

The Effect of Different Artificial Soil on Urban Non-Point Source Pollution Reduction in the Artificial Rapid Infiltration System

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Abstract

The non-point source pollution posed great risks to the urban water environment which has aroused great concerns. Artificial rapid infiltration systems have been widely used in sewage treatment, which have great environmental and economic values. This study investigated the potential of utilizing artificial rapid infiltration systems on the reduction of urban non-point source pollution. The obtained results showed that the components and composition of artificial soils were vital to the operational performance. The mixture of natural soil, coarse sand and zeolite was ideal for the construction of artificial soils. The permeability coefficient of soils could be improved to 0.166 cm/min at the optimized ratio of 1:1:0.05 (natural soil, coarse sand and zeolite). Also, high removal efficiency for the typical pollutants in rain runoffs (i.e. COD, NH_4^+ -N, TN and TP) could be simultaneous obtained which was above 74% in the artificial rapid infiltration systems. The results demonstrated the effectiveness on the reduction of urban non-point pollution by optimized artificial rapid infiltration system.

Keywords

Non-Point Source Pollution, Artificial Rapid Infiltration System, Permeability Coefficient, Zeolite, Pollutants, Removal Efficiency

1. Introduction

The pollution sources of urban water environment are mainly classified into point source pollution (derived from industrial and domestic wastewater) and

non-point source pollution. Currently, the industrial and domestic wastewater is commonly directly discharged into wastewater treatment plants (WWTPs). Therefore, the point source pollution has been effectively controlled. The non-point source pollution is becoming the key problem in addressing the issue of urban water environment. The non-point source is a dispersed pollution in urban area caused by rainfall runoffs. The contaminants are mainly consisted of organics, eutrophication substances (nitrogen and phosphorus) and suspended solids (Li et al., 2017; Zhuang et al., 2015; Huang et al., 2010). They would enter into surface water and groundwater from atmosphere, grounds and soils through leaching and scouring and ultimately cause serious water environment pollution (Qin et al., 2016). In China, the urban area is densely populated with anthropogenic activities while most of surface is impermeable. The non-point pollution caused by rainfalls is more severe. For example, Jing et al. found that the concentrations of total nitrogen and total phosphorus in storm pipelines of Beijing were respectively 3.2 and 25-folds higher than that of the natural rainfalls (Jing et al., 2013). Moreover, the natural environments and rainfall processes are varied in different cities. In Beijing, the concentrations of suspended solids, chemical oxygen demand, total phosphorus and total nitrogen were respectively 3.9, 13.6, 3.3 and 16-folds higher than that of the V class of Environmental Quality Standard for Surface Water. However, they were respectively 1.7, 8.4, 1.4 and 3.9 folds in Shanghai, correspondingly (Li et al., 2006; Ding & Liu, 2011). Therefore, the urban non-point source pollution is characteristic of high intensity and wide space-time variation which make its effective control quite difficult (Qin et al., 2016; Huang & Xiang, 2014; Coppola et al., 2014).

Currently, the main measures taken for urban non-point source pollution control are through vegetation, percolation, wetland retention systems, and so on (Feng et al., 2016; Li et al., 2018; Lai et al., 2016). However, the application of these strategies was frequently restricted by the availability of lands, risks of ecological and environmental pollution, and the high costs of maintenance and management. Therefore, they are usually applied as auxiliary measures rather than the key control measures to control urban non-point source pollution.

The natural soils have the ability of physical retention, chemical precipitation, physicochemical adsorption and exchange due to the specific composition and properties of soil minerals. Moreover, they also provide necessary habitats for various microorganisms. It seems to be a good alternative to effectively and economically decompose and purify the organic and inorganic substances in the wastewater (Liu et al., 2018). However, the suitable permeability and high biological activity (commonly correlated with the soil fertility) were required for the efficient pollutants removal by soil treatment which was hard to meet simultaneously in natural environments. Artificial interference is usually necessary to make the natural soil be an ideal medium for sewage treatment.

The artificial rapid filtration systems mainly enhance the treatment efficiency of wastewater by improving the physical properties of original natural soils (i.e.

permeability) (Huang, 2005). The basic principles for constructing artificial rapid filtration systems mainly follow three aspects: 1) good permeability 2) high treatment efficiency, and 3) low costs. The typical strategies to improve the permeability of natural soil were accomplished by the addition of coarse sand, zeolite and so on (Wang & Wang, 2011). Among them, zeolite has been reported to improve the permeability of soil effectively and simultaneously remove ammonia nitrogen, heavy metals and organic pollutants (Boostani et al., 2017; Aljerf, 2018; Wang et al., 2018). For example, the results obtained by Rozic (Rozić et al., 2000) show that the adsorption capacity of zeolite for ammonia nitrogen was about 2 times higher than that of clay. Xue et al. also confirmed the positive effects of artificial wetland systems amended with zeolite on ammonia nitrogen removal. The average removal efficiency of ammonia nitrogen in rainstorm water was up to 85% which could reduce the runoff pollution with short residence time (Xue et al., 2003).

Therefore, the main aim of this study is to investigate the performance of artificial rapid filtration systems on the reduction of urban non-point source in Suzhou optimizing the composition and characteristics of organic soils with different additives. Moreover, the main mechanisms for its promotion on pollutants removal are also explored.

2. Materials and Methods

2.1. Materials

The soils and coarse sand was obtained in the local regions of Suzhou, Jiangsu, China. The zeolites used in this study are synthetic 13X4A zeolites. The main characteristics are as follows: specific surface area: 200 - 300 m²/g, K⁺ exchange capacity: 420 mg/g, adsorption capacity for H₂O: 20 g/100 g, specific gravity: 2.6%, crushing strength: 50 - 60 n/particle, bulk density: 0.8 - 0.9 g/cm³ and the particle diameter: 1.5 - 1.8 mm.

According to the previous monitoring results of surface runoff water in Suzhou, the main pollutants are organic pollutants, eutrophication substances and suspended solids (Huang, 2005). Therefore, the concentrations of chemical oxygen demand (COD), total phosphorus (TP), total nitrogen (TN) and ammonia nitrogen (NH₄⁺-N) were set as the main indices. The wastewater is synthetic to simulate the natural surface runoffs in Suzhou and the main characteristics are shown in Table 1.

2.2. Correlations of Soil Compositions with the Performance of Artificial Rapid Infiltration System

The natural soil, coarse sand and zeolite were mixed well with different mixing ratios (shown in Table 2) and then filled into the polymethyl methacrylate (PMMA) soil columns.

The PMMA soil column was shown as Figure 1. The inner diameter of plexiglass soil column is 10 cm and the thickness of soil layer is 30 cm. The experiment

Table 1. Characteristics of synthetic runoffs.

Pollutants	COD	TP	TN	NH ₄ ⁺ -N
Concentration (mg/L)	500 ± 10	1 ± 0.02	20 ± 2	5 ± 0.4

Table 2. Characteristics of artificial soils with different mixing ratios.

Soil:Sand	1:4	1:3	1:2	1:1
Zeolite				
5%	1#	5#	9#	13#
10%	2#	6#	10#	14#
15%	3#	7#	11#	15#
20%	4#	8#	12#	16#

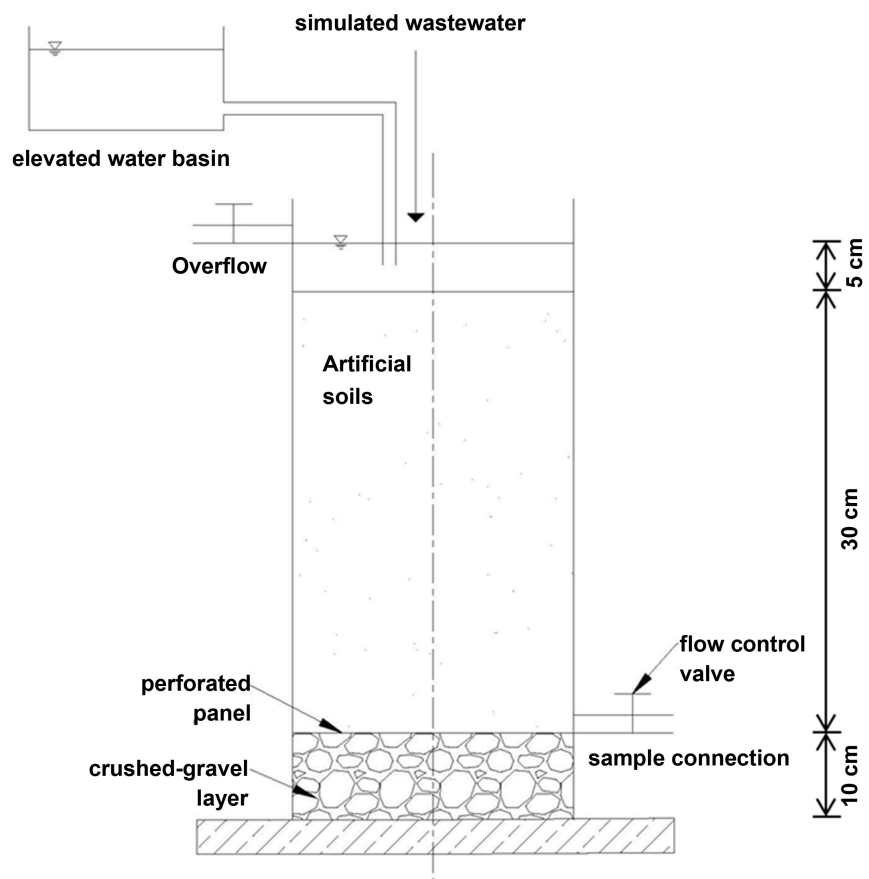


Figure 1. Reactor of artificial rapid infiltration system.

was carried out in indoor conditions for 35 d. The room temperature ranged from 20°C to 23°C while the water temperature ranges from 21°C to 24°C. The permeability and non-uniformity coefficient were firstly determined to test the specific requirements by artificial rapid infiltration system. Then the synthetic wastewater (mentioned in **Table 1**) was filtrated from the reactors and the concentrations of selected pollutants in effluents were analyzed to disclose the per-

formance of artificial rapid infiltration system on the reduction of non-point source pollution by runoffs.

2.3. Analytic Methods

The determinations of COD, TN, TP, NH_4^+ -N and SS were performed in accordance with standard methods (APHA, 1998). The measurement of permeability coefficient of artificial soil is according to Darcy's law (Equation (1)) (Huang, 2005).

$$Q = \frac{kA(h_1 - h_2)}{L} \quad (1)$$

where k is the permeability coefficient; A is the tested area.

The non-uniformity coefficient of artificial soils was obtained by screening test. 300 g of mixture were firstly taken and dried in a constant temperature box at 105°C. Then 100 g of them was weighed for screening tests with a series of screens of 2.00 mm (10 meshes), 1.43 mm (14 meshes), 1.00 mm (18 meshes), 0.45 mm (40 meshes), 0.10 mm (150 meshes) and 0.063 mm (250 meshes). The non-uniformity coefficient was calculated based on the grading distribution curve: $K_{80} = d_{80}/d_{10}$. The d_{80} and d_{10} represents the pore sized of screens that allow 80% and 10% amounts of particles to filtrate.

3. Results and Discussion

3.1. Permeability and Non-Uniformity with Different Artificial Soil Compositions

The permeability is one of the most significant features in evaluating the artificial rapid infiltration system. The basic requirement for the permeability coefficient (K) of an effective rapid soil infiltration system should be no less than 0.025 cm/min (Huang, 2005). The permeability coefficient of natural soils in Suzhou was only 2.17×10^{-4} cm/min which was far below the required limits and thus it was suitable for the construction of rapid infiltration system directly. However, the permeability coefficient was remarkably increased due to the addition of coarse sand and zeolite and it was highly correlated with the mixing ratio. As shown in Table 3, the reactors with high addition of coarse sand contributed to the permeability most (Reactors 1 - 4#). However, the sand was rich of inorganics which would affect the soil fertility and then the abundances of active microorganisms. The balance of permeability and soil fertility should be maintained. Considering these, the ratio of natural soil and sand should be set as 1:2 to 1:1 with proper addition of zeolite. Particularly, the permeability coefficient in reactor 13# with the mixture of 1:1:0.15 was up to 0.1660 cm/min which far exceeded the requirement of 0.025 cm/min.

Besides, the particle gradation level of artificial soils was also important to the final application which could be reflected by the non-uniformity coefficient K_{80} . The higher K_{80} indicated the inhomogeneous distribution of mixture which was disadvantageous to the performance of percolation.

Table 3. The permeability and non-uniformity coefficient in different reactors.

Reactor	K (cm/min)	K_{80}	Reactor	K (cm/min)	K_{80}
1#	0.1409	7.55	9#	0.0126	7.76
2#	0.0966	7.64	10#	0.0832	7.42
3#	0.1317	7.57	11#	0.0297	7.67
4#	0.3864	7.38	12#	0.0208	7.86
5#	0.0198	7.60	13#	0.1660	7.32
6#	0.0081	7.73	14#	0.0594	7.50
7#	0.0067	7.92	15#	0.0014	8.36
8#	0.0124	7.86	16#	0.0011	8.12

Further analysis showed that the permeability coefficient increases with the decrease of the non-uniformity coefficient (as shown in **Figure 2**). The permeability coefficient was negatively correlated with the non-uniformity coefficient which could be expressed as the following equation.

$$y = 7.1668x^{-0.0191} \quad R^2 = 0.8375 \quad (2)$$

The above results indicated that the particle gradation was one of the main factors affecting the permeability coefficient of artificial soil. By optimizing the mixing ratio of three different materials, the grading distribution level as well as permeability coefficient could be improved, which could stimulate the hydraulic loads of artificial soil rapid infiltration system for the reduction of non-point source pollution in urban areas.

3.2. Performance of Artificial Rapid Infiltration Systems on the Pollutants Removal

The removal efficiencies of various pollutants were shown in **Figure 3**. It can be seen that the removal efficiency of NH_4^+ -N could reach above 60% in all artificial soil columns (**Figure 3(A)**). Correspondingly, the TN removal was above 45% (**Figure 3(B)**). The reason may be mainly attributed to the presence of zeolites which has been reported to have a strong adsorption effect on ammonia nitrogen (RozÍc et al., 2000). The dynamic adsorption tests also showed that the adsorptive ability of NH_4^+ -N was improved by 1.15 - 10.92 mg/L and the effective adsorption time was increased by 50% in the artificial soil with 5% zeolite addition.

However, the removal of COD and TP varied greatly in the reactors with different artificial soil proportions. As shown in **Figure 3(C)**, the COD removal efficiency in reactors 1 - 4# was all less than 15%. It was mainly caused by the large permeability coefficient of artificial soil in reactors 1 - 4#. In the artificial rapid infiltration system, the removal of organics could be accomplished through mechanical filtration, adsorption and biological oxidation of microorganisms. The microbial degradation was considered as the main mechanism for organics removal. However, the organic matters must be first hydrolyzed before the microbial

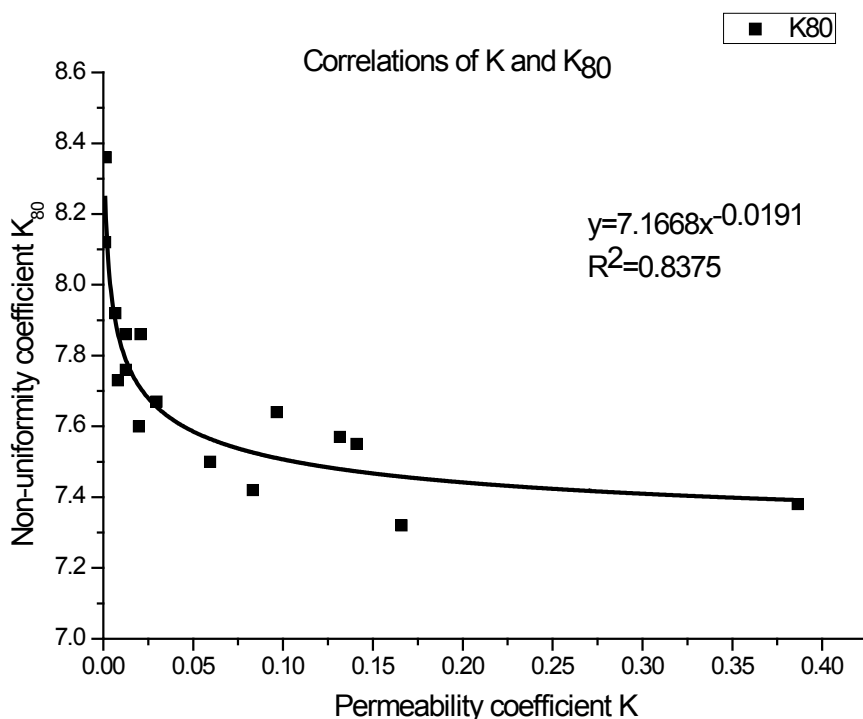


Figure 2. Correlations of permeability and non-uniformity coefficient.

absorption and utilization which required sufficient time. In the present study, the hydraulic retention time was short which was below 6 h considering the height of columns tested. Therefore, mechanical filtration and adsorption may become the main mechanism for the removal of organics removal in a short time. The treating performances in other artificial soil columns were all significantly higher than that of reactors 1 - 4#.

As to the TP removal, high removal efficiency was obtained in the reactors of 1# and 13#, which was respectively 78.8% and 74.1%. However, the lowest removal efficiency was observed in reactor 8# which was only 6.4%. The removal of TP in soils could be achieved via plants intake, soil adsorption, chemical precipitation and microbial accumulation (APHA, 1998). In this study, the plants intake could be excluded. Also, the biological accumulation of phosphorus by microorganisms was limited considering the short hydraulic retention time. The TP removal was also mainly attributed to the soils adsorption and chemical precipitation. However, they were also affected by numerous factors, such as the ions exchange capacity, pH, hydraulic loads and retention time in the systems (Reneau et al., 1989; Zhu et al., 2017; Semerci et al., 2010). Due to the different composition of artificial soils that resulted in the variations of physiochemical characteristics, the adsorption and chemical precipitation of phosphorus were affected in different degrees.

Considering the cumulative performance of pollutants removal in different reactors (as shown in **Figure 3(E)**), the 9#, 13# and 14# reactors showed promising application as artificial rapid infiltration system, particularly reactor 13#

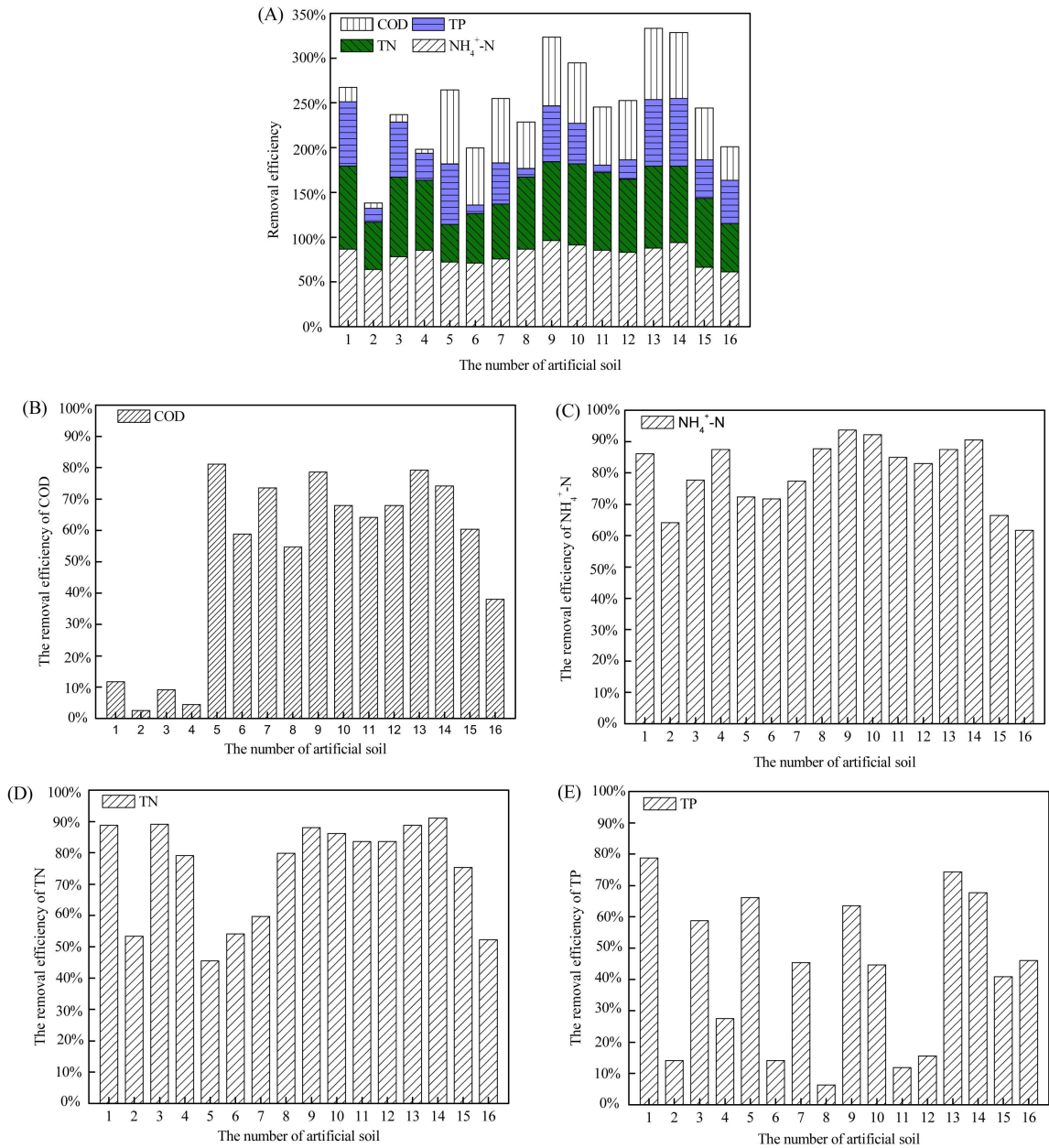


Figure 3. Removal rates of various pollutants with different artificial soils.

with a removal efficiency of 74% for all pollutants. Moreover, the permeability coefficient in reactor 13# met the requirement for the rapid infiltration system (not the case in 9# reactor) and the cost was also relatively economic considering the low zeolite consumption (5% versus the 10% in 14# reactor).

4. Conclusion

The natural soil, coarse sand and zeolite were suitable for the components of artificial rapid infiltration systems with optimized mixing ratios. With the ratio of 1:1:0.05 for natural soil, coarse sand and zeolite, the permeability coefficient of artificial soils was improved to 0.166 cm/min which met the requirement of ar-

tificial soil rapid infiltration systems. The removal efficiency of COD, NH_4^+ -N, TN and TP in synthetic rain runoffs was respectively 79.2%, 88.1%, 88.8% and 74.1% in the artificial rapid infiltration systems, which exhibited the feasibility and effectiveness on the reduction of urban non-point pollution.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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