

## 路缘沉积： 利用原型思维过程探究如何通过路缘 及路肩设计截留暴雨中的路面污染物

# CURBING SEDIMENT: A PROTOTYPING PROCESS TO EXPLORE HOW TO CAPTURE ROAD POLLUTANTS IN STORMWATER EVENTS VIA CURB AND APRON REDESIGN

## 1 引言

纵横交错的道路形成了不断扩张的沥青路网。根据美国联邦公路管理局公布的数据，全美国的沥青公路总长度约为670万公里<sup>[1]</sup>，它们主要由各城市和各州政府进行维护，对于促进人员流动和货物流通至关重要<sup>[1]</sup>，也是经济生活的必要基础。然而，路面上也存积着各种污染物，包括沉积物、草坪肥料中的营养物质、细菌、病毒、杀虫

### 哈丽娜·斯坦纳

俄亥俄州立大学诺尔顿建筑学院景观系助理教授

### 瑞恩·温斯顿

俄亥俄州立大学食品、农业与生物工程系及土木工程、环境与测量工程系助理教授

### 艾薇·欧贝尔

俄亥俄州立大学诺尔顿建筑学院景观系本科生

### 亚力克·格林姆

俄亥俄州立大学环境与自然资源学院本科生

### Halina STEINER\*

Assistant Professor at Landscape Architecture Section, Knowlton School of Architecture, Ohio State University

### Ryan WINSTON

Assistant Professor at Department of Food, Agricultural, and Biological Engineering, and Civil, Environmental, and Geodetic Engineering, Ohio State University

### Avee OABEL

Undergraduate Student at Landscape Architecture Section, Knowlton School of Architecture, Ohio State University

### Alec GRIMM

Undergraduate Student at School of Environment and Natural Resources, Ohio State University

\*Corresponding Author

Address: 1279 City Park Ave., Columbus, OH 43206, USA

Email: steiner.298@osu.edu

## 摘要

路缘的设计简单明了：路缘本身为雨水提供了输送途径，促使水和污染物由街道汇入河道。路面上存积着各种沉积物，包括草坪肥料中的营养物质、细菌、病毒、杀虫剂、金属元素，以及各种油和油脂。当暴雨发生时，这些物质会在未经处理的情况下被冲入雨水管道，而后排入河道，进而影响水质乃至整个生态系统。那么，如何通过提升路缘设计标准来产生更大的系统性影响？

如果重新设计路缘，使其可以像磁石一样吸附雨水中的污染物，则将打破路缘固有的设计标准。2019年夏，一支跨学科研究团队在俄亥俄州立大学对标准混凝土路缘及路肩的替代方案进行了测试。该团队使用迭代设计过程在路缘和路肩表面增加了不同的图案和凹槽，并使用全尺寸模型测试了模拟暴雨事件，收集了相关数据以评估21种替代设计方案的表现。结果表明，新的路缘及路肩组合设计方案可以有效地在道路上拦截污染物，避免其进一步危害水体及水生生态系统。

## 关键词

基础设施；水文学；雨洪；路缘；沉积物；城市设计

## ABSTRACT

The design of a curb is straight forward. The curb itself provides a conveyance of stormwater, facilitating the movement of water and pollutants from the street into waterways. Pollutants such as sediment, nutrients from lawn fertilizers, bacteria, viruses, pesticides, metals, and petroleum by-products accumulate on the road surface and are released during storm events, carried to storm drains, and deposited into waterways, often without treatment. Once pollutants enter the waterways they impact the ecosystem and affect water quality. How can discrete standards—like a curb—be leveraged to have larger systemic impacts?

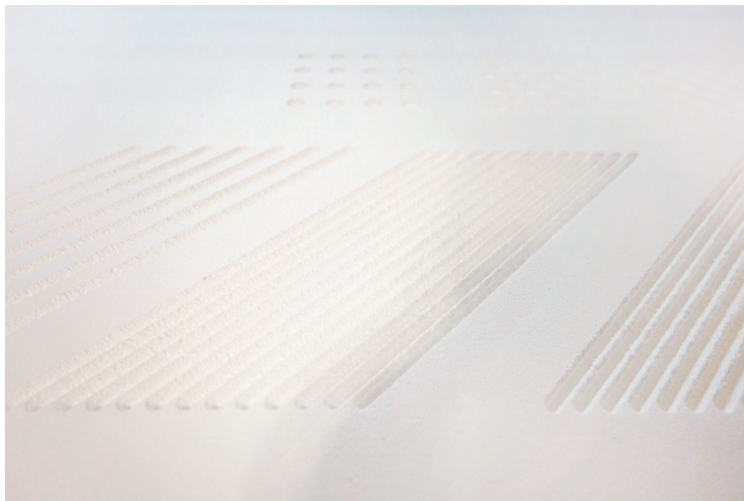
The redesign of the curb to perform as a magnet for pollutants can challenge this design standard. During the summer of 2019, the interdisciplinary research team tested alternatives to the standard concrete curb and apron at Ohio State University. The team used an iterative design process to add patterning and crenellations to the face of the curb and apron. Using full scale models to test simulated storm events, the team collected data to evaluate the performance of 21 alternative designs. The results suggest the new combined curb and apron designs can abstract pollutants from roadways before they are detrimental to water bodies and aquatic ecosystems.

## KEYWORDS

Infrastructure; Hydrology; Stormwater; Curb; Sediment; Urban Design

编辑 田晓劼 翻译 田晓劼 王胤瑜 李慧彦

EDITED BY TIAN Xiaojie TRANSLATED BY TIAN Xiaojie WANG Yinyu LI Huiyan



1 © Halima Steiner, Ryan Winston

剂、金属元素、塑料微粒、融雪剂，以及各种油和油脂<sup>[2]</sup>。当暴雨发生时，这些物质会在未经处理的情况下，经混凝土路缘 / 排水沟 / 路肩被冲入雨水管道，而后排入河道<sup>[2]</sup>，进而影响水质乃至整个生态系统。但是，水体中的塑料微粒等污染物清除起来非常困难，那么，是否可以通过街道设计的创新来解决这一问题？用于排水的路缘和排水沟能否发挥其他作用？

当代的街道、人行道及路缘 / 排水沟 / 路肩系统的设计已沿用了数个世纪，就连路缘坡道这样简单的创新性设计也直到1945年才在密歇根州卡拉马祖市首次引入（以帮助坐轮椅的退伍军人便利出行）<sup>[3]</sup>，

这一设计后来也为骑行、推婴儿车和携带行李箱的行人提供了便利。然而，这一设计并未迅速普及，直到1992年路缘坡道才被写入《美国残疾人法案》，成为人行道建造的法定规范之一<sup>[4]</sup>。近些年来，与绿色基础设施有关的道路设计创新不断涌现。早在20世纪90年代初，马里兰州乔治王子郡就采用了路缘切口引导水流进入生态草沟<sup>[5]</sup>。近年来这一技术被广泛应用于那些未能达到《清洁水法》规定的水质标准的美国城市，并引发了设计的迭代与提升——从试点或原型性探索项目逐步转向制定新的设计标准。生态草沟可以在降雨高峰期有效降低雨水流量，同时过滤污染物，但沉积物和垃圾可能使生态草沟堵塞而丧失过滤能力。由美国环境保护署签发的《接收公路与停车场径流的绿色基础设施运行与维护技术备忘录》指出，施工活动、受侵蚀的裸露土壤（植被稀少区域），以及冬季路面覆砂是城市径流中常见的沉积物来源，并进一步解释了沉积物如何在不透水地表堆积，并在流向生态草沟的过程中堵塞排水口及土壤空隙，阻碍植物根系呼吸<sup>[6]</sup>。那么，如何利用路缘这一常见的道路元素截留尚未进入河道的污染物，从而改善流域健康？

## 2 设计过程

### 2.1 原型开发前

原型开发过程需要考量诸多因素。设计团队首先与俄亥俄州立大学模拟创新与建模中心合作，探索了数字模拟模型的使用。数字模型可用于流体动力学计算，能够比物理模型更精确地模拟沉积物粒度和暴雨事件，它可对单个路缘横截面进行测试，而无法分析连续的路缘表面。由于尚不具备开发一套连续路缘表面数字模型所需的运算技

1. 通过小型样本测试探索不同的铣刀钻头尺寸、图案密度和铣削深度，是了解数控雕刻机优势和局限性的关键起始步骤。
2. 首轮测试中某一方形路缘设计的定格照片

1. Small scale sample tests explored different router bit sizes, pattern densities, and depths, which was a critical first step to understand the opportunities and constraints of the CNC Mill.
2. A still photograph of the first-round test for a square curb configuration



2 © Halima Steiner, Ryan Winston

术，团队未对数字模型展开进一步研究。

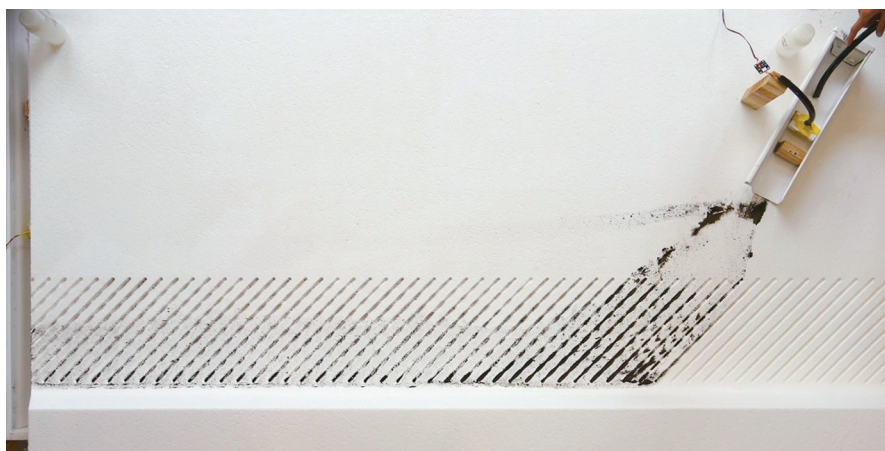
团队最终选择使用物理模型进行设计验证测试，并根据已有的原型设计技术及水文挟沙水流建模方法来确定物理模型的制作方法。其中，俄亥俄州立大学副教授杰克·博斯韦尔在关于浮动混凝土容器的研究中，在校内的MAT/FAB实验室运用数控雕刻技术制作聚苯乙烯泡沫模具，上油之后再用水密度小于水的浮式混凝土浇筑成可支撑植物生长的容器，以对抗伊利湖中的藻华<sup>[7]</sup>。毕业于俄亥俄州立大学的吴浩文（音译）也使用数控铣床和聚苯乙烯泡沫制作了赛欧托河模型，该模型采用乳胶漆进行防水，并将水墨混合物泵入水体，以研究河水的流动轨迹。弗吉尼亚大学副教授布雷恩·戴维斯和宾夕法尼亚大学助理教授肖恩·伯克霍尔德在“未来健康港口”项目中亦融入了建模技术。他们通过将计算机建模与在明尼苏达大学圣安东尼瀑布实验室进行的物理建模进行结合，研发了一种可用于探究五大湖中潜在沉积物流动的方法。<sup>[8]</sup>上述项目从多个角度为本研究提供了启发与借鉴。

## 2.2 制作过程

本次研究选用的聚苯乙烯泡沫型材尺寸为1.2m × 2.4m × 0.2m，适宜制作全比例模型，可清晰显示并准确模拟出沉积物的截留过程；轻盈的材质也使得型材与成品模型的存储、制造和运输较为便捷。此外，经过热丝切割及数控雕刻的泡沫表面纹理也与混凝土十分相似。

为了制作路缘模型，首先要将1.2m × 2.4m × 0.2m的聚苯乙烯泡沫型材块制成标准道路剖面。团队最初采用数控铣床铣削轮廓，大约耗费4小时才将一块型材泡沫铣削成一个不带路缘和路肩图案的街道截面。为了最大程度地缩短制作时间，团队最终使用了一台热丝长度为2.4m的热丝切割机来制作基本公路断面，包括高15.24cm的路缘和横向坡度为1.5%的1m宽路面；为适应某些路缘的特殊形态，路缘高度可降至11.4~12.7cm。由于制作15.24cm高的路缘时，铣削机刀头与路缘模型的顶部会产生碰撞，导致设备与模型损坏，故研究先用Rhino三维建模软件对路缘和路肩进行数字建模，然后在RhinoCAM插件中模拟铣削迭代过程以映射刀具轨迹，并预测可能出现的刀具碰撞或与原始Rhino模型的不符之处。数字模拟完成后将生成一个5轴G代码，将其输入昂思路5轴数控铣床中，即可在热丝切割机加工过的基础路缘剖面上雕刻路肩和路缘图案。由于图案和凹槽受限于数控刀具的尺寸，本次研究使用了一系列直径为6.3~25mm的平口和球面刀具。模型一端被铣削成45°角的锥形，以将水流导入测试台末端的路缘排水沟，用于检测水质。最后，清除模型上的泡沫边角料，并涂上一层环保乳胶漆底漆，以起到防水作用。

在设计路肩图案时，团队从路面现有元素的形态中获得了灵感。盲道铺装单元由高5.08 ± 0.51mm、直径3.5cm的平顶圆形凸起组成，提示有视力障碍的行人前方有十字路口。团队采用了相似的尺寸设计了最初的点状路肩图案，并在后续迭代中设计了相似尺寸的凹槽，以提高路面的步行友好性，确保行人和骑行者的安全。



3. 如图所示的点状图案以盲道铺装为灵感。
4. 不同斜线图案沿线条走向的凹陷深度不同。
5. 波浪式斜线图案的转弯处截留了更多沉积物。
6. 平行于路缘的直线图案在靠近路面的一端截留了更多沉积物。

3. Tactile pavement was the inspiration for the dot-pattern.
4. The base of the diagonal lines varied in depth along the run of each line.
5. The diagonal squiggle pattern noticeably collected more sediment where the lines turned to change direction.
6. Line pattern parallel to the curb collected more sediment closer to the road surface.

### 2.3 原型设计过程

设计过程具有迭代性，每个阶段的设计都是基于上一轮测试的数据和观察结果。1:1全尺寸模型充分呈现了设计方案的真实效果。在进行测试之前，团队先将模型放置在人行道和街道旁以实地观察实际比例，从而了解其在景观中的尺度和视觉效果。

首轮测试仅对单独改变路缘面或路肩表面设计进行考察。在铣削全尺寸模型之前，团队测试了不同的铣削密度和深度以了解雕刻机的作业极限（图1）。团队对每种路缘或路肩改造方案分别进行测试，以便了解其单独运作的情况，以及二者最佳的组合方案。测试将一种人工合成的雨水混合物倾倒在模型路面上，使之流经路肩或路缘上的图案凹槽，整个过程持续8分钟。测试完成后，用肉眼观察沉积物淤积情况，并测量排出水体的浊度降低量（水的清澈度表征之一）及总悬浮固体物（TSS）减少量，以评估设计效果。

这一轮测试选定了圆形、方形和三角形三种路缘面凹槽设计。图2所示的方形路缘凹槽可截留的沉积物明显多于其他设计，因此研究团队在此基础上进行进一步探索。在路肩设计的测试中，团队采用重复利用模型的方式测试了不同密度的点状、直线及水波形图案，即首先铣削出图案密度最低的模型，测试后再次铣削，以增加图案的密度（图3~6），并根据模型水流入口和出口的浊度传感器读数来评估不同设计的截污效果。结果证明，直线形设计的截污效率最高；通过改变直线的角度及路径形态（波浪斜线、梳齿状、网格状）等来增加截留沉积物的表面积，进而降低雨水流速。

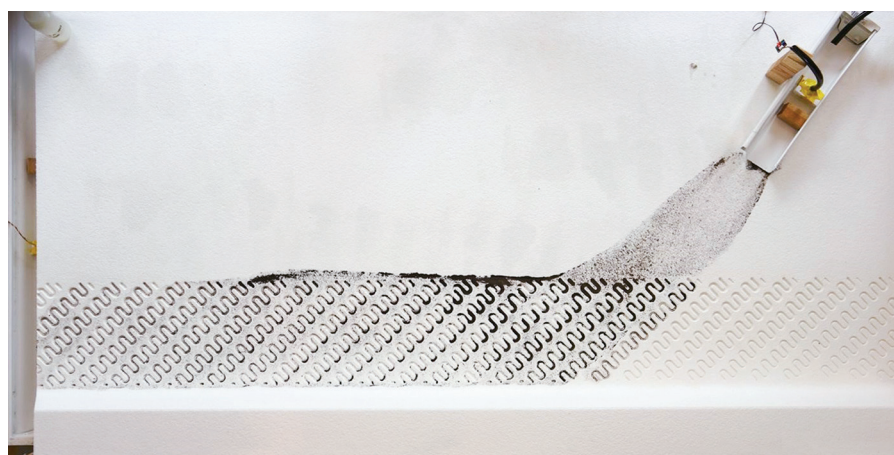
进一步测试的对象为单独截污效果最佳的路缘和路肩组合设计，主要考察路肩向路缘凹槽体转移沉积物的能力。在若干次迭代设计中，团队不断改变路缘凹槽的间距和尺寸、路肩凹槽的连接方式，以及路肩图案的排列方式和间距，并发现当路肩凹槽与路缘面凹槽相连

时组合设计的效果更好，且以此三种组合为最佳：网格状路肩和7.62cm宽的方形路缘凹槽，各组凹槽之间间隔7.62cm（图7）；线形路肩和5.08cm宽的方形路缘凹槽，凹槽每隔45cm有15.24cm的间隙（图8）；以及梳齿状路肩和等距分布的5cm宽的方形路缘凹槽（图9）。

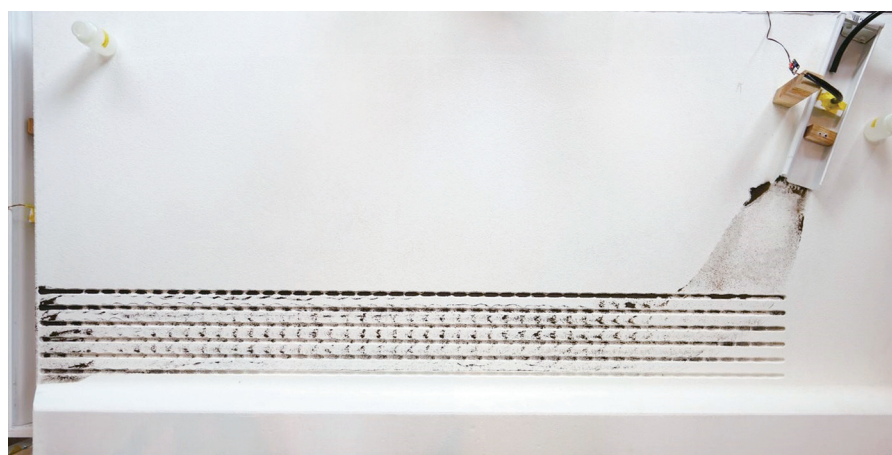
### 2.4 模拟暴雨测试

原型测试在俄亥俄州立大学的MAT/FAB实验室中进行。实体装备包括一端连接着乙烯塑料排水沟的1.2m×2.4m的试验台、1.2m×2.4m×0.2m的聚苯乙烯泡沫型材块、两个约117L的手提式塑料桶、一台工业搅拌机、一台秤、从当地获取的土壤、沙子、数个采样瓶、两个配有模拟浊度传感器的Arduino微控制器、一台iPad、一台GoPro Hero 6数码摄像机、三台笔记本电脑，以及一部索尼a7RII数码相机。将经过铣削并做过防水处理的泡沫块放置在试验台上，在其上方悬挂数码摄像机和数码相机。摄像机用于记录整个测试过程，相机每隔10秒拍摄一张照片。测试开始时，在塑料桶内倒入70~80kg的水，并将当地土壤和沙子以6:4或7:3的比例进行混合，以模拟雨水。为确保在模拟暴雨事件全过程中“雨水”的沉积物浓度一致，需用搅拌机使土壤和沙子混合物均匀地分散在水中，并由放置在桶底的潜水泵泵至模型表面，模型入水口处的浊度传感器将记录其水质变化情况。在每轮测试中，模拟雨水将在模型表面自由流动8分钟，随后流入装有第二个传感器的排水沟，经出水口排至第二个桶内，最后将出水口桶中的水及进水口桶中剩余的水进行称重。在每轮测试中，每隔2分钟在进水口和出水口用采样瓶随机采样一次。

本次研究对21种路缘和路肩设计进行了测试，并对每个设计进行了三次重复测试（图10）。对每次测试后残留在模型表面的泥沙进行测定可得出每个设计的有效泥沙截留量（图11）。之后对三个截留量



5 © Halina Steiner, Ryan Winsten



6 © Halina Steiner, Ryan Winsten



7 © Halina Steiner, Ryan Winston



8 © Halina Steiner, Ryan Winston



9 © Halina Steiner, Ryan Winston

7. 网格状路肩与方形路缘凹槽
8. 15.24cm间隔的斜线路肩与方形路缘凹槽
9. 梳齿状路肩与方形路缘凹槽

7. Cross hatch apron with square curb crenellations
8. Diagonal line apron at 6" gap with square curb crenellations
9. The prototype model of comb apron with square curb crenellations

最大的设计再进行1~7轮模拟暴雨测试，逐轮增加模拟雨水中的沉积物量，以确定设计的最大截留量及截留时间。

## 2.5 研究发现

团队在测试过程中采取了三种方式进行数据收集：一是通过相机和摄像机收集可视化数据；二是对采样瓶和出水口桶中水体的清澈度进行肉眼评估；三是在俄亥俄州立大学雨洪管理项目实验室中对随机样本进行TSS和粒度分布分析，并将结果与测试期间获得的传感器实时数据进行对比（表1）。

团队对每项设计的沉积物数据进行了收集和分析，发现同时改造路缘和路肩的组合设计比仅改造路缘或路肩的设计效果更好。据美国国家污染物排放削减体系规定，俄亥俄州雨水的排放标准要求TSS降低量不得低于80%，本研究提出的8种组合设计中有7种达到或超过了这一要求（图12）。

## 3 结论

通过对21种设计原型进行测试，“路缘沉积”研究表明，对路缘和路肩的设计标准进行重新设定是提升路面污染物截留水平的可行选择。这些新型设计可与绿色基础设施相结合，以减少污染物造成的堵塞，也可以单独应用于路面。本研究提出的设计方案占地面积小，适用于种植大树和人行道狭窄的路面，其图案也可根据商业改造区或城市特定的美学、水文或其他环境条件进行定制，且使用常见的街道清洁设备即可完成日常维护。

尽管如此，在受控环境中进行测试也存在一定的局限性。下一阶段的设计将进行现场测试，对可能影响设计效果的多种时空参数（如雨水水质）进行进一步校准和调整，届时设计将被置于不同的暴雨强度和不同的径流流速条件下，同时承受车辆、自行车和行人日常使用的磨损测试。这将有助于进一步制定最佳维护方法及所需的维护频率，从而优化设计。生态草沟的推广案例已经证明，场地尺度的小型干预设计即可改善区域水质；“路缘沉积”项目则从设计标准的角度引发当前设计实践的思考：单个设计元素能否发挥更大的作用？原型测试是回答这个问题的第一步，而景观设计师则可能是设计出具有多重功能且美观的城市元素的最佳人选。LAF

### 项目信息

测试地点：美国俄亥俄州哥伦布市俄亥俄州立大学MAT / FAB实验室  
 项目资助：俄亥俄州立大学工程学院暑期研究项目（启动资金来自Ryan Winston及Halina Steiner）  
 设计团队：Halina Steiner、Ryan Winston、Avee Oabel、Alec Grimm  
 设计时间：2019年2月至今  
 测试设计：2019年5-8月

## 1 Introduction

Roads crisscross the landscape forming an ever-expanding network of asphalt. According to the Federal Highway Administration, this network comprises 6.7 million kilometers of road in the United States<sup>[1]</sup>. They are the system of public space primarily maintained by cities and states and critical in facilitating movement of people and goods within cities<sup>[1]</sup>. They are a vehicle for connection and an integral component of USA economy. However, this network also acts as a magnet for pollutants, such as sediments, nutrients from lawn fertilizers, bacteria, viruses, pesticides, metals, microplastics, deicing salt, and oil and grease<sup>[2]</sup>. Pollutants accumulate on the road surface and are washed off during storm events, carried to storm drains via concrete curbs / gutters / aprons, and deposited into waterways often without treatment<sup>[2]</sup>. Once pollutants enter the waterways, they negatively impact the water quality and even the ecosystem, while the removal of pollutants, such as microplastics, is challenging. How can innovations in street design work to remedy this problem? Curbs and gutters are designed to move water, but can they do more?

The design of a street, sidewalk, and the curb / gutter / apron system has maintained a relative stasis for centuries. For example, innovations as simple as curb ramps were first introduced in 1945 in Kalamazoo, Michigan to aid veterans in wheelchairs<sup>[3]</sup>. Benefits of the curb ramp then extend to cyclists, strollers, and suitcases. Yet adoption was slow, curb ramps were not made a legal requirement of sidewalks until 1992, as part of the Americans with Disabilities Act<sup>[4]</sup>. Recently, it has seen increasing innovations primarily tied to green infrastructure. Curb cuts allow water to flow into bioswales and were first used in the early 1990s at the Prince George's County, Maryland<sup>[5]</sup>. However, the recent adoption of this technology is largely driven by U.S. cities failing to meet the Environmental Protection Agency's (EPA) water quality standards set by the Clean Water Act. As a result, the large-scale implementation and development of bioswales has led to iteration and improvement of designs as they move from pilot- or prototype-scale projects to new design standards. Bioswales are useful and effective in reducing stormwater flow at peak hours and filtering pollutants. Sediment and trash impair the ability of bioswales to function properly as they may cause clogging and failure to filter. In EPA's Operation and Maintenance of Green Infrastructure Receiving Runoff from Roads and Parking Lots Technical Memorandum, construction activities, bare soil (i.e. poorly vegetated area) erosion, and winter sand application are cited as common sources of sediment in urban runoff. The EPA further explains how

sediments accumulate on impervious surfaces and, when routed to bioswales, build up at inlets, clog soil, and smother plants<sup>[6]</sup>. How can we leverage the curb, a commonplace design in urban areas, to collect pollutants before they enter the waterways and in so doing improve the health of watersheds?

## 2 Design Process

### 2.1 Pre-prototype Process

Many factors were considered in the prototype process. The team initially explored the use of digital simulation models in partnership with the Ohio State University (OSU) Simulation Innovation and Modeling Center. Digital model allows for fluid dynamical computation with a greater specificity of sediment size and storm events than a physical model, and is able to test one cross section of the curb, rather than a continuous curb face. Advanced computing would be necessary to develop a digital model of a continuous curb face, and the computational technology required to develop such a model was not available. So digital model was not further researched.

Then, the team chose physical testing to address the proof of concept goal, and examined prototyping techniques and hydrological sediment flow modeling. In the research on floating concrete vessels, Jake Boswell, associate professor at OSU, used CNC router to create EPS foam molds in the OSU MAT / FAB Lab, then coated them with oil and cast with floating concrete that is less dense than water. The vessels provide a structure for plant life that can aid in combating algal blooms in Lake Erie<sup>[7]</sup>. Wu Haowen, a former graduate student at OSU, fabricated a model of the Scioto River also using the CNC mill and EPS foam. The model was waterproofed with latex paint, a mixture of water and ink was pumped through the water to study river flow. Brain Davis, Associate Professor at University of Virginia, and Sean Burkholder, Assistant Professor at University of Pennsylvania, have integrated modeling into their project Healthy Port Futures. Through physical modeling, conducted at the St. Anthony Falls Lab at the University of Minnesota, coupled with computational modeling, they have developed a methodology to understand potential sediment flows in the Great Lakes.<sup>[8]</sup> Facets of each of these projects informed or were integrated into the current Curbing Sediment research.

### 2.2 Fabrication Process

EPS foam was chosen for modeling due to its appropriate stock size, lightweight nature, and surface textural property. The 1.2 m × 2.4 m × 0.2 m EPS stock size allows the team to create full scale models, clearly showing and accurately simulating



© Halina Steiner, Ryan Winston  
10

sediment capture. The foam's light weight makes the stocks and models easy for transporting from storage to the various stages of fabrication and testing. The surface texture of EPS foam becomes similar to concrete once cut with the hot wire and passed through the CNC router.

To create the curb models, the stock pieces of EPS foam were cut down to a standard road profile. The team originally milled this profile using the CNC mill. The CNC mill took approximately 4 hours to mill the stock foam into a street section model with no curb or apron patterns. To minimize fabrication time, a 2.4-meter hot wire cutter was used to cut the stock pieces into basic curb and road profiles consisting of a 15.24-centimeter-high curb and a 1-meter-wide roadway with a 1.5% cross slope. To fit the geometry of some curb designs, the curb height would be reduced to 11.4 ~ 12.7 cm. However, fully modeling a 15.24-centimeter curb would cause colliding damage of both the router bits and the top of the curb model, thus Rhino 3D Modeling software was used to create digital models of curb and apron alterations. The physical process of milling these iterations was then digitally simulated in RhinoCAM to map tool paths and predict potential tool collisions or inconsistencies from the original Rhino model. After simulating the models in RhinoCAM, a 5-axis G-code was created and

exported to an Onsrud 5-Axis CNC Router for milling apron and curb patterns on the basic curb profiles from the hot wire cutter. The patterns and crenellations were limited to the sizes of CNC tools available: a series of flat and ball tools ranging from 6.3 ~ 25 mm in diameter were used. One end of the model was milled to taper at a 45° angle to direct water into the curb gutter at the end of the testing table, which was used to assess water quality downstream of the crenellations. Finally, the curb models were cleared of excess EPS foam and painted with a layer of latex primer to prevent the models from absorbing water during tests.

When designing apron patterns, the team took inspiration from the dimensions of elements already present on roadways. Tactile paving units, made up of truncated flat-topped domes ( $5.08 \pm 0.51$  mm in height and 3.5 cm in diameter), are used to signal an upcoming intersection to pedestrians with visual impairments. The team used similar dimensions for the initial "dot" apron patterns. Design iterations featured similarly-scaled crenellations to ensure walkability and maintain safety of pedestrians and cyclists.

### 2.3 Prototype Design Process

The design process was iterative, with each phase built on the

10. 多轮测试的定格照片
  11. 测试后模型上留下的水和沉积物
10. Stills from each round of testing
  11. Water and sediment left on the model after test



© Halina Steiner, Ryan Winston

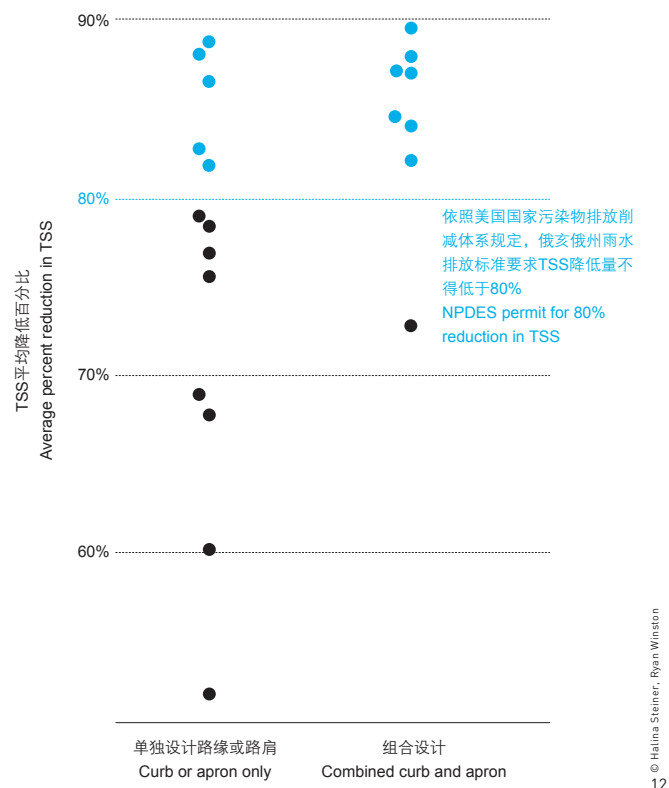
data and observations from the previous round of testing. The 1:1 prototyping helped the team understand how the proposed designs would look at full scale. Before testing, the team placed models next to a sidewalk and a street for additional insights about scale and visibility in the landscape.

The first designs tested were limited to alterations of either the curb face or the apron surface. Before full scale models were milled, the team tested different densities and depths to understand the limits of the routers (Fig. 1). The team tested the curb and apron modifications respectively to better understand how they function alone and how they may be incorporated best to become a system. The testing process involved 8-minute trials during which a synthetic stormwater mixture was pumped across the patterned crenellations in the apron or curb. After testing, designs were evaluated based on visual observations in sediment accumulation, measured turbidity reduction (i.e., a measure of water clarity), and total suspended solids (TSS) reduction.

The first round of testing focused on 3 curb face modifications: rounded, square, and triangular crenellations.

表1: 在TSS和浊度降低方面表现良好的组合设计  
Table 1: Combined designs that perform well in TSS and turbidity reduction

设计类型 Design type	测试次数 Number of trials	进水口TSS平均浓度 (mg/L) Average TSS at inlet (mg/L)	出水口TSS平均浓度 (mg/L) Average TSS at outlet (mg/L)	TSS平均减少量 (%) Average reduction in TSS (%)	进水口浊度平均水平 (NTU) Average turbidity at inlet (NTU)	出水口浊度平均水平 (NTU) Average turbidity at outlet (NTU)	浊度平均降低量 (%) Average reduction in turbidity (%)
网格状路肩与方形路缘凹槽 Cross hatch apron with square curb crenellations	7	1,717	212	87	1,402	1,044	22
15.24cm间隔的斜线路肩与方形路缘凹槽 Diagonal line apron at 6" gap with square curb crenellations	4	1,262	150	87	1,249	541	61
梳齿状路肩与方形路缘凹槽 Comb apron with square curb crenellations	4	829	142	82	1,189	752	42
花式斜线路肩与方形路缘 Squiggles apron with square curb crenellations	3	1,440	129	89	995	324	66
P+P方形路缘凹槽 P + P square curb crenellations	3	839	104	87	818	394	53
水波形路肩与方形路缘凹槽 Zigzag apron with square curb crenellations	3	920	145	84	938	1,085	42
网格状路肩与反向方形路缘凹槽 Cross hatch apron with inverted square curb crenellations	3	842	117	84	1,239	552	55
交替水波形路肩与方形路缘凹槽 Alt zigzag apron with square curb crenellations	3	642	163	72	947	236	76



12. 单独设计路缘或路肩与组合设计中TSS浓度降低百分比的分布
12. Distribution of percentage reduction in TSS concentrations for independent or combined designs of curb and apron

The square crenellation noticeably outperformed the other modifications in terms of sediment trapping and was selected for further development (Fig. 2). For apron design modifications, the team initially tested dot, line, and zigzag patterns at varying densities. This was achieved by reuse of models, first milling a lower density then re-milling the model to increase the density of the design (Fig. 3 ~ 6). The team evaluated each design using data from the turbidity sensors located at the inlet and outlet of the model. Among the 3 initial patterns, the line design was proved to be the most effective in sediment capture and chosen for further development. Variations on the line design were focused on providing additional surface area for sediment capture and slowing the velocity of the stormwater. This included altering the angle of the line, making the line path into combs, squiggles, and cross-hatches among others.

Further testing focused on designs combining the best performing curb and apron modifications, evaluating the apron's ability to convey sediments into curb extrusions. Iterations altered the spacing and sizing of curb crenellations, the way apron crenellations connected, and the placement and spacing of apron patterns. Then better performances were observed when connected apron crenellations were connected to curb

extrusions, and the most effective 3 combinations were: the cross hatch apron with 7.62 cm square curb crenellations with 7.62 cm spacing between each curb crenellation (Fig. 7), the line apron with 5.08 cm square curb crenellations with 15.24 cm gaps every 45 cm (Fig. 8), and the “comb” apron design with 5 cm square curb crenellations with uniform spacing (Fig. 9).

#### 2.4 Simulated Stormwater Tests

The prototypes were tested at the OSU MAT / FAB Lab. The physical setup included a 1.2 m × 2.4 m platform with a vinyl gutter attached to one end, 1.2 m × 2.4 m × 0.2 m stock pieces of EPS foam, two 31-gallon tote plastic tubs, an industrial mixer, scale, native soil, sand, sampler bottles, 2 Arduino microcontrollers with analog turbidity sensors, an iPad, GoPro Hero 6, three laptops, and a Sony a7RII. Milled and sealed foam pieces were placed on the platform with the GoPro Hero 6 and Sony a7RII suspended above them. The GoPro recorded video of the tests and the camera took still images every 10 seconds. The testing began with weighing approximately 70 ~ 80 kg of water into the tote plastic tubs. A mixture of roughly 60% ~ 70% native soil and 30% ~ 40% sand was added to the water to simulate stormwater. The mixer dispersed the soil and sand

mixture uniformly in the tub, ensuring simulated sediment concentrations were consistent throughout the simulated storm event. A submersible pump, placed at the bottom of the tub, conveyed the water onto the surface of the model. A turbidity sensor was placed to gather data at the pumped simulated stormwater inlet. Simulated stormwater moved freely over the surface of the model during each 8-minute test. The water then flowed into the gutter where the second sensor was located and finally into the outlet tub. Outlet water in the tub was weighted as well as any remaining water in the inlet tub. During the tests grab samples were taken at the inlet and outlet at 2-minute intervals with the sampler bottles.

21 curb and apron designs were tested. Each design was tested in triplicate in succession (Fig. 10). Sediment from each test was left on the model's surface to determine how much sediment each design could effectively capture (Fig. 11). The 3 most successful designs received 1 ~ 7 rounds of additional simulated storm events, each with increased volumes of sediment to determine the failure modes and timing.

## 2.5 Findings

Data was collected via 3 means. Visual data were collected with the camera and GoPro during the tests. Additionally, the team could visually assess water clarity in grab sample bottles and outlet tub water. Grab samples were tested in the lab at the OSU Stormwater Management Program for TSS and particle size distribution. Sensor data were reviewed during the tests and further analysis was conducted to compare findings with grab sample data (Table 1).

Sediment data analyses were conducted for all designs tested. The results showed that designs with both curb and apron modifications performed better than those with only a curb or an apron modification. According to an 80% reduction in TSS for discharged stormwater management in Ohio required by the National Pollution Discharge Elimination System (NPDES) permit program, 7 of the 8 combined curb and apron designs met this standard (Fig. 12).

## 3 Conclusion

Prototype testing of 21 designs in Curbing Sediment proved that redesigning curb and apron standards can be a viable option to collect pollutants on roadways. These new designs can be used in concert with green infrastructure to reduce clogging or independently on roadways as a feasible alternative to the existing standards for curb and apron design with small footprint, mature trees, and narrow sidewalks. Custom patterns

could be developed for Business Improvement Districts or by municipalities to adapt to specific aesthetic, hydrologic, and / or other physical conditions. Regular maintenance of curb and apron designs can be performed by street cleaning machines already in use.

However, testing in a controlled environment has its limits. The next phase of design will include field testing. This will allow the team to further calibrate and adjust the designs to temporally and spatially varied parameters which might affect the performance of Curbing Sediment, including rainfall and stormwater quality. By exposing the designs to varied storm events and flow rates, and regular use by vehicles, cyclists, and pedestrians, this will help with the analysis of best maintenance methods and required frequency of maintenance to optimize Curbing Sediment. Bioswales have proven that small-site-scale interventions deployed at a regional scale can improve water quality. Curbing Sediment leverages the design standard to question current design practices: Can each element do more? Prototype testing is the first step in answering this question and landscape architects may be best suited to design productive and beautiful alternatives. **LAF**

---

### PROJECT INFORMATION

**TESTING LOCATION:** MAT / FAB Lab at Ohio State University, Columbus, Ohio, USA

**FUNDED BY:** College of Engineering Summer Research Program, Ohio State University (Start-up funds from Ryan Winston and Halina Steiner)

**DESIGN TEAM:** Halina Steiner, Ryan Winston, Avey Oabel, Alec Grimm

**DESIGN PERIOD:** Since February, 2019

**TESTING PERIOD:** May - August, 2019

---

### REFERENCES

- [1] U.S. Department of Transportation: Federal Highway Administration. (2018, August 23). Public Road Length - 2017, Miles by Ownership. Retrieved from <https://www.fhwa.dot.gov/policyinformation/statistics/2017/hm10.cfm>
- [2] Rasmussen, T. J., & Schmidt, H. C. (2009, December). Stormwater Runoff: What it is and why it is important in Johnson County, Kansas. Retrieved from <https://pubs.usgs.gov/fs/2009/3103/pdf/FS2009-3103.pdf>
- [3] Brown, S. (1999). The Curb Ramps of Kalamazoo: Discovering Our Unrecorded History. *Disability Studies Quarterly*, 19(3), 203-205.
- [4] The Civil Rights Division of the U.S. Department of Justice. (2016). Curb Ramps and Pedestrian Crossings under Title II of the ADA. Retrieved from [https://www.ada.gov/pcatoolkit/ch6\\_toolkit.pdf](https://www.ada.gov/pcatoolkit/ch6_toolkit.pdf)
- [5] James, W. (1994). *Current Practices in Modelling the Management of Stormwater*. Boca Raton: CRC Press.
- [6] United States Environmental Protection Agency. (2016, September). Operation and Maintenance of Green Infrastructure Receiving Runoff from Roads and Parking Lots. Retrieved from [https://www.epa.gov/sites/production/files/2016-11/documents/final\\_gi\\_maintenance\\_508.pdf](https://www.epa.gov/sites/production/files/2016-11/documents/final_gi_maintenance_508.pdf)
- [7] Knowlton School of Architecture of Ohio State University. (2017, October 26). Landscape Architecture Faculty/Student Design Collaboration Leads to Possible Patent. Retrieved from <https://knowlton.osu.edu/news/2018/10/landscape-facultystudent-design-collaboration-leads-possible-patent>
- [8] Healthy Port Futures. (n.d.). Methodology. Retrieved from [http://healthyportfutures.com/methodology/#\\_edn2](http://healthyportfutures.com/methodology/#_edn2)