

# Novel advanced porous concrete in constructed wetlands: preparation, characterization and application in urban storm runoff treatment

Van Tai Tang and Kannan Pakshirajan

## ABSTRACT

Common porous concrete templates (CPCT) and advanced porous concrete templates (APCT) were employed in this study to construct wetlands for their applications in pollutant removal from storm runoff. The planting ability of the concrete was investigated by growing *Festuca elata* plants in them. Strength of the porous concrete ( $7.21 \pm 0.19$  Mpa) decreased by 1.8 and 4.9% over a period of six and 12 months, respectively, due to its immersion in lake water. The height and weight of *Festuca elata* grass growth on the porous concrete were observed to be 12.6–16.9 mm and 63.4–95.4 mg, respectively, after a duration of one month. Advanced porous concrete template based constructed wetland (APCT-CW) showed better removal of chemical oxygen demand (COD) (49.6%), total suspended solids (TSS) (58.9%),  $\text{NH}_3\text{-N}$  (52.4%), total nitrogen (TN) (47.7%) and total phosphorus (TP) (45.5%) in storm water, when compared with the common porous concrete template based constructed wetland (CPCT-CW) with 20.6, 29.8, 30.1, 35.4 and 26.9%, respectively. The removal of Pb, Ni, Zn by the CPCT-CW unit were 28.9, 33.3 and 42.3%, respectively, whereas these were 51.1, 62.5 and 53.8%, respectively, with the APCT-CW unit. These results demonstrate that the advanced porous concrete template in constructed wetland could be employed successfully for the removal of pollutants from urban storm water runoff.

**Key words** | constructed wetlands, porous concrete, storm water treatment, urban water pollution

**Van Tai Tang** (corresponding author)  
Green Processing, Bioremediation and Alternative  
Energies Research Group, Faculty of  
Environment and Labour Safety,  
Ton Duc Thang University,  
Ho Chi Minh City,  
Vietnam  
E-mail: tangvantai@tdtu.edu.vn

**Kannan Pakshirajan**  
Department of Biosciences and Bioengineering,  
Indian Institute of Technology Guwahati,  
Guwahati, Assam 781039,  
India

## INTRODUCTION

Urban activities related to people, production and transportation have resulted in discharge of large amounts of garbage and sewage into the environment. The current infrastructure construction technology is unable to meet the demand for collection and treatment of urban pollution at source due to certain limitations associated with it (Zhao *et al.* 2010). In addition, storm runoff following heavy rainfall leads to scouring and dissolution of ground surface pollutants which ultimately results in urban water pollution (Hettler 2010; Zhao *et al.* 2010). Wetlands are often filled in with dirt, plant and filler materials to filter out contaminants before they end up in larger bodies of urban water sources. The early research proposed a lot of design to construct wetland for removing contamination in the storm runoff. Saeed *et al.* (2018) proposed using construction materials (recycled bricks) and *Canna indica* plant to construct wetland media to treat industrial wastewater. Li *et al.* (2015) investigated the removal of nutrients from water by using zeolite and calcium

silicate hydrate as functional filtration substrates in a wetland. Welz *et al.* (2018) studied the influence of sand grain mineralogy on the shape and packing of sand particles in wetlands for treating synthetic winery wastewater. These studies mainly focused on using the filler materials to construct wetlands for removing pollutants from wastewater. Clogging of filler due to organics is a serious problem in wetlands, which is difficult to locate and repair (Welz *et al.* 2018). In addition, clogging reduces the porosity of filter layer, thereby diminishing the wetland permeability and pollutant removal efficiency (Wang & Jiao 2004).

Porous concrete due to its void space provides easy growth of microorganisms and plants inside that serves as an excellent material for storm water purification. The porosity of the materials can be established by controlling the material mix ratio. In addition, porous concrete with a certain compressive strength ensures that its inner porosity is not compromised under external force. Using precast

**Table 1** | Mixture ratio of porous concrete

W/C <sup>a</sup>	Void ratio (%)	Unit volume material consumption/(kg·m <sup>-3</sup> )		
0.24	35	Ceram site 348	Cement 272	Water 83

<sup>a</sup>Water cement ratio.

porous concrete in constructed wetlands not only reduces construction time, but also minimizes repair and operation problems associated with it. Hence, this study evaluated the use of porous concrete template in the constructed wetlands has not been demonstrated so far for storm water treatment. Common porous concrete templates (CPCT) and advanced porous concrete templates (APCT) were used to construct wetlands (Figure 1), which ensured sufficient strength and plant biomass growth on porous concrete. The advanced porous concrete template type was designed with holes to fill with high-performance adsorption filler materials composed of zeolite, slag and activated carbon. Fifteen porous concrete blocks were prepared to investigate compressive strength of the materials when immersed in storm water. Two kinds of constructed wetlands (CW) based on CPCT and APCT were applied to remove pollutant from urban storm water. Concentrations of nutrients and heavy metals in the storm water were determined to investigate the pollutant removal efficiency in this study.

## MATERIALS AND METHODS

### Material

In order to ensure proper strength and porosity of the porous concrete templates, 5–15 mm size of porous concrete aggregate was selected (Park *et al.* 2004). Portland cement

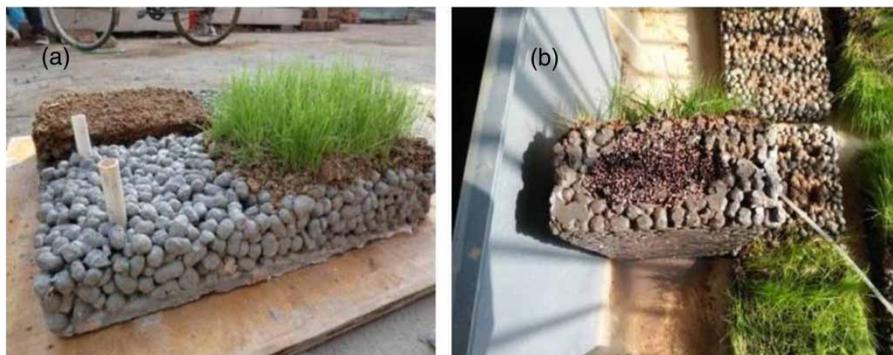
(P52.5 model) was used as the cementing material. Burnt ceramic grains were used as the coarse aggregate material to keep the weight of the porous concrete template low. In order to ensure plant biomass growth, permeability, strength and storm water purification ability of the constructed wetland, the void ratio of porous concrete was fixed as 35% (Park *et al.* 2004; Kim & Park 2016). Table 1 presents the values of void, and water cement ratios chosen to prepare the porous concrete templates and blocks in this study.

For ease of installation, the CPCT (Figure 2(a)) and the APCT (Figure 2(b)) were prepared as modular type with a volume of 60 × 30 × 12 cm<sup>3</sup> each. In the case of APCT of same volume, holes of dimensions 50 × 20 × 4 cm<sup>3</sup> at the centre were made for filling with a mixture of zeolite, slag and activated carbon at a ratio of 4:1:11 in order to enhance the pollutant removal efficiency (Figure 2(b)), which was based on the ratio of pollutants present in storm water (Maniquiz *et al.* 2010; Geng *et al.* 2015).

### Porous concrete compressive strength test

Fifteen porous concrete blocks with side length of 15 cm each were prepared to determine the material's compressive strength. The concretes were divided into three groups, P1, P2 and P3, with each group consisting of five blocks. Group P1 blocks were tested for strength after a curing period of 60 days. Groups P2 and P3 blocks were placed inside plastic containers with storm water. The water was replaced every week to ensure simulation of the actual storm rainfall events. Groups P2 and P3 were tested for strength after immersion in storm water for six and 12 months, respectively. Compressive strength of the porous concrete blocks were determined by the following Equation (1):

$$f = \frac{F}{A} \times 1000 \quad (1)$$

**Figure 1** | Image showing (a) CPCT and (b) APCT prepared in this study.



**Figure 2** | Picture showing plant growth ability of the different porous concrete templates.

where  $f$ : compressive strength of porous concrete test block (MPa);  $F$ : test block failure load (KN); and  $A$ : test block pressure area ( $\text{cm}^2$ ).

### Porous concrete with plant biomass

Five CPCT were planted with *Festuca elata* grass to test planting ability of the porous concrete (Figure 2). Seeds of *Festuca elata* grass were mixed with soil, and the mixture was evenly spread over the surface of the porous concrete templates. After a time period of one month, 15 plant samples from different points of the template were selected to determine the plant height and weight. The height of the plant samples was determined by using a ruler scale,

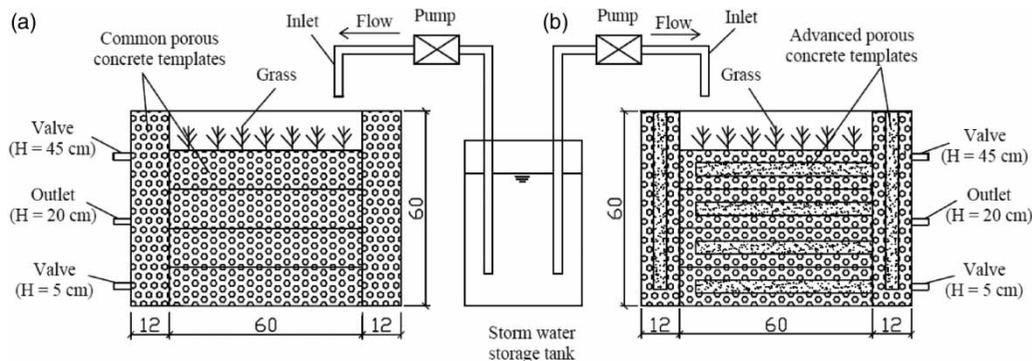
whereas the weight of the plant samples was determined using a BSM electronic balance (Zhuojing, Shanghai, China). The average height and weight of the plants were determined to observe plant biomass growth on the concrete template surface.

### Constructed wetland unit structure

Two plastic containers of the volume  $84 \times 30 \times 60 \text{ cm}^3$  each with the porous cement template were used as the constructed wetlands units for pollutant removal from storm water. Two valves were located at a height of 5 and 45 cm to discharge storm water and control water level in the constructed wetland. An outlet port at 20 cm height was used to sample the storm water. Two constructed wetland with six numbers of CPCT and the other with six numbers of APCT were installed to evaluate their performance for pollutant removal from storm water runoff. Schematic of the two units along with their dimensions is shown in Figure 3. For investigating storm water purification, *Festuca elata* grass was planted on top of the constructed wetlands. It is reported that under the rainfall events, the storm runoff formation with low flow rate contained a high concentrations of pollutants and caused urban water pollution (Maniquiz *et al.* 2010). Therefore, the flow was set at 0.25 L/min to simulate low flow rate of storm runoff in this study (Hettler 2010), which gave a hydraulic retention time of 24 h, in the constructed wetlands (Li *et al.* 2015).

### Storm water sample collection and analysis

Thirteen storm water samples were collected from the storm runoff collecting well located in Chengxianjie Street, Xuanwu area, Nanjing City, Jiangsu province, China. The collecting well received storm water runoff from



**Figure 3** | Schematic diagram of constructed wetland units (a) CPCT-CW unit and (b) APCT-CW unit.

neighboring residential, road and square area in the locality. The storm water samples were collected during the rainfall event from 17th April 2017 to 12th September 2017. In the each rainfall event, storm runoff was collected in a 500 L plastic storage tank for one hour when it contained a high pollutant concentration (Maniquiz *et al.* 2010). Following collection, the storm water tank was transferred to the laboratory for analysis and further experiments.

## RESULTS AND DISCUSSION

### Compressive strength of porous concrete

The actual void ratio of the porous concrete unit was 34.5–36.8%. The voids ratio difference in the design was in the range 0.9–5.1%, which was found to be well suited for experimental work. The data strength of P1, P2 and P3 porous concrete blocks group is presented in Table 2.

After the standard curing period, strength of Group P1 blocks was observed to be  $7.21 \pm 0.19$  Mpa. After immersing in storm water for six months, the strength of Group P2 blocks was found to be  $7.08 \pm 0.15$  Mpa, whereas strength of Group P3 block after 12 months' immersion in water strength was  $6.86 \pm 0.22$  Mpa. The porous concrete strength of groups P2 and P3 blocks were thus lower by 1.8 and 4.9%, respectively, when compared with that of Group P1 blocks. These results reveal that the strength of the porous concrete decreased due to contact with storm water, which indicates that the cement used as the main binding material in porous concrete gets eroded due to immersion in storm water. Akashi *et al.* (1991) reported that when immersed in lake water for a long time, concrete releases alkaline minerals such as  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Al}^{3+}$ ,  $\text{Na}^+$ ,  $\text{K}^+$ . The releasing of alkaline minerals will reduce the ability of cement-linked aggregates that decrease porous concrete strength. In addition, some minerals in the cement chemically react with acid present in storm water causing erosion of the concrete, leading to the reduction of the strength in a porous concrete block. Kanazu *et al.* (2001) investigated the effect of acid rain on deterioration of concrete and observed that the erosion

**Table 2** | The P1, P2 and P3 porous concrete block group strength

Group	N	Mean (Mpa)	SD (Mpa)	Min (Mpa)	Max (Mpa)
P1	5	7.21	0.19	6.91	7.42
P2	5	7.08	0.15	6.83	7.21
P3	5	6.86	0.22	6.74	7.08

rate of mortar specimens ( $40 \times 15 \times 160 \text{ mm}^3$ ) under simulated acid rains with pH 3 and 2.5 were about 1.2 and 3 times greater than that under acid rain with pH 5.6. These results show that the strength of porous concrete template could be slightly decreased affecting the overall stability of constructed wetlands used for storm water treatment.

### Plant growth ability of porous concrete

The results of height and weight of plant biomass grown on porous concrete are presented in Table 3.

During a period of one month, *Festuca elata* grass height and weight could reach 12.6–16.9 mm and 63.4–95.4 mg, respectively, revealing that the porous concrete with high porosity provided the necessary space for the development of grass roots (Kim & Park 2016). In addition, the voids of porous concrete provided a good habitat for microorganisms breeding within the structure. Moreover, microbes present degraded complex organic substances in the water to simple inorganic substances, which further facilitated the plant growth and metabolism (Long *et al.* 2017). Kim & Park (2016) investigated plant growth on different kinds of porous concrete with porosity approximately 25% and showed that the grass height reached 12–16 mm in a period of 25 days. These results proved that plants could strongly develop on the surface of the porous concrete material developed in this study.

### Removal of COD, $\text{NH}_3\text{-N}$ and TN

The results of chemical oxygen demand (COD),  $\text{NH}_3\text{-N}$  and total nitrogen (TN) removal efficiency by CPCT-CW and APCT-CW units are presented in Figures 4–6 and Table 4.

The removal of COD,  $\text{NH}_3\text{-N}$  and TN using CPCT-CW was 20.6, 30.1 and 35.4%, respectively, which is attributed to the biofilm formed on the porous concrete surface due to microbial growth and attachment (Long *et al.* 2017). Zhang *et al.* (2015) reported that during 70–170 days of the laboratory experiment using porous concrete material, the removal of total organic carbon (TOC), TN, total

**Table 3** | Plant growth effect of porous concrete

Template type	A B C D E				
	A	B	C	D	E
Height (mm)	$12.6 \pm 1.3$	$14.6 \pm 1.1$	$15.9 \pm 1.7$	$16.5 \pm 1.1$	$16.9 \pm 1.9$
Weight (mg)	$63.4 \pm 6.1$	$78.3 \pm 6.9$	$89.1 \pm 7.3$	$95.4 \pm 8.4$	$94.1 \pm 8.9$

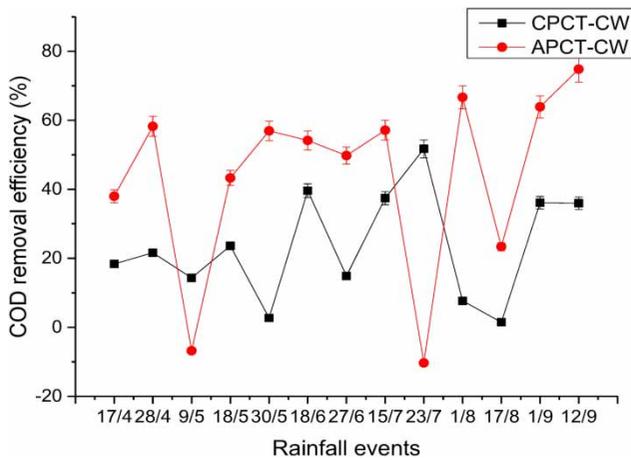


Figure 4 | COD removal with CPCT-CW and CPCT-CW units.

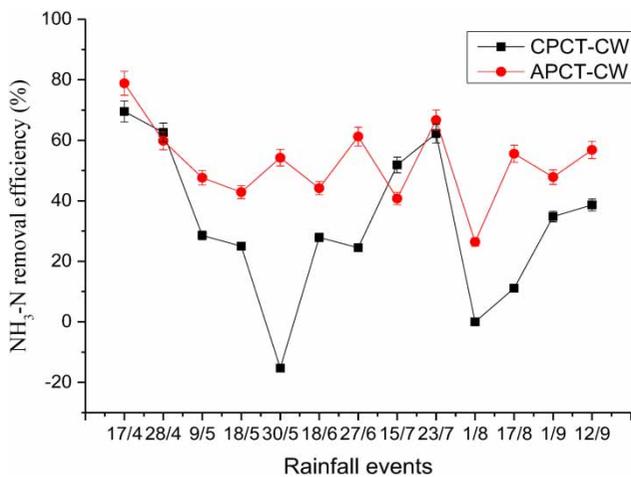


Figure 5 | NH<sub>3</sub>-N removal with CPCT-CW and CPCT-CW units.

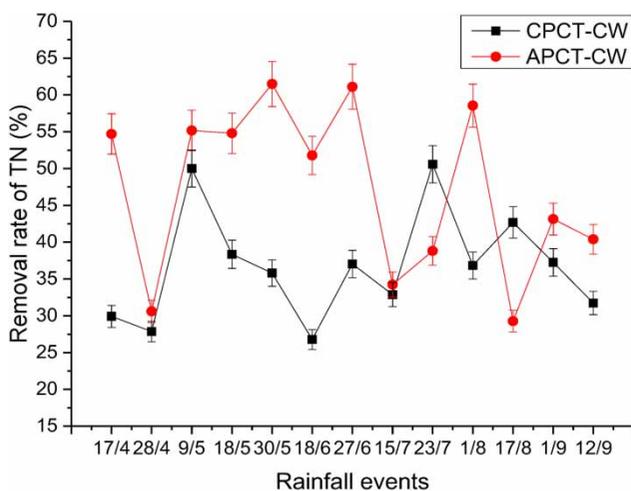


Figure 6 | TN removal with CPCT-CW and CPCT-CW units.

phosphorus (TP) was 60–80, 85–95, 20–40%, respectively. The microorganisms existing in biofilm of the porous concrete surface would decompose and transform the organic matters and nutrients that decrease the pollutants concentration in the storm water (Zhang *et al.* 2015; Long *et al.* 2017). The grass planted on top of the porous concrete templates plays an important role in storm-runoff pollution treatment. Long *et al.* (2017) reported presence of Proteobacteria, Actinobacteria, Cyanobacteria, Acidobacteria, Chloroflexi, Bacteroidetes, Planctomycetes, Firmicutes and Gemmatimonadetes bacterial communities in both planted and unplanted porous concrete systems, which played a role in storm water runoff pollutant treatment. Kim & Park (2016) reported that plants growing on porous concrete could remove 7.38–10.85% of NH<sub>3</sub>-N, 6.14–9.40% of TN and 9.17–11.24% of phosphate-phosphorus. The storm water infiltrated through the porous concrete provided abundant nutrient source and moisture which facilitated the growth and metabolism of both microbes and the plant, thereby resulting in the improved water purification efficiency (Kim & Park 2016; Long *et al.* 2017). These results revealed that the combination of porous concrete and plant used in the CPCT-CW played a significant effect in removing the pollutants from urban storm water.

The removal of COD, NH<sub>3</sub>-N and TN in storm water using APCT-CW was 49.6, 52.4 and 47.7%, respectively. The removal of COD, NH<sub>3</sub>-N and TN in storm water using APCT-CW is higher than CPCT-CW as 2.41, 1.74 and 1.34 time, respectively. These values are significantly higher than those obtained using the CPCT-CW, which is attributed to the high pollutant absorption capacity of the APCT that consisted of a mixture of activated carbon, zeolite and slag. Fu & Jiang (2010) reported maximum pollutant adsorption capacity of 8.758, 2.799 and 1.311 mg/L using activated carbon, zeolite and slag, respectively. The mixture containing a large internal pores material of activated carbon, zeolite and slag provide the nutrients, heavy metal and organic matters adsorption capacity that could reduce the pollution concentration in the storm water (Pak *et al.* 2002; Fu & Jiang 2010). In addition, the filler with a high void ratio provided very good habitat for microorganism growth and metabolism. The microbes are also capable of forming biofilm on the surface of activated carbon, zeolite and slag grains. Pak *et al.* (2002) showed that biofilm grown on activated carbon and zeolite consisted of  $1.8 \times 10^9$  and  $1.3 \times 10^9$  colony forming units (CFU)/mL of heterotrophs, respectively. In this study, the combination of *Festuca elata* grass, porous concrete and filler materials in the APCT thus enhanced the water purification efficiency.

**Table 4** | Results of pollutant removal efficiency with CPCT-CW and APCT-CW units

Water quality parameters	Water runoff quality (mg·L <sup>-1</sup> )	Influent (mg·L <sup>-1</sup> )	CPCT-CW		APCT-CW	
			Effluent (mg·L <sup>-1</sup> )	Average removal (%)	Effluent (mg·L <sup>-1</sup> )	Removal (%)
COD ( <i>n</i> = 13)	26–273	158.5 ± 65.9	125.8 ± 64.4	20.6	79.9 ± 27.2	49.6
TSS ( <i>n</i> = 13)	23–217	126.2 ± 52.3	88.6 ± 58.7	29.8	51.9 ± 23.1	58.9
NH <sub>3</sub> -N ( <i>n</i> = 13)	0.9–7.2	4.21 ± 1.52	2.94 ± 1.96	30.1	2.01 ± 1.12	52.4
TN ( <i>n</i> = 13)	2.6–18.3	10.35 ± 3.92	6.69 ± 3.00	35.4	5.42 ± 2.51	47.7
TP ( <i>n</i> = 13)	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 (°C)	18.5–30.2			25.7 ± 3.3		

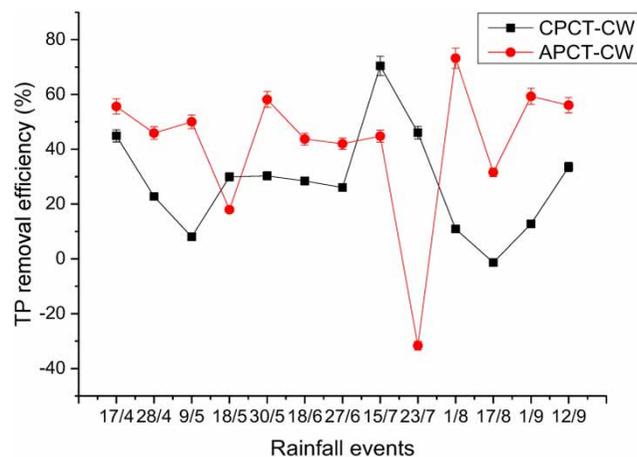
Park *et al.* (2004) reported high adsorption capacities of activated carbon for peptone and phenol with values of 50 COD mg/g and 43.8 COD mg/g, respectively; in the case of zeolite it was 3.47 mg/g for ammonium. Geng *et al.* (2015) reported that 2.27 g zeolite could adsorb 25 mg/L NH<sub>3</sub>-N, whereas 0.56 g steel slags were able to adsorb 3 mg/L P and 6.41 g activated carbon adsorbs 100 mg/L organics. Many other reports have also proved that activated carbon, zeolite and slag have strong capacity to absorb nutrients. In addition, each advanced porous concrete contains filler space that functions as an independent bio-filter to retain and treat pollutants in the storm water. Syafalni *et al.* (2012) used a 6.35 cm diameter column filled with 10 cm of granular activated carbon and 10 cm of zeolite to filter dye wastewater and showed that the removal of COD and NH<sub>3</sub>-N was 59.46 and 60.82%, respectively. Wu *et al.* (2013) showed that the removal of NH<sub>4</sub><sup>+</sup>-N and COD using a mixture of zeolite and activated bio-filter carbon was 78 and 28%, respectively. Hence, a combination of grass, porous concrete and filler materials is essential for achieving a very high water purification efficiency of the APCT-CW.

### Removal of TSS, TP and heavy metal

Filtration acted as the main mechanism for the removal of total suspended solids (TSS) and particulate phosphorus by the constructed wetlands. The correlation coefficients of TSS removal ratio to Pb, Ni and Zn removal ratio in CPCT-CW is 0.683 ( $p < 0.01$ ), 0.677 ( $p < 0.01$ ) and 0.721 ( $p < 0.01$ ), respectively. The correlation coefficients of TSS removed ratio to Pb, Ni and Zn removed ratio in

APCT-CW is 0.758 ( $p < 0.01$ ), 0.801 ( $p < 0.005$ ) and 0.658 ( $p < 0.01$ ), respectively. Heavy metals in the storm runoff were primarily in particulate form (Zhao *et al.* 2010) and, therefore, its removal also correlated with the TSS removal. Hence, heavy metals were removed by constructed wetlands is probably due to its adsorption on attached suspended solids present in the storm water. The removal of TSS, TP and heavy metal by CPCT and APCT is shown in Figures 7 and 8 and Table 4.

From Table 4, the removal of TSS, TP, Pb, Ni and Zn using the CPCT-CW was 29.8, 26.9, 28.9, 33.3 and 42.3%, respectively. Biofilm formed within the void of the porous concrete have a high affinity for the removal of dissolved phosphorus in the storm water (Zhang *et al.* 2015; Long *et al.* 2017). Thus, the porous concrete used in the CPCT-CW with a very good filtration ability could efficiently remove the phosphorus, TSS, and heavy metal present in

**Figure 7** | TP removal with CPCT-CW and APCT-CW units.

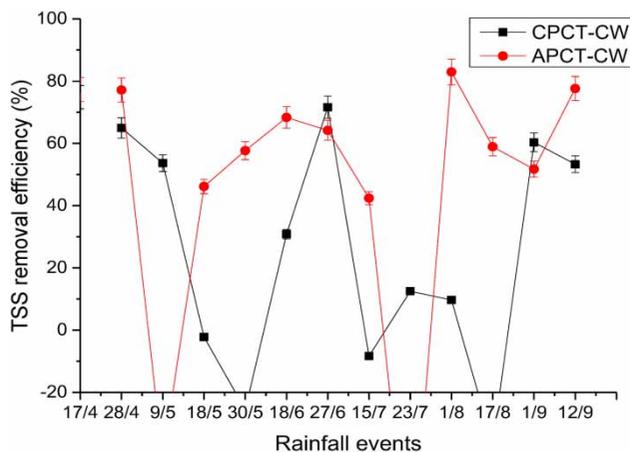


Figure 8 | TSS removal with CPCT-CW and APCT-CW units.

particulate form in the storm runoff. He *et al.* (2015) treated water using a porous concrete layer of 150 mm thickness and reported that 16–17% and 2–12% removal of TSS and TP, respectively. In some cases, the sediment, organic matter and heavy metal particles which accumulated in the voids of the porous concrete and filler could be released by the inflow storm water (Eck *et al.* 2012; He *et al.* 2015). The releasing of suspended solid particles caused the enhancement of TSS concentration in the out flow that decreased the removal ratio of TSS in the CPCT-CW (at 30/5 and 17/8 rainfall events) and APCT-CW (at 9/5 and 2/7 rainfall events). Eck *et al.* (2012) revealed that the storm water with low TSS concentration in some rainfall events could dissolve the accumulation in the voids of suspended solid particles that released to particulate matters discharged by permeable pavements. These results suggest that the porous concrete with its porous structure resulted in filtering the sediment and organic matter that aided in reducing the concentrations of TSS, TP and heavy metals from storm runoff.

The removal of TSS, TP, Pb, Ni and Zn with the APCT-CW was 58.9, 45.5, 51.1, 62.5 and 53.8% respectively. The removal of TSS, TP, Pb, Ni and Zn in storm water using APCT-CW is higher than CPCT-CW by 1.98, 1.69, 1.77, 1.88 and 1.27 times, respectively. The APCT used contained a mixture of filler materials, i.e. zeolite, slag and activated carbon, which absorbed a large amount of pollutants present in the storm water (Fu & Jiang 2010; Geng *et al.* 2015). These small sized filler materials on the concrete formed a large area of continuous small pores that provided necessary space for the accumulation of suspended solids, organic matters and heavy metal contained in the storm water (Pak *et al.* 2002). The biofilm formed in the voids of filler

mixture also acted to transform and absorb dissolved phosphorus and organic matters in the storm water (Pak *et al.* 2002; Tian *et al.* 2016). Tian *et al.* (2016) reported a maximum removal of 48% of total P in the influent that can be harvested and recovered using an alternating anaerobic/aerobic biofilter system. Pak *et al.* (2002) showed that for an initial 0.76–3.0 kg COD, suspended solids (0.20–1.05 kg SS) and NH<sub>3</sub>-N (0.056–0.181 kg NH<sub>3</sub>-N), the removal of these pollutants using a mixture of activated carbon and zeolite were more than 60, 65 and 30%, respectively. A large microorganism growth on the voids of porous concrete and filler will decompose the organic matters and absorb phosphorus particles to decrease the TSS in the storm water. The extracellular polymeric substances (EPS) in a biofilm could remove the particulate matter and heavy metal in wastewater via increased flocculation and adhesion properties (Lukasz *et al.* 2016; Nouha *et al.* 2016). Nouha *et al.* (2016) used 35 mg/L of EPS and reported removal of 85% nickel (Ni) in 120 min, whereas the value was 68 and 72% for aluminium (Al) and iron (Fe) in 60 and 30 min, respectively. In addition, the microorganism in the biofilm can absorb heavy metal and accumulate in the microbial cells that have high effect to reduce the heavy metal concentration in the storm water (Lukasz *et al.* 2016). Lukasz *et al.* (2016), through the sorption experiment, revealed that the microbial mats have high sorption capacity for As, Cd, Fe, Co and Cu. These results demonstrate that APCT-CW is more efficient than the CPCT-CW the removal of TSS, TP and heavy metal from storm water.

### Effect of temperature and pH on pollutant removal

Temperature and pH are two main parameters that directly influence pollutant removal using constructed wetlands. In this study, the experimental temperature is in the range 18.5–30.2 °C is highly suitable for bacterial nitrification and denitrification process that is required for nitrogen removal from storm water. Yoo *et al.* (1999) reported that temperature in the range of 22–27 °C is the best condition for nitrification and denitrification process. Ahsan *et al.* (2005) found that the removal COD and TSS increases with increase in temperature from 20 to 50 °C. The low temperature (18.5–30.2 °C) restricted the removal of COD and TSS effect by the microorganism in the CPCT-CW and APCT-CW units. The pH value in CPCT-CW and APCT-CW units were 7.9 ± 0.7 and 7.5 ± 0.5, respectively. Slightly higher pH value in the CPCT-CW than in APCT-CW is due to more quantity of porous cement used in preparing the CPCT. Upon immersion in water, the porous concrete

releases some alkaline minerals that could inhibit bacteria and disrupt EPS structure in the biofilm. Xiao *et al.* (2015) observed that under a high pH value (9–12), bound EPS, cell walls, cell membranes and cell nuclei were reduced by 46.2, 27.3, 34.2 and 44.4%, respectively. Hence, the low removal efficiency of nutrients and TSS with CPCT-CW with a high pH value is due to a reduction in the microbial count and the EPS structure.

## CONCLUSIONS

This study established that porous concrete, due to its high compressive strength, ensures the stability of constructed wetland. The strength of the concrete did not vary drastically even when immersed in storm water for six and 12 months. The APCT-CW unit with a combination of porous concrete and filling materials (zeolite, slag and activated carbon) yielded excellent results in terms of very high removal of nutrients, suspended solids and heavy metals from storm water when compared with CPCT-CW unit with only the porous concrete. Furthermore, both CPCT-CW and APCT-CW were found to be highly durable with a good ability to support plant as well as microbial growth for removal of pollutants from storm water. The results obtained in this study showed that the advanced porous concrete template in constructed wetland could be employed successfully for the removal of pollutants from urban storm water runoff.

## ACKNOWLEDGEMENTS

The current study was supported by Southeast University, Nanjing, 210096, China, and Green Processing, Bioremediation and Alternative Energies Research Group Ton Duc Thang University, Ho Chi Minh City, Vietnam.

## REFERENCES

- Ahsan, S., Rahman, M. A., Kaneco, S., Katsumata, H., Suzuki, T. & Ohta, K. 2005 Effect of temperature on wastewater treatment with natural and waste materials. *Clean Technologies & Environmental Policy* **7**, 198–202.
- Akashi, A., Matsuya, Y. & Nagasawa, H. 1991 Erosion process of calcium hydroxide cements in water. *Biomaterials* **12**, 795–800.
- Eck, B. J., Winston, R. J., Hunt, W. F. & Barret, M. E. 2012 Water quality of drainage from permeable friction course. *Journal of Environmental Engineering* **138**, 174–181.
- Fu, J. & Jiang, H. 2010 Adsorption of amantadine hydrochloride wastewater: the choice of adsorbent. In: *International Conference on E-Product E-Service & E-Entertainment, Henan, China*, pp. 1–4.
- Geng, X., Xiao, L. & Li, Y. 2015 The experimental study on treatment urban sewage by composite materials of zeolite, steel slag and activated carbon. *Non-Metallic Mines* **38**, 76–78.
- He, J., Huang, J., Valeo, C. & Chu, A. 2015 Water quality treatment efficacy model of porous concrete pavement. *Journal of Water Resource and Hydraulic Engineering* **4**, 115–124.
- Hettler, E. N. 2010 A Modified Elutriation Device to Measure Particle Settling Velocity in Urban Stormwater Runoff. PhD thesis, the faculty of the graduate school, University of Minnesota, Twin Cities, MN, USA.
- Kanazu, T., Matsumura, T., Nishiuchi, T. & Yamamoto, T. 2001 Effect of simulated acid rain on deterioration of concrete. *Water Air and Soil Pollution* **130**, 1481–1486.
- Kim, H. H. & Park, C. G. 2016 Plant growth and water purification of porous vegetation concrete formed of blast furnace slag, natural jute fiber and styrene butadiene latex. *Sustainability* **8**, 386 (1–16).
- Li, C., Dong, Y., Lei, Y., Wu, D. & Xu, P. 2015 Removal of low concentration nutrients in hydroponic wetlands integrated with zeolite and calcium silicate hydrate functional substrates. *Ecological Engineering* **82**, 442–450.
- Long, Y., Bing, Y., Zhang, Z., Cui, K., Pan, X., Yan, X., Li, B., Xie, S. & Guo, Q. 2017 Influence of plantation on microbial community in porous concrete treating polluted surface water. *International Biodeterioration & Biodegradation* **117**, 8–13.
- Lukasz, D., Krawczyk, P. S., Sebastian, M., Adamska, D., Sobczak, A., Lipinski, L., Burec-Drewniak, W. & Skłodowska, A. 2016 Physiological and metagenomic analyses of microbial mats involved in self-purification of mine waters contaminated with heavy metals. *Frontiers in Microbiology* **7**, 1252 (1–18).
- Maniquiz, M. C., Soyung, L. & Leehyung, K. 2010 Multiple linear regression models of urban runoff pollutant load and event mean concentration considering rainfall variables. *Journal of Environmental Sciences* **22**, 946–952.
- Nouha, K., Kumar, R. S. & Tyagi, R. D. 2016 Heavy metals removal from wastewater using extracellular polymeric substances produced by *Cloacibacterium normanense* in wastewater sludge supplemented with crude glycerol and study of extracellular polymeric substances extraction by different methods. *Bioresource Technology* **212**, 120–129.
- Pak, D., Chang, W. & Hong, S. 2002 Use of natural zeolite to enhance nitrification in biofilter. *Environmental Technology* **23**, 791–798.
- Park, S. J., Oh, J. W. & Yoon, T. I. 2004 The role of powdered zeolite and activated carbon carriers on nitrification in activated sludge with inhibitory materials. *Process Biochemistry* **39**, 211–219.
- Saeed, T., Muntaha, S., Rashid, M., Sun, G. & Hasnat, A. 2018 Industrial wastewater treatment in constructed wetlands packed with construction materials and agricultural by-products. *Journal of Cleaner Production* **189**, 442–453.

- Syafalni, S., Abustan, I., Dahlan, I. & Dahlan, I. 2012 Treatment of dye wastewater using granular activated carbon and zeolite filter. *Modern Applied Science* **6**, 37–51.
- Tian, Q., Ong, S. K., Xie, X., Li, F., Zhu, Y., Wang, F. R. & Yang, B. 2016 Enhanced phosphorus recovery and biofilm microbial community changes in an alternating anaerobic/aerobic biofilter. *Chemosphere* **144**, 1797–1806.
- Wang, X. & Jiao, J. J. 2004 Analysis of soil consolidation by vertical drains with double porosity model. *International Journal for Numerical and Analytical Methods in Geomechanics* **28**, 1385–1400.
- Welz, P. J., Mbasha, W., Smith, I., Holtman, G., Terblanche, G., Roes-Hill, M. L. & Haldenwang, R. 2018 The influence of grain physicochemistry and biomass on hydraulic conductivity in sand-filled treatment wetlands. *Ecological Engineering* **116**, 21–30.
- Wu, D. J., Wang, Y. J., Zhai, X. D. & Cheng, X. X. 2013 A pilot-scale study on start-up and operation of biofilter with composite media. *Applied Mechanics & Materials* **361–363**, 730–735.
- Xiao, B., Liu, C., Liu, J. & Guo, X. 2015 Evaluation of the microbial cell structure damages in alkaline pretreatment of waste activated sludge. *Bioresource Technology* **196**, 109–115.
- Yoo, H., Ahn, K., Lee, H., Lee, K., Kwak, Y. & Song, K. 1999 Nitrogen removal from synthetic wastewater by simultaneous nitrification and denitrification (SND) via nitrite in an intermittently reactor. *Water Research* **33**, 145–154.
- Zhang, R., Kanemaru, K. & Nakazawa, T. 2015 Purification of river water quality using precast porous concrete products. *Journal of Advanced Concrete Technology* **13**, 163–168.
- Zhao, H., Li, X., Wang, X. & Tian, D. 2010 Grain size distribution of road-deposited sediment and its contribution to heavy metal pollution in urban runoff in Beijing, China. *Journal of Hazardous Materials* **183**, 203–210.

First received 20 July 2018; accepted in revised form 12 December 2018. Available online 28 December 2018