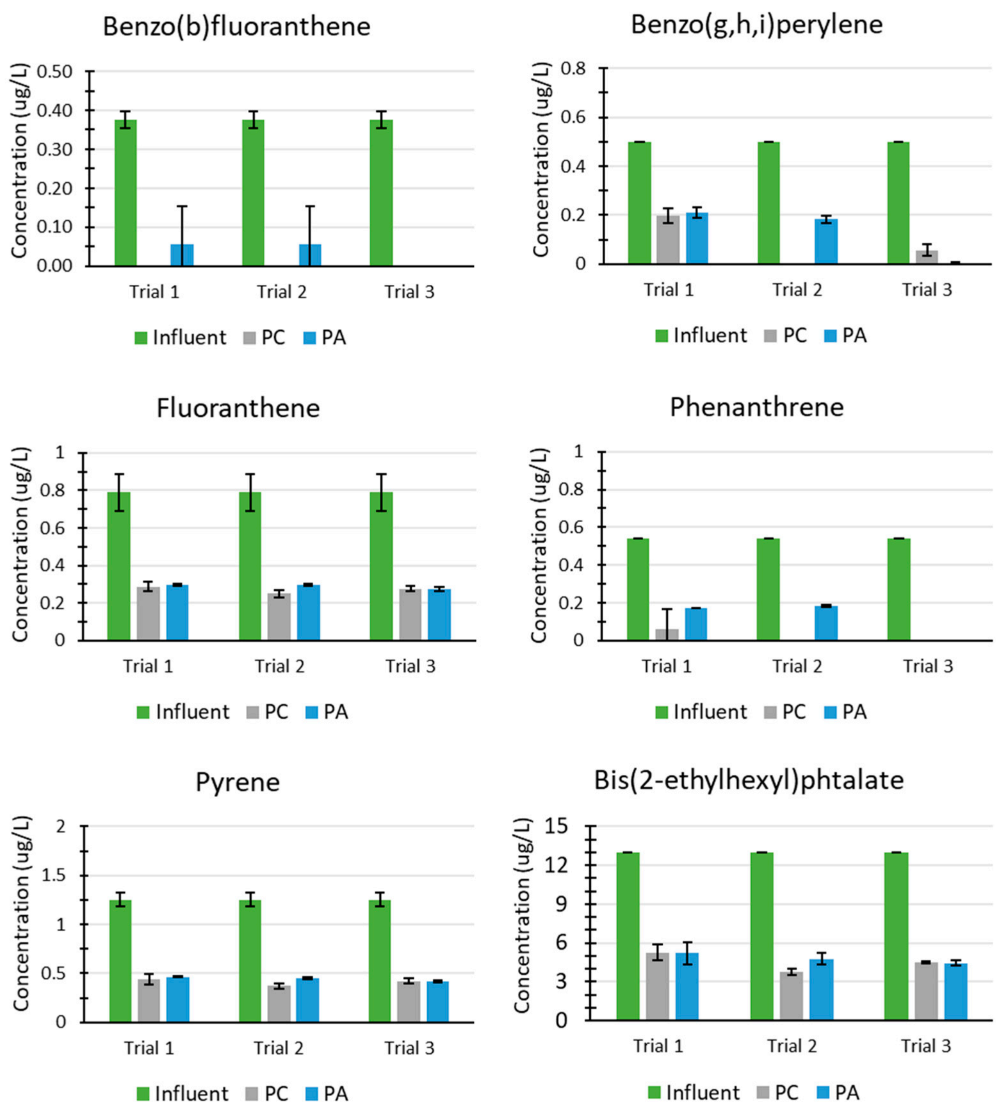

Figure 4. Influent and effluent concentrations of select semi-volatile organics during each trial. PC, pervious cement concrete; PA, porous asphalt concrete.

3.3. Phosphorus

Table 7 shows the average effluent concentrations of total phosphorus and phosphate during each trial, and Figure 5 shows influent and effluent concentrations. Table 8 shows the percent removal from the pervious cement concrete and porous asphalt concrete for total phosphorus and phosphate. The influent and effluent were statistically the same for total phosphorus during trials 1 and 2 (p = 0.44–0.59) but significantly lower (p = 0.03) during trial 3. Influent and effluent phosphate concentrations were statistically the same during all trials (p = 0.53–1.0), which indicates phosphate is not effectively removed in pervious cement concrete or porous asphalt concrete. For discharge to receiving waters, EPA recommends an effluent limit of 0.05 mg/L for discharge to streams entering lakes and 0.1 mg/l for streams with no reservoirs or lakes [40]. The effluent in this study was much higher (greater than 0.5 mg/L) than the recommended limit. Stormwater flowing through permeable pavements will likely flow through the aggregate base layers and soil before reaching receiving waters, where some of the phosphorus could be retained. Percent removal was low for most trials, with export occurring during some of the trials. This is in contrast to the significant total phosphorus removal observed by Jayasuriya et al. (2007) and does not meet the TAPE standards of 50% total phosphorus removal [6,38]. However, other studies have shown export of phosphorus [39]. Differences in removal may be due to the main removal mechanism that is likely removing phosphorus in the permeable pavement. Total phosphorus is typically associated with soils and has been observed to be transported with sediment [41]. Permeable pavements with larger pore sizes may be less effective at removing phosphorus via physical filtration compared to pavements with smaller pore sizes. Additional studies are needed to determine the mechanisms for phosphorus removal and how to optimize removal in pervious cement concrete and porous asphalt concrete.

Table 7. Average effluent concentrations of total phosphorus and phosphate for each trial, with standard deviation in parentheses.

	Effluent Concentrations (mg/L)					
	Pervious Concrete			Porous Asphalt		
Contaminant	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 1**	**Trial 2**	**Trial 3**
Total Phosphorus	1.08 (0.34)	0.68 (0.04)	0.68 (0.01)	2.8 (0.92)	0.71 (0.02)	0.63 (0.02)
Phosphate	0.03 (0.05)	0.11 (0.19)	0.12 (0.11)	0.19 (0.07)	0.06 (0.08)	0.09 (0.11)

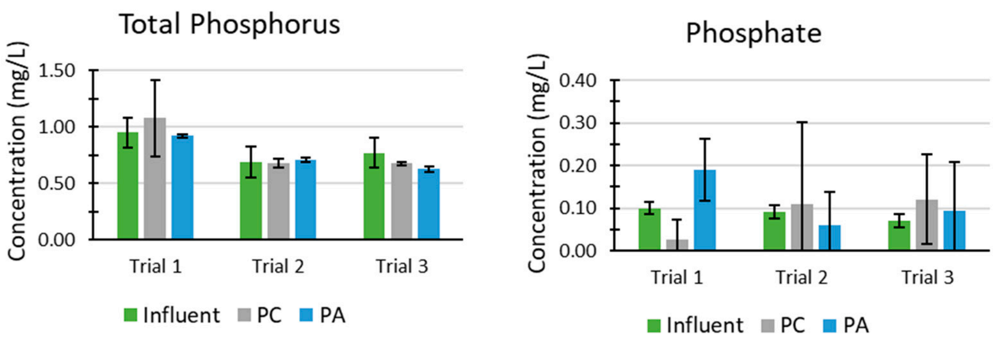

Figure 5. Influent and effluent concentrations of total phosphorus and phosphate during each trial. PC = pervious cement concrete, PA = porous asphalt concrete.

Table 8. Precent removal of total phosphorus and phosphate for each trial. Negative values indicate export.

	% Removal					
	Pervious Cement Concrete			Porous Asphalt Concrete		
Contaminant	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 1**	**Trial 2**	**Trial 3**
Total Phosphorus	−13.7	1.0	12.1	2.8	−2.4	18.6
Phosphate	73.3	−22.2	−71.4	−90.0	33.3	−33.3

3.4. Comparison to Drinking Water Standards

Table 9 shows average results compared to maximum contaminant levels (MCLs) set by the Oregon Health Authority and EPA (OAR-333-061-0030). Only contaminants with limits for drinking water are listed; many of the contaminants tested in this study do not have MCLs for drinking water. Both copper and lead have an action level, not an actual MCL. Public water systems must take action if copper concentrations are higher than 1.3 mg/L and/or lead concentrations are higher than 0.015 mg/L. Zinc does not have an enforceable MCL, but secondary guidelines recommend an MCL of 5 mg/L.

Table 9. Comparison of effluent concentrations to drinking water standards.

	Average Concentration (mg/L)		
Contaminant	**Pervious Cement Concrete**	**Porous Asphalt Concrete**	**MCL (mg/L)**
Arsenic	0.00132	0.00133	0.010
Cadmium	0.00033	0.00039	0.005
Copper	0.0423	0.0397	1.3 *
Lead	0.0177	0.0172	0.015 *
Zinc	1.13	1.28	5 **
Benzo(a)pyrene	ND	ND	0.0002
Pentachlorophenol	ND	ND	0.001

* Action level. ** Secondary contaminant level (not enforceable).

All contaminants are below the MCL or action levels for drinking water except for lead. Lead has an action level of 0.015 mg/L for drinking water, and average lead concentrations in this study were 0.018 for pervious cement concrete and 0.017 mg/L for porous asphalt concrete. Although there was 48–65% removal through both the pervious cement concrete and porous asphalt concrete, effluent concentrations were slightly higher than the action level. Additional lead will likely be removed in the soil layer beneath the pervious pavement. Legret et al. (1996) found a 79% decrease in lead concentrations through pervious pavement and the underlying soil layer compared to a catchment with no treatment [37]. Metals were observed to accumulate on the surface of the pervious asphalt as well as the underlying soil and geotextile layer. Contaminant transport modeling performed by the City of Portland to support their Underground Injection Control (UIC) Program for stormwater management indicated that lead was removed in the soil layers to levels below the action level [42]. In addition, bioretention studies have shown that 92–99% of lead is removed in 2 ft of soil [43]. If 90% removal is assumed in the soil layer, lead concentrations would be 0.002 mg/L, which is significantly below the action level. Thus, the stormwater flowing through pervious cement concrete and porous asphalt concrete likely meets drinking water standards and will not contaminate groundwater. Additional field studies would be needed to confirm.

4. Conclusions

This study indicates the following:

1. Pervious cement concrete and porous asphalt concrete can effectively remove most contaminants of concern for drinking water to below MCLs. Lead concentrations were slightly higher than the MCL, but further removal will likely occur in the soil layer beneath the pervious pavement;
2. Zinc was exported from the permeable pavements, but concentrations were still well below the secondary MCL. Total phosphorus and phosphate were either exported or minimally removed, but this does not pose a threat to groundwater in terms of drinking water safety;
3. Significant removal was observed for SVOCs, which indicates pervious cement concrete and porous asphalt concrete can effectively be used as a treatment method for organic contaminant removal;
4. Permeable pavements minimize the risk of infiltrating stormwater polluting groundwater and provide a method of removing pollutants before reaching the groundwater table.

4.1. Study Limitations

This study was limited to testing two types of permeable pavements in the laboratory: pervious cement concrete and porous asphalt concrete. Further removal in the soil layer beneath the pervious pavement was not evaluated. Additional testing would be needed to verify whether further removal occurs in the soil layer beneath the pervious pavement to levels below the MCL for lead. The study also did not evaluate long-term performance or possible accumulation in the pavements or underlying soils. Removal capabilities may vary seasonally or over time in the field as the pavements weather, experience wetting/drying cycles, and roads are maintained (e.g., cleaning and sweeping).

4.2. Future Work

Field studies are needed to verify these results would occur on a larger scale and on a long-term basis. Field studies could determine how changes in temperature, rainfall patterns, wetting/drying cycles, and other factors that are limited in laboratory studies impact water quality below installed permeable pavements. Long-term studies over at least 12–24 months to capture seasonally changes are also needed to evaluate changes in pavements due to weathering, pollutant accumulation in the pavement over time, and potential leaching. Pervious cement concrete and porous asphalt concrete can be a potentially powerful tool for increasing traffic safety, reducing flooding, lowering noise from roadways, reducing the heat-island effect, and protecting groundwater from stormwater contaminants. Increased use of permeable pavements can improve the sustainability of urban areas and protect valuable drinking water sources. Municipalities should consider using permeable pavements for new or replacement pavement projects more extensively where green infrastructure is not feasible.

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