Transportation Consortium of South-Central States

Tran-SET

Solving Emerging Transportation Resiliency, Sustainability, and Economic Challenges through the Use of Innovative Materials and Construction Methods: From Research to Implementation

Permeable Curbs for Storm Water Pollution

Project No. 21PUTSA01

Lead University: The University of Texas at San Antonio

Final Report

October 2022

Disclaimer

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16. Abstract

One of the problems that increased urbanization poses is storm water pollution. Several control measures exist that are used to treat and reduce pollution in our waterways, one of those being permeable concretes; but these have not been widely adopted. The goal of this project was to develop a permeable curb apparatus that could be used in retrofitting conventional streets. The permeable curb is comprised of a permeable concrete mix with a perforated pipe running through its center, this allows for water to filter through the porous concrete and continue downstream through the perforated pipe which would eventually lead to our water ways. Project goals include determining permeable curbs pollutant removal efficiencies, and best cleaning options needed to be optimally utilized in urban environments. A test apparatus simulating a typical street profile is used in the laboratory environment to determine the percentage of solids that can be removed from the water treated for typical design rain events, the potential for clogging and fouling of the curb, and the ability to recover lost performance through cleaning the permeable curb. Results to date show that 95% solids removal is possible for up to 15 years of simulated solids loading to the curb. The diameter size range of the 5% of solids that do pass through the curb were measured to be in the range of 2 - 55 µm. Particle sizes larger than this tend to be caught within the curb and contributed eventually to curb clogging resulting in reduced hydraulic flow capacity. Cleaning cycles of the curb at a moderate backwash rate of 0.1 m^3 m^{-2} min^{-1} did not recover solids trapped within the curb with only 7 % of the prior trapped solids removed from the curb in the cleaning process.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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ACRONYMS, ABBREVIATIONS, AND SYMBOLS

LID-SCMs - Low Impact Development – Storm Water Control Measures

TSS – Total Suspended Solids

BMP – Best Management Practices

EXECUTIVE SUMMARY

Increased urbanization poses a series of problems for communities, one of them being storm water pollution. Pollutants of concern include suspended solids, nutrients, metals, and others such as thermal pollution that leads to reduced dissolved oxygen levels in sensitive receiving waters. To mitigate the impact of these pollutants, there exists Low Impact Development – Storm Water Control Measures (LID-SCMs) which include bioretention ponds (also known as rain gardens), sand filters, permeable pavements, green roofs, rainwater harvesting systems, bioswales, infiltration trenches, retention basins, extended detention basins, grassy swales, vegetative filter strips, and constructed wetlands (Dorman, Frey et al. 2013).

While LID-SCMs have been successful to some extent in the past, none have reached a widespread adoption in practice. A reason for the inadequate implementation of LID-SCMs is the large footprint that they require in order to meet treatment criteria for the areas that they are implemented in. Most LID-SCMs require, on average, 18.6 square meters of area to treat one acre of drainage area. Therefore, there is an urgent need for either (1) reducing the footprint needed for LID-SCMs or (2) reconfiguration of LID-SCMs such that they can be incorporated into existing urban infrastructure as retrofits and facilitate their implementation at levels necessary for mitigating pollution. This study proposes to achieve both goals by modifying the use of permeable materials.

One of the LID-SCMs that is readily available is permeable concrete, this study was used to develop a permeable curb apparatus using permeable concrete that could be used in retrofitting conventional streets. The permeable curb is comprised of a permeable concrete mix with a perforated pipe running through its center. This allows for water to filter through the porous concrete and continue downstream through the perforated pipe which would eventually lead to receiving water ways. The project goals include determining permeable curb pollutant removal efficiencies, and best cleaning options needed to be optimally utilized in urban environments.

A test apparatus simulating a typical street profile is used in the laboratory environment to determine the percentage of solids that can be removed from the water treated for typical design rain events, the potential for clogging and fouling of the curb, and the ability to recover lost performance through cleaning the permeable curb. Results to date show that 95% solids removal is possible for up to 14 years of simulated solids loading to the curb. The diameter size range of the 5% of solids that do pass through the curb were measured to be in the range of 2 - 55 μm. Particle sizes larger than this tend to be caught within the curb and contributed eventually to curb clogging resulting in reduced hydraulic flow capacity. Cleaning cycles of the curb at a moderate backwash rate of 0.1 m^3 m^{-2} min^{-1} did not recover solids trapped within the curb with only 5% of the prior trapped solids removed from the curb in the cleaning process.

1. INTRODUCTION

There is a variety of Low Impact Development-Stormwater Control Measures (LID-SCMs) that have been studied and implemented for reducing pollutants in our waterways; however, none of these measures have been widely adopted at levels necessary to fully mitigate storm water pollution, especially in high density urban environments.

Permeable materials, such as permeable concrete, can be used as pavements in parking lots or sidewalks to improve water quality and reduce peak flow discharges. However, parking lots and sidewalk only represent a small fraction of the total paved surface in cities. Using permeable pavement directly for streets and highways is not practical for many reasons associated with costs and performance requirements of these materials; but these constraints do not prohibit the use of permeable materials for curbs and gutters. Adequate runoff collection can occur in curb and gutter linear portions of streets and these linear portions of streets represent accessible areas available for use as LID-SCMs.

2. OBJECTIVES

The research objective of this project is to develop a proof of concept for installing linear LID-SCM permeable materials along curb and gutters to treat non-point source pollution for regular streets. The configuration will entail hollow core permeable curbs that collect filtered water to be conveyed as storm drainage. Pollutants are then to be removed prior to entering receiving waters. Required permeability, porosity and associated material pollutant removal efficiencies and cleaning options need to be characterized for this storm water collection configuration to identify best form and function when utilized in urban environments.

The experimental test apparatus was built be to simulate a typical street profile and water depths expected to occur during typical storm events. This apparatus was used to determine: (1) The fraction of water that can be treated by the permeable curb, for a typical design rain event. (2) The amount of solids that may be removed from the water treated. (3) The potential for clogging and fouling of the permeable curb. (4) The ability to recover lost performance through backwash cleaning of the porous curb, and (5) training of students, outreach to the public, and dissemination of research findings to the broader scientific community.

3. LITERATURE REVIEW

A main function of permeable pavement filters is to capture solids and retain these solids from entering waterways. Key to designing an efficient capture mechanism is knowledge of particle size distributions making it to LID-SCMs. Mitchell et al. (2019) notes that sizes can vary greatly depending on catchment characteristics and road dynamics and provided a review of published research that shows that there is variability in particle size distributions of sediments on roads. They report that build-up of sediment on a suburban road, had a median particle size values ranging from 44 to 91 μm. However, for this road after periods of snowmelt, the mean particle size increased dramatically and ranged from 1,000 to 4,000 μm. They also report that the physical characteristics of solids transported in a lateral road runoff, had a median particle size ranging from 370 to 785 μm, with a mean of 555 μm. In terms of size ranges, in lieu of mean size, the particles themselves were noted to be as small as 1.0 μm to greater than 10,000 μm. This again is noted to highlight the fact that sediments an vary greatly. For sizes of solids that build-up of sediment on urban road surfaces, Mitchel et al. (2019) discuss studies that show individual particle diameters ranged from 53 to 4,000 μm and a median size ranging from 100 to 600 μm. In other cited studies, Mitchel et al (2019) find that only about 10% of the solids are <50 μm in some studies while in other studies they report that the percentage of particles <200 μm ranges from 10% to 30%. Yet other studies cited by Mitchel et al (2019) report that between 30% and 60% of the particle mass can be found in particles <50 μm or that more than 70% of road deposited solids particles are finer than 150 μm. In general, Mitchel et al (2019) concluded that these studies highlight that roads can have many different soil loading values that may depend on wind, rain, vehicle speeds, flows, contributing impervious areas, and what type of road maintenance happens in the area. Also noted by Mitchel et al (2019), differences in methods of collection and analysis are will result in a wide range of concentrations and distributions being reported.

Size analyses for particles common to road surfaces include simple sieving methods, and also more sophisticated particle counting measurements such as laser diffraction, optical sensors, settling rates, or electrical resistance methods. Given the variety of methods, differences in reported results may be attributed to the lack of analytical equipment capable of covering the wide range of particle sizes found in urban stormwater (Selbig and Bannerman, 2011). For particles of 32 – 500 μm in diameter, sieve analyses along with gravimetric methods can be used for size and mass measurements (Selbig and Bannerman, 2011). For smaller particles, less than 32 μm, coulter counting methods can be used (Selbig and Bannerman, 2011). Coulter counting methods rely upon the principle of conductivity to estimate a spherical particle size. As a particle travels through an aperture, solution conductivity decreases due to the added resistance provided between an anode and cathode from the particle in the flow path.

Results reported for particle size can also be skewed based on collection methods (Selbig and Bannerman, 2011) where samplers that collect from the bottom portion of the flow traveling within a conduit may be skewed towards larger particle sizes due to the accumulation of larger particles near the bottom of the conduit. To overcome this limitation and bias towards larger particles, depth integrated sampling can be utilized where the entire water column is sampled. These sampling techniques generally show smaller particle size distributions when compared with bottom collection methods (Selbig and Bannerman, 2011).

Given the large variability in particle sizes needing treatment, a relatively high porosity curb design is chosen for study such that large particles will be able to penetrate curb and be removed from the road surface. As such, solids removal efficiencies will be considered as conservative estimates as small particles may have a higher potential to transport through the large pore opening without treatment. The use of a highly porous curb also provides benefits to address one of the disadvantages of permeable pavement systems; the risk of clogging, which is a cause of various problems regarding serviceability.

Because pervious concrete has an open structure that acts as a filter and retains contaminants, such as sediments, chemicals, and organics, during precipitation events. This retention can reduce up to 75% of total urban contaminant loads (Othman and Hardiman, 2005), making it a valuable stormwater management tool under Environmental Protection Agency regulations. However, the retention of contaminants may lead to clogging of the permeable concrete system, reducing its effective service life and impeding its widespread use. Clogging has been identified as a primary cause of failure in permeable pavements. Schaefer and Kevern (2011) tested a permeable concrete with 20 years' worth of what they considered a small yearly load of sediment. Less than 3% of sediments were able to pass through their pervious concrete and the material passing was in the range of the number 200 sieve size when loading with sand. The sandy materials are what they noticed was clogging and sticking to the face of the curb for the most part. Silty clay particles are what are able to pass more easily and clog voids within the curb itself.

The operational performance of permeable paving materials can be described in terms of water flow rate through the face of the material divided by surface area, as an infiltration rate or permeability value. Common units are millimeters per minute or inches per hour. Schaefer and Kevern (2011) report between 250 – 1607 inches per hour for permeable pavements in the range of 15 – 25% porosity. These filter rates decreased by up to 96% when clogged with silty clay sands. Zhao et al (2020) report filter rates of 279 – 303 mm /min (660 – 715 inches per hour) for permeable pavements with 18% porosity. After 2 years of use and operation, these values reduced between 60 – 98% due to clogging.

Schaefer and Kevern, (2011) summarize the important factors controlling clogging with pore size being key and the relative size of the pore to particle, with similar pore and particle sizes resulting in the highest clogging potential. They also note that a narrower particle size distribution with mixed coarse aggregates has a high clogging resistance and high residual permeabilities as compared to blended mixed aggregates hat have more clogging potential and recommended to avoid clogging that construction runoff and vehicles should be prevented from running on permeable pavements, and ideally, the pavement should be constructed after the adjacent areas are well finished and have established ground cover

To minimize clogging effects, Schaefer and Kevern (2011) suggest a minimum design porosity of 20% and note that for a 15% as a design porosity, there is a possibility of poor hydraulic performance. The also caution that for a 25% as a design porosity, the hydraulic performance may be overdesigned and other considerations such as strength may be an overriding factor of concern at higher porosities. In terms of particle sizes, Schaefer and Kevern, (2011) found that silty clay materials have negligible effects on clogging permeability, while the sand and blended materials cause significant decreases in permeability. However, the residual permeabilities measured were still above 30 in./hr (for blended materials with no cleaning), values that should provide sufficient water flow under even the heaviest rainstorms.

Cleaning methods have been investigated as a way to alleviate clogging detrimental effects on permeability. In general, cleaning frequencies between 1 – 4 time per year are used in practice with no standard frequency or procedure recommended overall (Zhao et al, 2020). Traditional cleaning methods include sweeping, pressure washing in which a narrow cone of water is sprayed on the sample surface with a pressure of approximately 1000 psi, and vacuum sweeping where a reduced pressure is created at ~ 4 psi at the porous surface. Vacuum sweeping recovery rates are generally low, and negative effects in terms of resulting permeabilities has been reported in some cases (Zhao et al, 2020). Zhao et al (2020) reported that the infiltration rates obtained after pressure washing or vacuuming on permeable pavements clogged with sand and silty sand recovered to only 15% of the initial permeability. Schaefer and Kevern (2011) investigated pressure washing and vacuum leaning methods. They found that both pressure washing and vacuum cleaning produced similar residual permeabilities, while the combination of the two provided a slight improvement over the individual methods. The rehabilitation methods were always more effective on the higher-porosity specimens. The rehabilitation methods had negligible effect on the permeabilities of specimens with 15% porosity. Permeabilities after cleaning for the sand and blended materials were well above 100 in./hr except for the 15% porosity samples (Schaefer and Kevern, 2011).

Because of the novel curb design of this study where filtered water is collected within the central pipe housed in the curb itself, the design does lend itself easily to more novel backwashing methods of cleaning to mitigate clogging. In backwashing, a reverse flow bath can be created where water flows through the porous structure in the opposite direction to the normal filter operations. In this process, any solids accumulated on the face of the curb, or within the curb porous structure, can be flushed from the porous structure and carried away for external collection with the backwash water. Few studies exist that employ novel cleaning methods outside of the conventional sweeping, pressure washing and vacuuming or combinations thereof. Zhao et al (2020) did explore a backwashing method for permeable concrete pavements. To facilitate backwashing on a planar surface, a double ring method was used where the outer ring served the water supply. The inner ring was fitted with a vacuum such that water permeated from the outer ring, downward through the permeable pavement and also radially inward toward the inner ring. The water was collected from the surface of the inner ring, along with any sediments that were washed with the traveling water flow moving through the porous pavement material. For clogged pavements with permeabilities reduced in the range of 60 – 98 % after 2 years of undergoing only road sweeping maintenance, this backwashing method performed better than conventional methods. The backwashing process provided an 18-fold increase in permeability after cleaning. This was greater than conventional methods that had between 3.5 to 14-fold increases in permeability. Due to constraints of the experimental setup, backwashing parameters were not varied to elucidate the most important parameters controlling the cleaning performance.

4. METHODOLOGY

In this section the methodology for porous curb construction is described as well as the testing configuration used to assess the solids trapping potential of the curb.

The materials used started with a permeable concrete cast curb with a cross sectional dimension of 15.24-by-15.24 cm and 0.91 meters in length. The permeable curb dimensions had a volume of 28316.8 cm^3 which equaled roughly 2402.77 kg m^{-3} based on concrete densities. Using these values, it was determined that a typical permeable concrete curb would use 22.45 kg of 12.7 mm aggregate, 38.78 kg of 9.52 mm aggregate, 4.08 kg of 4.75 mm aggregate, and 2.24 kg of 2.36 mm aggregate. For a typical water to cement ratio of 0.4, 10.07 kg of cement and roughly 4.08 kg of water was estimated. The mixers were started off by adding a small amount of each material to ensure that the product was not runny or dry with more of an oatmeal consistency. The mixing apparatus used is shown in Figure 1.

Figure 1. Concrete Mixer for Pouring of Permeable Curb.

The mix provided a porosity of 24.8% which is in line with typical pervious concrete pavement porosity. The porosity was measured by sinking three different concrete samples that were obtained from the extra concrete when the curb was poured into a large beaker. The change in water volume within the beaker was measured and divided by the volume of the curb sample cylinders. These samples were also used to measure the compressive strength of the curb due to an expected reduction in strength because of porosity. The average compression strength was 3749.37 kpa which was obtained by dividing the maximum axial force by the cross-sectional area of the sample. To gather these values, the MTS Series 793 instrument was used by placing the sample in a dish to catch the crushed sample and then beginning the load application. Figure 2 shows the loaded sample, and Figure 3 shows the crushed sample after test completion. The load was applied in a displacement-controlled mode at a rate of 0.5 cm min^{-1} with monitored loads shown in Figures 4 and 5 for the two samples. The load was stopped when the sample was crushed, and the load decreased to less than half the maximum value. Resulting compressive strength from this testing for the two samples is given in Table 1.

Figure 2. 10.16 cm Diameter x 15.24 cm Tall Curb Sample.

Figure 3. 10.16 cm Diameter x 15.24 cm Tall Curb Sample Crushed.

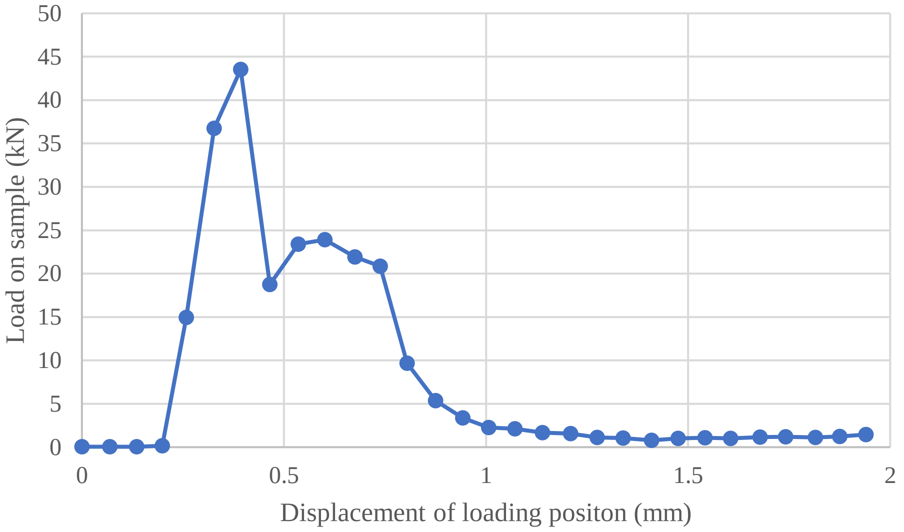

Figure 4. Results of Sample 1.

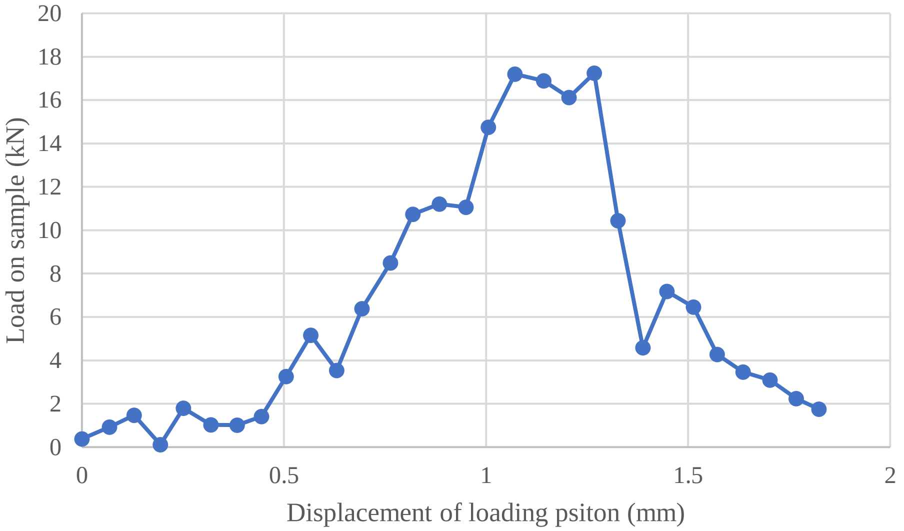

Figure 5. Results of Sample 2.

Table 1. Results of Compressive Strength.

Sample No.	Diameter (mm)	Maximus axial force (kN)	Compressive strength (MPa)
1	101.6	43.55	5.37
2	101.6	17.21	2.12
Average value			3.75

The curb sat inside a steel crate with only the top 7.62 cm of one of the long side curb faces exposed, as well as one of the curb short side faces at the outflow. This crate had a sheet that extended two feet out from the curb face and was angled at a two percent slope transversely and longitudinally to the curb. Inside the curb, a perforated pipe of 2.54 cm diameter with 5 rows of perforations was placed and each row had 24-0.95 cm holes evenly spaced-out laying at the bottom center and extended past the curb and crate which elbowed down into a flowmeter. The flowmeter at the outlet was a Cole-Parmer SPX-038 that allows for flows ranging from 1.89 to 151.41 L min^{-1}. This system then outflowed into a 18.93-liter bucket similar to every other bucket used throughout the whole testing procedure; this was put together using iron and PVC fixtures. The permeable curb and metal crate housing the curb are shown in Figure 6.

Also shown in Figure 6 is the inflow distribution method. The inflow was spread out along the 1.22-meter side of the curb face by a 1.22-meter perforated pipe of 2.56 cm diameter and 40 perforations each with a diameter of 0.32 cm diameter facing the curb which had an attached hose leading to a pump with another flowmeter in between to read the inflow. This flowmeter was a Cole-Parmer SPX-100 that allowed to capture flow data within 1.89 and 151.41 L min^{-1} range. The pump would draw water from a bucket that was continuously being filled by a conventional faucet.

Figure 6. Permeable Curb in Metal Crate.

Sediment tests started with measuring out 150 g of sediment with a particle size distribution as shown in Figure 7. The sediment mix was prepared using appropriate mass additions from sieved soils. The solids distribution was chosen to simulate typical solids in runoff from feeder streets as reported in a study that characterized the size distribution of particles in urban stormwater by use of fixed-point sample collection methods (Selbig and Bannerman, 2011). This size distribution is similar to values included in the international stormwater Best Management Practice (BMP) database. Based on the concentrations reported by Selbig and Bannerman (2011), the 150 g utilized in the tests represented an equivalent amount of one year worth of solids fed to the curb.

Testing methodology started with addition of the sediments at the face of the curb that were manually spread evenly along the face of the curb to facilitate equal straining of sediment into the curb face. The maximum flow through the curb without overtopping when the curb was new and unfouled was 25.24 mL s^{-1} and this set as constant feed flowrate for all tests filtering solids. As testing progressed with clogging, this value generally decreased as measured through the curb outlet. Each of the “yearly” solids loadings produced 4 18.93-liter buckets worth of effluent water treated by the curb. Each bucket captured approximately 10 minutes of effluent. In general, the majority of sediment that passed into or through the curb was captured within the 10 minutes of run time. Once the curb was clogged, the sediment no longer entered the curb and remained at the curb face even after four buckets of effluent was captured.

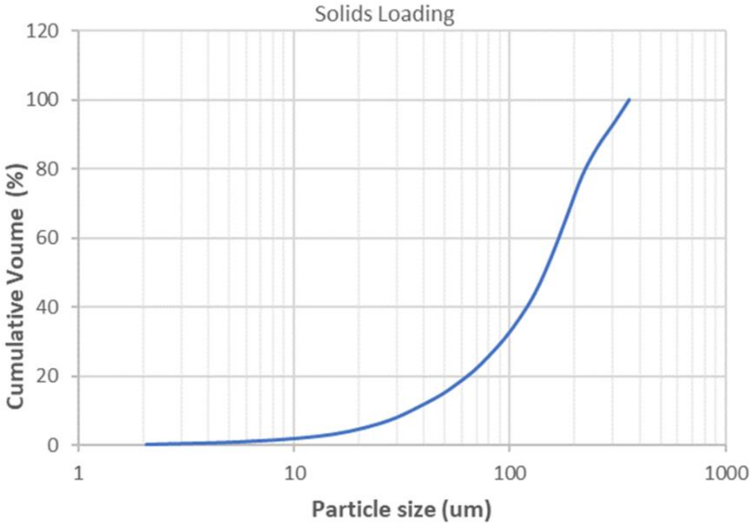

Figure 7. Solids Size Distribution for Table Loading.

The buckets were separated by the time when they were filled for each test. 100 mL samples taken from each bucket were analyzed for total suspended solids (TSS) according to the methodology as described in USEPA 160.2 (1979). In addition, 300 mL samples taken from each bucket were analyzed for captured solids particle size distribution utilizing portable light scattering laser diffraction methods (LISST, Sequoia Scientific Inc, Bellevue, WA). Samples for laser diffraction analyses are shown in Figure 8 with visual differences in turbidity apparent between the first bucket containing the majority of solids and subsequent buckets. The portable instrument used for these tests is shown in Figure 9.

Figure 8. From Left to Right, 300 mL Samples from Buckets 1, 2, 3 and 4.

Figure 9. LISST-Portable.

Upon completion of each solids removal test, a separate hydraulic test of the curb was completed with the influent set at 34.70 mL s^{-1} to provide a constant saturated condition with a constant hydraulic head for measuring effluent flow rate. The hydraulic tests lasted for 20-25 minutes for filling 2 - 18.93-liter buckets.

Tests for yearly solids loading to the curb and subsequent impact on flow through the curb from the hydraulic test were repeated until the curb was no longer accepting solids. The curb no longer being able to process solids corresponded with significant clogging and reduction of flow through the curb. Upon this flow reduction, backwashing testing commenced to measure the mass of solids that could be removed from the curb by forcing the water to flow in a reverse direction through curb. Backwashing was performed by connecting the inflow hose to the curb effluent pipe. A pressure transducer (Cole-Parmer, 07356-68001) connected to flow meter and effluent pipe of the curb allowed for monitoring water pressures needed to backwash the curb. The backwashing rate used was limited by the pressure and flow capabilities of the tap water faucet and was set at 176.65 mL s^{-1}. The exposed filtration face of the curb was 1161.29 cm^2 and the backwash rate in terms of backwash flow per area of filtration was 0.1 m^3 m^{-2} min^{-1}.

5. ANALYSIS AND FINDINGS

Figure 10 shows the results for 17 years of solids loadings. A downward trend in flow out, both for sediment runs and the hydraulic tests, coincides with clogged media and after 15 years worth of solids, the curb no longer was able to pass the water and solids into the curb.

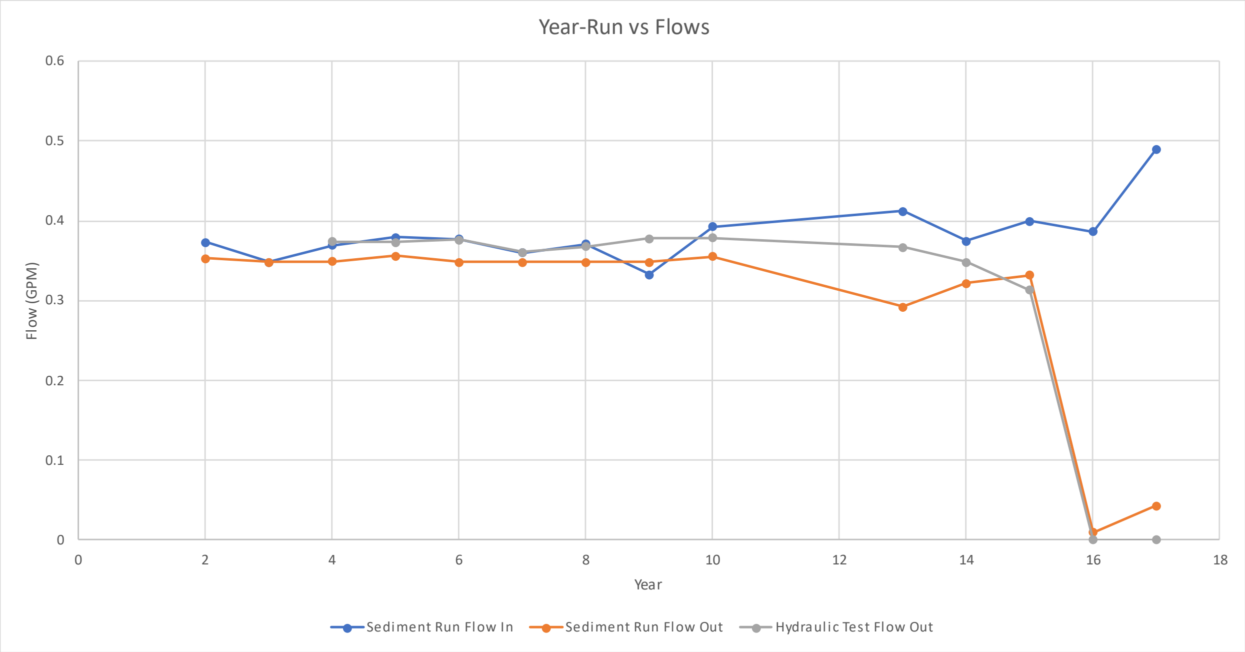

Figure 10. Sediment and Hydraulic Test Flow Comparison for Each Run.

Results for solids captured in the curb effluent for all years of data are shown in Table 2. Most solids that passed through the curb occurred within the first bucket equating to 18.93 L of water passed through the 1.22 m curb section. Solids removal exceeded the typical 80% required for storm water treatment systems and ranged between 95.6 – 99.6% over the simulated 15 years where solids were collected in the effluent.

Tables 2. TSS Results for Year-Run Buckets.

Yr 1 Bucket #	**TSS mg/L**	**Mass (g)**	
1	186.06	3.52	
2	147.66	2.79	
3	7.37	0.14	
4	2.36	0.04	
5	1.03	0.02	
6	2.57	0.05	
7	1.43	0.03	
8	1.97	0.04	**% Removal**
	Total	6.63	95.58

Yr 2 Bucket #	**TSS mg/L**	**Mass (g)**	
1	161.33	3.05	
2	0.33	0.01	
3	0	0.00	
4	0	0.00	**% Removal**
	Total	3.06	97.96

Yr 3 Bucket #	TSS mg/L	Mass (g)	
1	102.11	1.93	
2	0	0.00	
3	0	0.00	
4	0	0.00	% Removal
	Total	1.93	98.71

Yr 4 Bucket #	TSS mg/L	Mass (g)	
1	123.44	2.34	
2	0	0.00	
3	10.11	0.19	
4	0	0.00	% Removal
	Total	2.53	98.32

Yr 5 Bucket #	TSS mg/L	Mass (g)	
1	132.67	2.51	
2	0	0.00	
3	0	0.00	
4	0	0.00	% Removal
	Total	2.51	98.33

Yr 6 Bucket #	TSS mg/L	Mass (g)	
1	35.33	0.67	
2	0	0.00	
3	0	0.00	
4	0	0.00	% Removal
	Total	0.67	99.55

Yr 7 Bucket #	TSS mg/L	Mass (g)	
1	97.33	1.84	
2	0	0.00	
3	0	0.00	
4	0	0.00	% Removal
	Total	1.84	98.77

Yr 8 Bucket #	TSS mg/L	Mass (g)	
1	98.66	1.87	
2	0	0.00	
3	0	0.00	
4	0	0.00	% Removal
	Total	1.87	98.76

Yr 9 Bucket #	TSS mg/L	Mass (g)	
1	142.33	2.69	
2	0	0.00	
3	0	0.00	
4	0	0.00	% Removal
	Total	2.69	98.20

Yr 10 Bucket #	TSS mg/l	Mass (g)	
1	147	2.78	
2	8	0.15	
3	0	0.00	
4	0	0.00	% Removal
	Total	2.93	98.04

Yr 11 Bucket #	TSS mg/l	Mass (g)	

Yr 12 Bucket #	TSS mg/l	Mass (g)	

1	689	13.04	
2	94	1.78	
3	45	0.85	
4	12.66	0.24	**% Removal**
	Total	15.91	96.46

1	246	4.66	
2	28	0.53	
3	6.33	0.12	
4	0	0.00	**% Removal**
	Total	5.31	96.46

Yr 13 Bucket #	**TSS mg/l**	**Mass (g)**	
1	178	3.37	
2	100	1.89	
3	20	0.38	
4	15	0.28	**% Removal**
	Total	5.92	96.05

Yr 14 Bucket #	**TSS mg/l**	**Mass (g)**	
1	37	0.70	
2	0	0.00	
3	0	0.00	
4	0	0.00	**% Removal**
	Total	0.70	99.53

Yr 15 Bucket #	**TSS mg/l**	**Mass (g)**	
1	36	0.68	
2	0	0.00	
3	0	0.00	
4	0	0.00	**% Removal**
	Total	0.68	99.55

Shown in Figure 11 are the size of the solids that passed through the curb. The majority of runs only allowed particle sizes of 2 - 55 μm to pass through the curb. Although, tests for year 1 and year 2 allowed particles as large as 300 microns to pass through the curb. As the curb clogged, larger particles did not pass through the curb. Once significant clogging was reached and no more sediment was visibly passing through the curb, the curb was backwashed and TSS analyses were conducted for captured backwash. Only 126.64 g of the 1700 g of sediment that was captured by the curb could be recovered through backwashing the curb. The low backwash cleaning efficiency of ~ 7% may be attributed to the backwash rate used. The backwashing rate used was limited by the pressure and flow capabilities of the tap water faucet and was set at 176.65 mL/s. The exposed filtration face of the curb was 1161.29 cm^2 and the backwash rate in terms of backwash flow per area of filtration was 0.1 m^3 m^{-2} min^{-1}. This is roughly 10 times lower than backwash rates used for conventional sand filters in drinking water treatment systems (Davis, 2019). High backwash rates may prove more effective in cleaning operations and should be investigated in future studies.

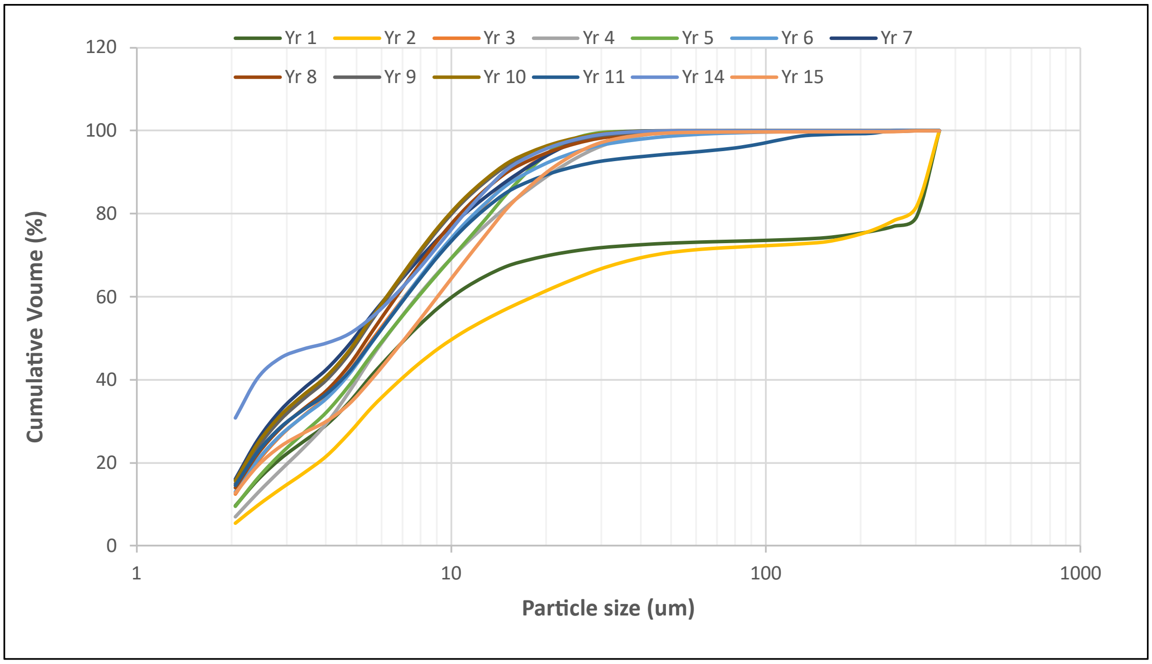

Figure 11. Curb Outflow Solids Size Distribution.

6. CONCLUSIONS

The work done on the project started with fabrication of the metal crate along with the permeable curb itself. Moving forward the apparatus placed together was loaded with sediment that was formulated to resemble what one would usually see on a roadway. Clogging sessions continued until the curb was clogged and outflow was not present. The final phase consisted of attempting to clean the curb. The permeable curb filtered more than 95% of representative solids for up to 15 years of solids loadings before the curb clogged. This solid removal efficiency is adequate for use in LID-SCMs. Solids that did pass through the curb were small and in the range of 2 to 55 µm in diameter. Backwashing the curb only cleaned ~ 7% of the solids captured by the curb. Higher backwashing rates may be required to fully clean the curb than those currently investigated.

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