Van Tai Tang. 2025. Chapter 8: Application of Permeable Concrete Material in Constructed Wetlands for Urban Stormwater Runoff Treatment. In Thi Thuong Nguyen (ed.), *New Challenges in Constructed Wetlands for Sustainable Wastewater Treatment: Intensification Strategies Based on Asian Experiences*. Osaka: Asia-Japan Research Institute, Ritsumeikan University. ISBN 978-4-910550-06-0

Chapter 8
Application of Permeable Concrete Material in Constructed Wetlands for Urban Stormwater Runoff Treatment

Van Tai TANG

1. Introduction

I would like to introduce a case study using novel advanced porous concrete in constructed wetlands (CWs) for urban storm runoff treatment in Vietnam. The findings of this research were published in Water Science and Technology (Tang and Pakshirajan 2018). First, I will share the research background. As you may know, the current infrastructure construction technology fails to meet the requirements for collecting and treating urban stormwater adequately, leading to two major challenges: urban river pollution and urban flooding. Furthermore, the increase in sea levels, heavy rainfall, and the extensive use of impermeable concrete surfaces in urban areas have exacerbated this problem. Figure 1 illustrates the impervious surface and the percentage of infiltration in various residential density areas.

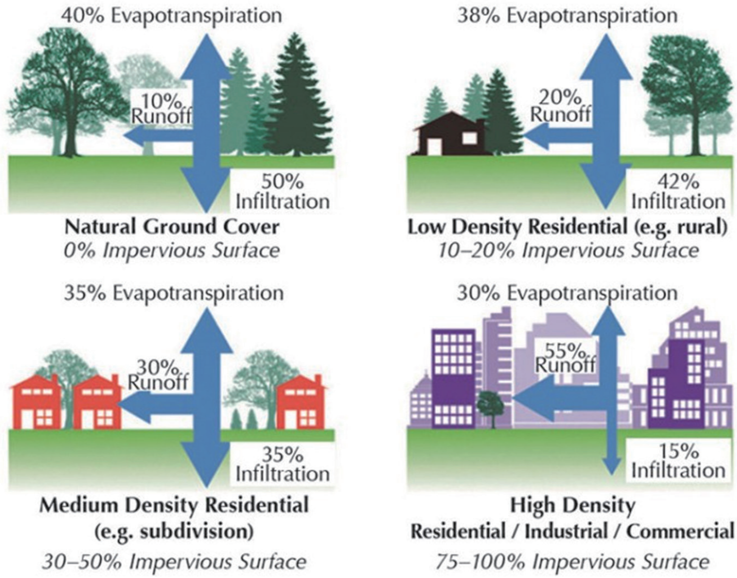

Figure 1: The impervious surface and the percentage of infiltration in various residential density areas. Source: Author

Estimates suggest that under natural ground cover, approximately 50% of stormwater infiltrates into the soil, with only 10% resulting in runoff. However, in low-density residential areas, the infiltration rate decreases to 42%, and in medium-density residential regions, it further reduces to 35%. In high-density residential areas, this rate drops significantly to only 15%, leading to approximately 55% of stormwater runoff reaching the river surface and causing flooding in urban areas. Figure 2 shows the urban river pollution and urban flooding in Ho Chi Minh City, Vietnam.

Figure 2: The urban river pollution and urban flooding in Ho Chi Minh City, Vietnam. Source: Author

Due to the inability of rainwater to penetrate the soil, it accumulates and forms large streams. Storm runoff resulting from heavy rainfall leads to the erosion and dissolution of surface pollutants like organic matter, nutrients, and heavy metals into riverbeds, resulting in significant pollution. Addressing these challenges requires comprehensive strategies such as promoting sustainable urban planning and development practices, enhancing green infrastructure, implementing flood mitigation measures, and reducing greenhouse gas emissions to mitigate climate change impacts. Additionally, it is crucial to urgently develop sustainable urban stormwater treatment systems to minimize the contribution of impermeable surfaces to urban flooding and pollution. To control pollution from stormwater, the term Best Management Practices (BMPs) has been introduced into stormwater management in the US and Canada. Stormwater management BMPs can typically be categorized into four basic types: Storage practices, Vegetative practices, Filtration/ Infiltration practices, and Water-Sensitive Development. By this approach, we provided an urban stormwater treatment method utilizing novel advanced porous concrete in CWs. This method offers advantages such as permeable pavements, bioretention areas, and wetlands.

CWs can be used to control urban floods and water sources pollution caused by stormwater. The porous structure of CWs with high permeability can effectively absorb floodwater. The complex interaction of three main components — absorption material, plants, and microorganisms — within CWs facilitates the removal of pollutants from stormwater runoff. Also, CWs offer a cost-effective and sustainable solution for treating stormwater pollution, providing numerous benefits for water quality improvement, habitat enhancement, and ecosystem restoration. By harnessing natural processes and ecological functions, CWs can efficiently mitigate the impacts of urbanization and land development on water resources. Figure 3 shows a CW designed for stormwater treatment and landscape creation in Ho Chi Minh City, Vietnam.

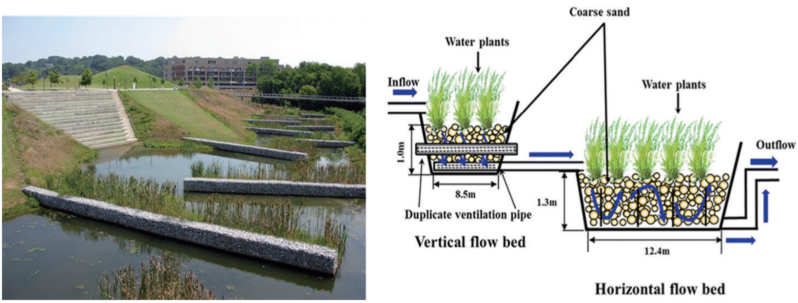

Figure 3: A CW designed for stormwater treatment and landscape creation. Source: Author

2. Methodology

(1) Materials

In this study, to prepare porous concrete, we used ceramics, cement, and water with a ratio of 348:272:83 kg/m^3, respectively. Porous concrete aggregates, ranging from 5 to 15 mm in size, were chosen, with a water-cement ratio of 0.24. To ensure the growth of plant biomass, permeability, strength, and stormwater purification capability of the CWs, the void ratio of porous concrete was set at 35%, as reported by Kim and Park (2016). For the sake of simplified installation, both the common porous concrete templates (CPCT) and advanced porous concrete templates (APCT) were prepared in a modular format with dimensions of 60 × 30 × 12 cm^3 each. In the case of APCT of the same volume, holes measuring 50 × 20 × 4 cm^3 were incorporated at the center for filling with a mixture of zeolite, slag, and activated carbon in a ratio of 4:1:11. This was aimed at boosting pollutant removal efficiency, determined based on the ratio of pollutants present in stormwater (Maniquiz et al. 2010). Figure 4 shows the photos of CPCT and APCT.

Figure 4: Photos of CPCT and APCT. Source: Author

The planting capacity of the porous concrete was evaluated through the incorporation of *Festuca elata* grass. *Festuca elata* seeds were mixed with soil, and the resulting mixture was spread evenly over the surface of the dried porous concrete. After a period of one month, samples of *Festuca elata* grass were collected from 15 different points from each porous concrete template to measure both their height and weight.

(2) CW Experimental Setup and Operation

We utilized two plastic containers, each measuring 84 × 30 × 60 cm^3, housing porous cement templates as CW units for the removal of pollutants from stormwater. These units were equipped with two valves positioned at 5 and 45 cm heights to manage stormwater discharge and regulate water levels within the constructed wetland. A sampling outlet at a height of 20 cm was utilized for stormwater analysis. Two CWs, one containing six CPCT units and the other with six APCT units, were set up to assess their effectiveness in removing pollutants from stormwater runoff. Schematics displaying the dimensions of both units and CW treatment systems are presented in Figure 5.

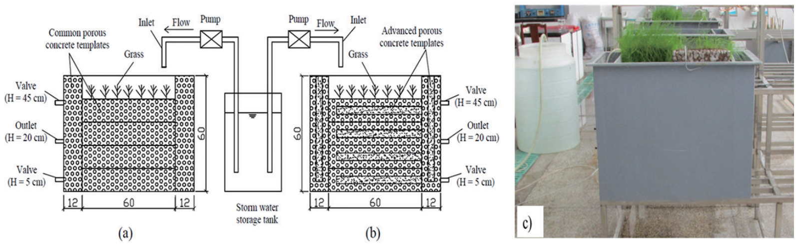

Figure 5: Diagram of (a) CPCT-CW unit and (b) APCT-CW unit, (c) CW treatment systems. Source: Author

For each CW treatment unit, *Festuca elata* grass was planted on top of the CW. In this study, we set the flow rate to 0.25 L/min, simulating the actual flow rate of rainwater as per previous studies (Hettler 2010; Maniquiz et al. 2010), with an HRT of 24 hours. This HRT was also utilized in the study conducted by Li et al. in 2015.

Stormwater was collected at Chengxianjie Road, Xuanwu Area, Nanjing City, Jiangsu Province, China, during rainfall events from April 17 to September 12, 2017. The stormwater was collected using a 500 L plastic tank and subsequently transferred to the laboratory for analysis and other experiments. In total, we obtained 13 stormwater samples.

3. Results

(1) Plant Growth on Porous Concretes

After one month from sowing, *Festuca elata* grass exhibited heights ranging from 12.6 to 16.9 mm and weights from 63.4 to 95.4 mg, indicating that the high porosity of the porous concrete provided sufficient space for root growth. Additionally, the voids within the porous concrete create favorable conditions for microbial reproduction. It is well recognized that bacteria contribute significantly to nutrient cycling processes in CWs, supporting plant growth and maintaining ecological balance. These findings highlight the robust growth potential of plants on the surface of the porous concrete.

(2) CW Treatment Performance

The treatment performance of CPCT-CW and APCT-CW is shown in Table 1. The CPCT-CW system achieved pollutant removal rates of 20.6% for COD, 30.1% for NH_3-N, and 35.4% for TN, primarily attributed to the formation of a biofilm on the porous concrete surface, facilitating microbial decomposition of organic matter and nutrients in stormwater. Additionally, grass planted atop the porous concrete aided in storm runoff pollution treatment by providing a nutrient-rich environment and moisture for microbial and plant growth, ultimately improving water purification efficiency. Overall, the combination of porous concrete and vegetation in CPCT-CW significantly contributed to pollutant removal from urban stormwater. In comparison, the APCT-CW system exhibited higher removal rates of 49.6% for COD, 52.4% for NH_3-N, and 47.7% for TN, outperforming CPCT-CW by 2.41, 1.74, and 1.34 times, respectively. This superior performance was attributed to the high pollutant absorption capacity of APCT, composed of activated carbon, zeolite, and slag, which provided ample space for nutrient, heavy metal, and organic matter adsorption. Additionally, the high void ratio of the filler material created an ideal habitat for microbial growth and biofilm formation on the surface of activated carbon, zeolite, and slag grains. Previous studies confirmed the effectiveness of biofilm in absorbing pollutants such as COD, BOD, and nutrients. Furthermore, each advanced porous concrete unit contained filler space acting as an independent bio-filter to retain and treat pollutants in stormwater. These findings emphasized the necessity of combining grass, porous concrete, and filler materials for achieving high water purification efficiency in APCT-CW systems.

Table 1: Pollutant removal efficiencies of CPCT-CW and APCT-CW

Water quality parameters (n = 13)	Water runoff quality (mg/L)	Influent	CPCT-CW		APCT-CW	
			Effluent (mg/L)	Average removal (%)	Effluent (mg/L)	Average removal (%)
COD	26-273	158.5± 65.9	125.8± 64.4	20.6	79.9± 27.2	49.6
TSS	23-217	126.2± 52.3	88.6± 58.7	29.8	51.9± 23.1	58.9
NH_3-N	0.9-7.2	4.21± 1.52	2.94± 1.96	30.1	2.01± 1.12	52.4
TN	2.6-18.3	10.35± 3.92	6.69± 3.00	35.4	5.42± 2.51	47.7
TP	0.35-3.21	1.73± 0.67	1.27± 0.65	26.9	0.95± 0.38	45.5
Pb	0.27-0.53	0.45± 0.12	0.32± 0.09	28.9	0.22± 0.06	51.1
Ni	0.11-0.31	0.24± 0.06	0.16± 0.03	33.3	0.09± 0.02	62.5
Zn	0.15-0.36	0.26± 0.05	0.15± 0.04	42.3	0.12± 0.03	53.8
pH	6.8-7.7	7.2 ± 0.3	7.9 ± 0.7	-	7.5 ± 0.5	-
Temperature (^{o}C)	18.5-30.2			25.7 ± 3.3		

Filtration serves as the primary mechanism for removing TSS and particulate phosphorus in CWs. Since heavy metals in storm runoff are mainly in particulate form, their removal is closely linked to TSS removal. Therefore, CWs are likely to remove heavy metals by adsorbing them onto attached suspended solids in stormwater. The removal of TSS, TP, and heavy metals by CPCT-CW and APCT-CW is presented in Table 1. In stormwater, the removal of TSS, TP, Pb, Ni, and Zn using APCT-CW exceeded that of CPCT-CW by factors of 1.98, 1.69, 1.77, 1.88, and 1.27, respectively. APCT incorporates a mixture of filler materials — zeolite, slag, and activated carbon — that effectively absorb pollutants in stormwater. These small-sized filler materials on the concrete created numerous continuous small pores, allowing for the accumulation of suspended solids, organic matter, and heavy metals present in stormwater. The biofilm formed in the voids of the filler mixture contributed to the transformation and absorption of dissolved phosphorus and organic matter in stormwater. Robust microbial growth on the voids of porous concrete and filler decomposed organic matter and absorbs phosphorus particles, thereby reducing TSS in stormwater. Extracellular polymeric substances (EPS) in a biofilm enhanced the removal of particulate matter and heavy metals in wastewater through increased flocculation and adhesion properties. These findings highlighted the superior efficiency of APCT-CW over CPCT-CW in removing TSS, TP, and heavy metals from stormwater.

Temperature and pH play vital roles in the removal of pollutants within CWs. In this study, the experimental temperature range of 18.5 to 30.2 °C provided favorable conditions for the essential bacterial processes of nitrification and denitrification, crucial for nitrogen removal from stormwater. Previous studies have highlighted the optimum temperature range for these processes as between 22 and 27 °C (Yoo et al. 1999). The pH levels measured in CPCT-CW and APCT-CW units were 7.9 ± 0.7 and 7.5 ± 0.5, respectively. The slightly higher pH observed in CPCT-CW compared to APCT-CW can be attributed to the larger quantity of porous cement utilized in CPCT preparation. When the porous concrete was immersed in water, it released alkaline minerals that might hinder bacterial activity and disrupt the structure of EPS within the biofilm. Consequently, the decreased efficiency in removing nutrients and TSS observed in CPCT-CW with higher pH values was likely due to a reduction in microbial populations and disruption of EPS structure.

4. Conclusion

This study has shown the role of porous concrete in ensuring the stability of CWs due to its high compressive strength. The APCT-CW unit, which combined porous concrete with absorption materials like zeolite, slag, and activated carbon, showed outstanding effectiveness in removing nutrients, suspended solids, and heavy metals from stormwater compared to the CPCT-CW unit that solely relies on porous concrete. Moreover, both CPCT-CW and APCT-CW units demonstrated durability and supported plant and microbial growth effectively for pollutant removal from stormwater. These findings highlight the potential of utilizing advanced porous concrete templates in CWs to effectively address urban stormwater runoff pollutants. Incorporating such templates offers a sustainable and efficient approach to managing urban stormwater runoff, thereby contributing to the improvement and preservation of water quality in urban environments.

References

Hettler, E.N. 2010. A Modified Elutriation Device to Measure Particle Settling Velocity in Urban Stormwater Runoff. Master's thesis, the faculty of the graduate school, University of Minnesota, Twin Cities, MN, USA.

Kim, H. H. and C. G. Park. 2016. Plant Growth and Water Purification of Porous Vegetation Concrete Formed of Blast Furnace Slag, Natural Jute Fiber and Styrene Butadiene Latex. *Sustainability*, 8(4), 386.

Li, C., Y. Dong, Y. Lei, D. Wu and P. Xu. 2015. Removal of Low Concentration Nutrients in Hydroponic Wetlands Integrated with Zeolite and Calcium Silicate Hydrate Functional Substrates. *Ecological Engineering*, 82, 442–450.

Maniquiz, M. C., S. Lee and L. H. Kim. 2010. Multiple Linear Regression Models of Urban Runoff Pollutant Load and Event Mean Concentration Considering Rainfall Variables. *Journal of Environmental Sciences*, 22(6), 946–952.

Tang, V. T. and K. Pakshirajan. 2018. Novel Advanced Porous Concrete in Constructed Wetlands: Preparation, Characterization and Application in Urban Storm Runoff Treatment. *Water Science and Technology*, 78(11), 2374–2382.

Yoo, H., K. H. Ahn, H. J. Lee, K. H. Lee, Y. J. Kwak and K. G. Song. 1999. Nitrogen Removal from Synthetic Wastewater by Simultaneous Nitrification and Denitrification (SND) via Nitrite in an Intermittently Reactor. *Water Research*, 33(1), 145–154.

8. Dr. Van Tai TANG

Chapter 8. Application of Permeable Concrete Material in Constructed Wetlands for Urban Stormwater Runoff Treatment

Dr. Van Tai Tang did his Ph.D. program in Municipal Engineering at the School of Civil Engineering Southeast University, China. He is currently a lecturer at the Faculty of Technology, Dong Nai Technology University in Bien Hoa City, Vietnam. He also serves as a special scientific advisor to CEC Construction and Environmental Safety Investment Joint Stock Company in Hanoi, Vietnam. His research focuses on several issues and technical aspects of water and wastewater treatment technologies as well as eco-restoration technologies.