Constructed Rapid Infiltration Systems for Urban Runoff Control: Influences of Medium Contents, Medium Depth and Hydraulic Load Cycle

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Abstract. The constructed rapid infiltration system (CRIS) has been widely used in urban stormwater management. However, limited knowledge has been acquired for the selection and optimization of mediums in CRIS. In this paper, the performance of CRIS was improved by different contents of natural soil, natural sand and zeolite. Permeability coefficient (K), uniformity coefficient (K_{80}) and pollutants removal efficiencies were used to evaluate the influences of medium contents on the operation of CRIS in static test. Using the best medium contents, the effects of medium depth and hydraulic load cycle on CRIS performance were further investigated. The result shows that the best and cost-effective permeability coefficient (0.166 cm/min) and high pollutant removal efficiency (> 70%) were obtained when the ratio of sand : soil : zeolite was 47.5% : 47.5% : 5%. The pollutant removal efficiency in the surface layer (0 - 30 cm) was significantly higher than that in bottom (50 - 80 cm). Higher pollutants removal were gotten at hydraulic load cycle of submergencing for 2 hours and drying for 10 hours. The main factor affecting the removal of COD and ammonia nitrogen was the change of aerobic environment in CRIS which mainly relied on biofilms to degrade and adsorb pollutants.

1. Introduction

The amount of pollutants from urban runoff has gradually increased with fast urbanization, which would cause severe damage to water environment in urban area [1]. Land infiltration system is a typical green infrastructure [2]. Because of its low operating cost, good environmental benefits, and slight ecological impact, it has been used in urban runoff management recently. Nevertheless, the reduction of soil permeability caused by clogging affects the performance of infiltration system [3]. Therefore, it is important to find effective ways, such as medium improvement and operation optimization, to solve these problems in land infiltration system.

Constructed rapid infiltration system (CRIS) is developed based on traditional land infiltration system [4-6]. Compared with land infiltration systems used in wastewater treatment, multi-medium with high permeability and strong adsorption capacity such as natural sand, ceramic particles, gangue, and zeolite were used to replace part of the natural soil in order to improve system performance [7].

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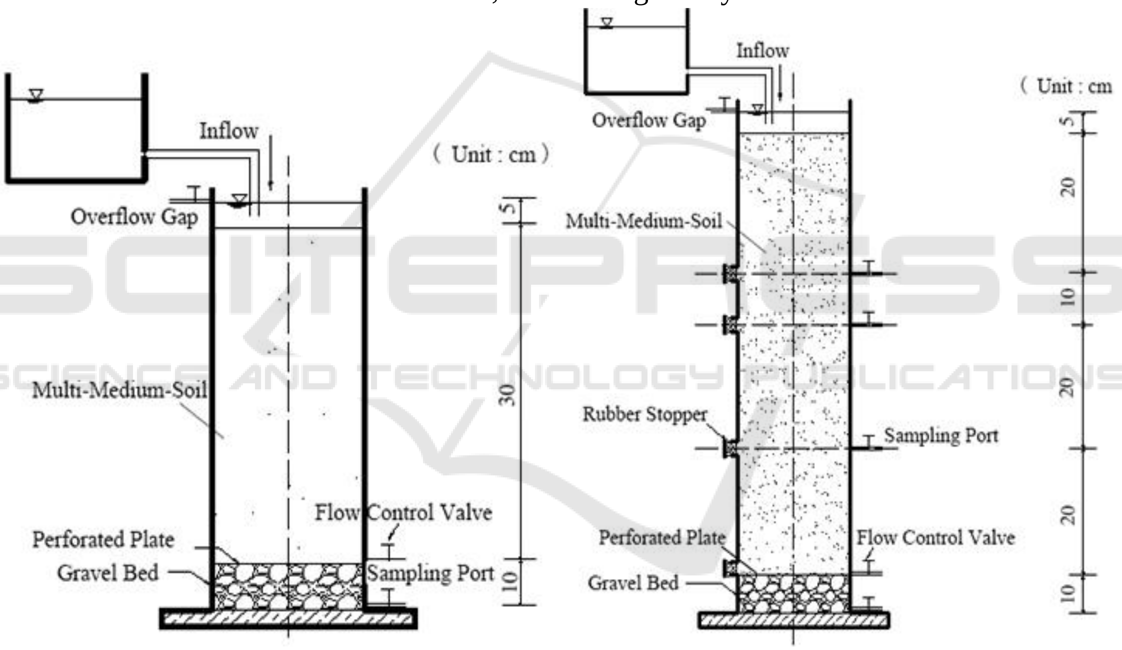
Current researches have confirmed that the use of particulate filter and adsorbing materials could increase hydraulic load and enrich pollutants removal [8]. However, limited knowledge has been acquired of the selection of mediums and optimization of CRIS during urban runoff control.

In view of this, the objective of this paper is to investigate the influences of medium contents, medium depth and hydraulic load cycle on the pollutants removal by CRIS. Different contents of natural soil, sand and zeolite were used in CRIS. Permeability coefficient, nonuniformity coefficient, and pollutant removal efficiencies were used to evaluate the influences of medium contents on the operation of CRIS. Using the best medium contents, the effects of medium depth and hydraulic load cycle on CRIS performance were further investigated.

2. Materials and methods

2.1. Experimental set-up

The experiments were conducted in the CRIS columns for static test and dynamic test, respectively (Figure 1). The diameter of the CRIS columns was 10 cm. The height of the medium layer of CRIS columns in static test was 30 cm, and the height in dynamic test was 80 cm.



(A) (B)

Figure 1. CRIS columns in static test (A) and dynamic test (B).

2.2. Materials

The columns were filled with different mediums that were uniformly mixed with local natural soil, coarse sand, and zeolite. Natural soil was from surface silty clay in southern Jiangsu province, and the maximum permeability coefficient was 0.003 m/d. Coarse sand and zeolite were purchased locally. The particle size of zeolite was 1.5 - 1.8 mm, which had a specific surface area 200 - 300 m^2/g.

The urban runoff used in the test was synthesized with potassium hydrogen phthalate ($HOOCC_6H_4COOK$), glucose ($C_6H_{12}O_6$), ammonium sulfate ($(NH_4)_2SO_4$), potassium dihydrogen phosphate (KH_2PO_4) and potassium nitrate (KNO_3). The water quality of runoff was determined according to the monitoring results of rainfall runoff in a certain city in Southern Jiangsu, in which

COD was 500 ± 10 mg/L, NH_4^+-N was 5 ± 0.4 mg/L, TN was 20 ± 2 mg/L, and TP was 1 ± 0.02 mg/L.

2.3. Experimental procedure

Influence of medium content on CRIS performance. Four different volume percentages of zeolites such as 5%, 10%, 15%, and 20% were set in CRIS. Meanwhile, the volume ratios of natural soil and coarse sand were respectively set to 1 : 4, 1 : 3, 1 : 2, and 1 : 1. Thus, 16 kinds of mediums were conducted in static test (Table 1). Permeability coefficient, uniformity coefficient (K_{80}), and pollutants removal efficiency were measured to evaluate the influences of medium contents in static test.

Table 1. Contents of different mediums in CRIS (in volume, %).

No.	1	2	3	4	5	6	7	8
Natural Soil	19.00	18.00	17.00	16.00	23.75	22.50	21.25	20.00
Coarse Sand	76.00	72.00	68.00	64.00	71.25	67.50	63.75	60.00
Zeolite	5.00	10.00	15.00	20.00	5.00	10.00	15.00	20.00
No.	9	10	11	12	13	14	15	16
Natural Soil	31.67	30.00	28.33	26.67	47.50	45.00	42.50	40.00
Coarse Sand	63.33	60.00	56.67	53.33	47.50	45.00	42.50	40.00
Zeolite	5.00	10.00	15.00	20.00	5.00	10.00	15.00	20.00

Influence of medium depth and hydraulic load cycle on CRIS performance. Five sampling ports were set in CRIS at the depth of 20, 30, 50, 70, and 80 cm to investigate the impacts of medium depth on CRIS performance in dynamic test. Four operating conditions, including the ratio of water submerging time and drying time of 1 : 5 and 1 : 8 while water submerging time was set by 2h and 4h, were respectively determined to examine the water quality at the end of land infiltration system. The test operating conditions for the study of hydraulic load cycle effects are shown in Table 2. The depth of submerging in the upper part of the layer was ensured to be 5 cm, so that the test columns could be maintained at constant head with the temperature from 19 °C to 24 °C in water.

Table 2. Test conditions setting for different hydraulic load cycle.

No.	1	2	3	4
Submerging Time (h)	2	4	2	4
Drying Time (h)	10	20	16	32

2.4. Analytical methods

The permeability coefficient (K) and the nonuniformity coefficient (K_{80}) were determined by the Standard Methods. The procedures for determining COD, TN, NH_4^+-N and TP were detailed in the Standard Methods[9]. The pH and DO values were determined with pH meter (HACH-sension2) and portable dissolved oxygen meter (HACH-HQ30d), respectively[10]. The temperature was measured with a thermometer. All assays were performed in triplicate, an analysis of variance (ANOVA) was used to test the significance of the results and $p < 0.05$ was considered to be statistically significant.

3. Results and discussion

3.1. Selection and optimization of multi-medium proportion of CRIS

Figure 2 showed the static removal effect of CRIS on various pollutants in rainfall runoff under different medium contents. The removal of COD and TP varied greatly in different reactors. However, the presence of zeolite in CRIS effectively improved the adsorption of nitrogen. The removal efficiency of NH_4^+-N from all multi-medium-soil can reach over 60%, and the removal efficiencies of

TN were also above 45%, which was significantly higher than that of COD and TP. By comprehensive evaluation of the removal efficiency of all typical pollutants, the reactors with No. 9, 13, and 14 soil medium were preferred in CRISs (The pollutant removal efficiencies were > 80% for NH_4^+-N and TN, and > 60% for COD and TP).

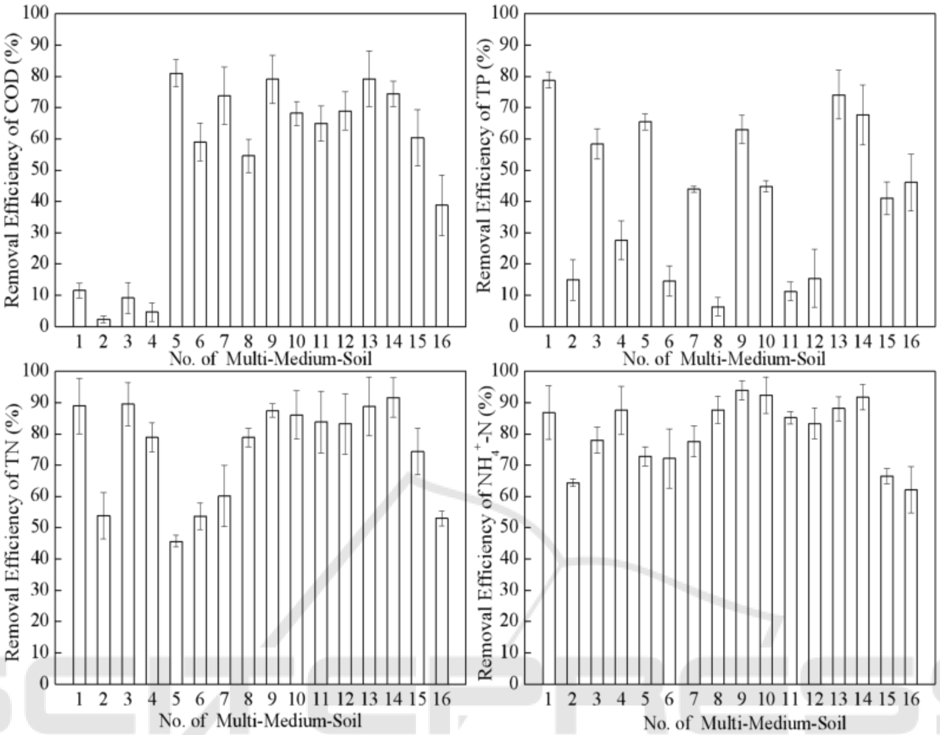


Figure 2. Effects of CRIS on the static removal of various pollutants in rainfall runoff under different medium contents.

Figure 3 shows the nonuniformity coefficient K_{80} and the permeability coefficient K of the matrix under different medium contents. K_{80} of the matrix from the mediums with different ratios ranged from 7.32 to 8.36, and K ranged 0.011 to 0.166 cm/min. Further analysis indicated that the negative correlation between the permeability coefficient and the nonuniformity coefficient was evident.

It was also found that the particle grading condition was the main factor affecting the permeability coefficient of the mixed matrix. By changing the composition of three different materials and grades of infiltration medium, the permeability coefficient can be changed with the same proportions of medium materials. The permeability coefficient of the infiltration medium was increased, and thus the hydraulic load of the CRIS can be improved.

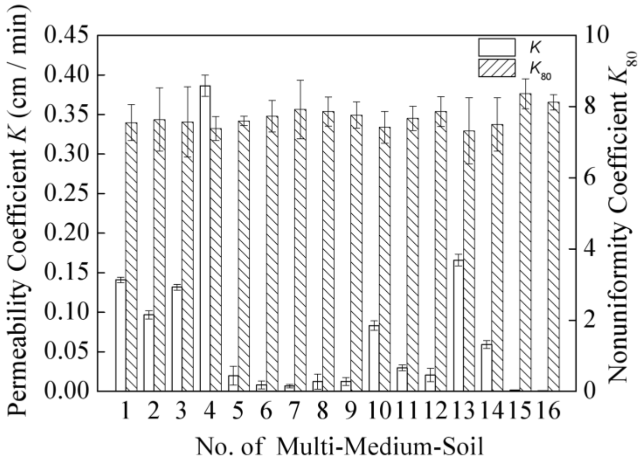


Figure 3. Nonuniformity coefficient K_{80} and the permeability coefficient K of the matrix under different medium contents.

The permeability coefficient of the No. 13 soil medium was 0.1660 cm/min, which was much higher than 0.0126 cm/min of No. 9 and 0.0594 cm/min of No. 14. Meanwhile, its removal efficiency of COD, NH_4^+-N, TN, and TP reached respectively 79.20%, 88.09%, 88.76%, and 74.11%, which was also the highest in all the three reactors. The best and cost-effective permeability coefficient (0.166 cm/min) and high pollutant removal efficiency (> 70%) were obtained when the ratio of sand : soil : zeolite was 47.5% : 47.5% : 5%.

3.2. Influence of different medium depth on pollutants degradation

The thickness of the soil layer was an important parameter in the design of CRIS. To achieve better treatment effects, the thickness of the soil layer should not be too thin. Meanwhile, it should not be too thick due to the terrain conditions and the difficulty of construction. Figure 4 shows the treatment effects of medium depth (20, 30, 50, 70 and 80 cm) on various contaminants.

As can be seen from Figure 4, the removal efficiency of contaminants incremented with the increase of medium depth in CRIS. The removal efficiency of NH_4^+-N, TN, and COD showed that the pollutants removal efficiency in the upper of CRIS (30 - 50 cm) was significantly higher than that in the lower part except TP. In general, increasing medium depth in certain range can enhance the treatment effects of CRIS and ultimately improve the quality of the effluent water. However, a plateau would be observed with the excessive increase of medium depth which was quite uneconomic.

The removal of organic contaminants by CRIS was mainly caused by mechanical interception, adsorption and biodegradation. The organic contaminants in the influent were all soluble, so they were mainly removed by the adsorption and biodegradation of the biofilm on the surface of the multi-medium material.

The mechanism for the nitrogen removal included volatilization, adsorption, nitrification, and denitrification in CRIS. The volatilization is very weak with pH ranged from 6.5 to 7.5 in this test. The zeolites configured in CRIS had a strong NH_4^+-N selective adsorption capacity and played important roles in the initial nitrogen removal. Meanwhile, the dynamic test results showed that the degradation of nitrogen by CRIS kept at a high level, which indicating the major role of nitrification and denitrification processes for nitrogen reduction. The short of oxygen supply was supposed to be the main reason that limited the NH_4^+-N removal in CRIS. The surface reoxygenation in CRIS was advantageous to the increase of nitrifying bacteria abundances and activities, which was in accordance with the efficient nitrogen removal in surface layer (30 cm). It further confirmed the fact from another aspect that microbial nitrification played an important role in the nitrogen removal from CRIS.

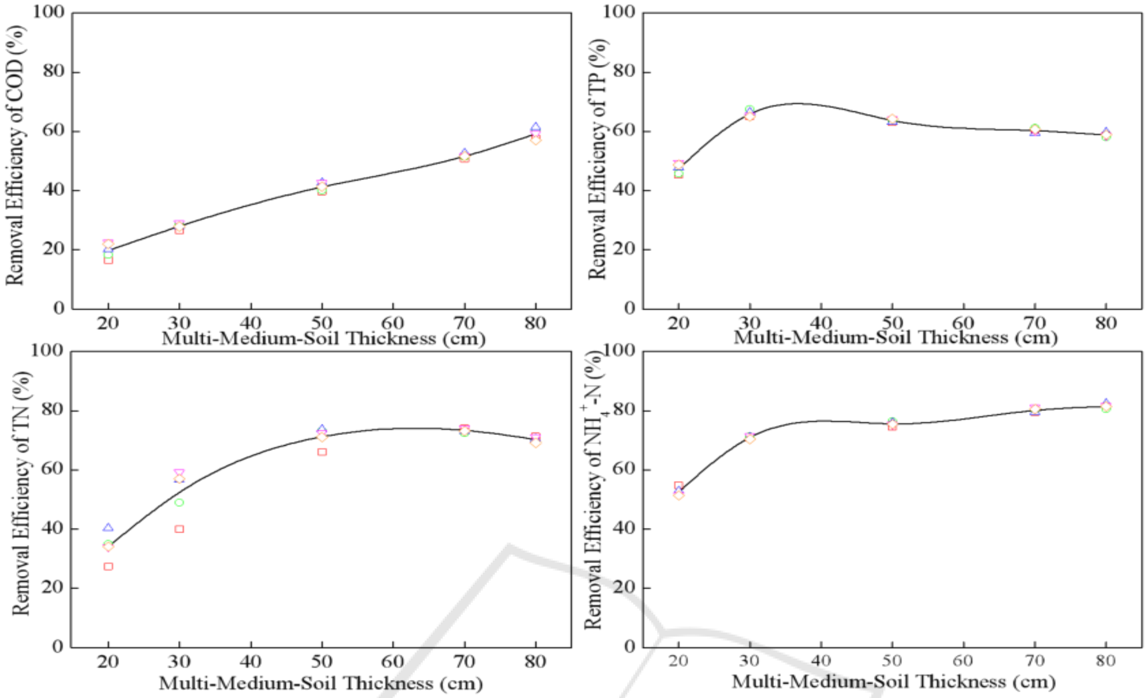


Figure 4. Removal efficiency of various contaminants with different medium depth.

The removal efficiency of TP was declined with the increase of medium depth. It may be attributed to the release of phosphorus under anaerobic conditions by related microorganisms. The surface layer (30 cm) in CRIS was in aerobic conditions. Microorganisms could absorb phosphorus from water efficiently, and thus the removal efficiency of TP gradually increased. However, in deep layer (50 - 80 cm), the phosphorus release increased significantly by the microorganism due to the scarcity of DO, resulting in a decrease of TP removal efficiency.

3.3. Effects of different hydraulic load cycles on the pollutants degradation

It can be seen from Figure 5 that the removal efficiencies of COD and NH_4^+-N were in the order of column 1> column 2> column 4> column 3. It can be mainly explained via the influence of different submerging-drying time cycles on the internal aerobic environment and microbial community in CRIS. The submerging-drying time ratio of column 1 and column 2 was 1 : 5, while the submerging-drying time radio of column 3 and column 4 was 1 : 8. Since the DO of CRIS mainly depended on its saturation in influent . The reoxygenation of the surface medium was more complete and thus was beneficial to the formation of the aerobic environment for columns 1 and 2 with higher submerging-drying frequency while the ability of COD degradation and NH_4^+-N nitrification were stronger. In addition, the cycle of submerging-drying contributed to the stability of the internal aerobic environment of the CRIS, which was also the key to the removal of COD and NH_4^+-N. Compared with other hydraulic load cycles, the submerging time of 2 hours and the drying time of 10 hours created a more stable microscopic aerobic environment. However, the submerging time of 2 hours and the drying time of 16 hours may cause drastic changes in aerobic environment of microorganisms inside the CRIS, resulting in the worst removal efficiency of COD and NH_4^+-N.

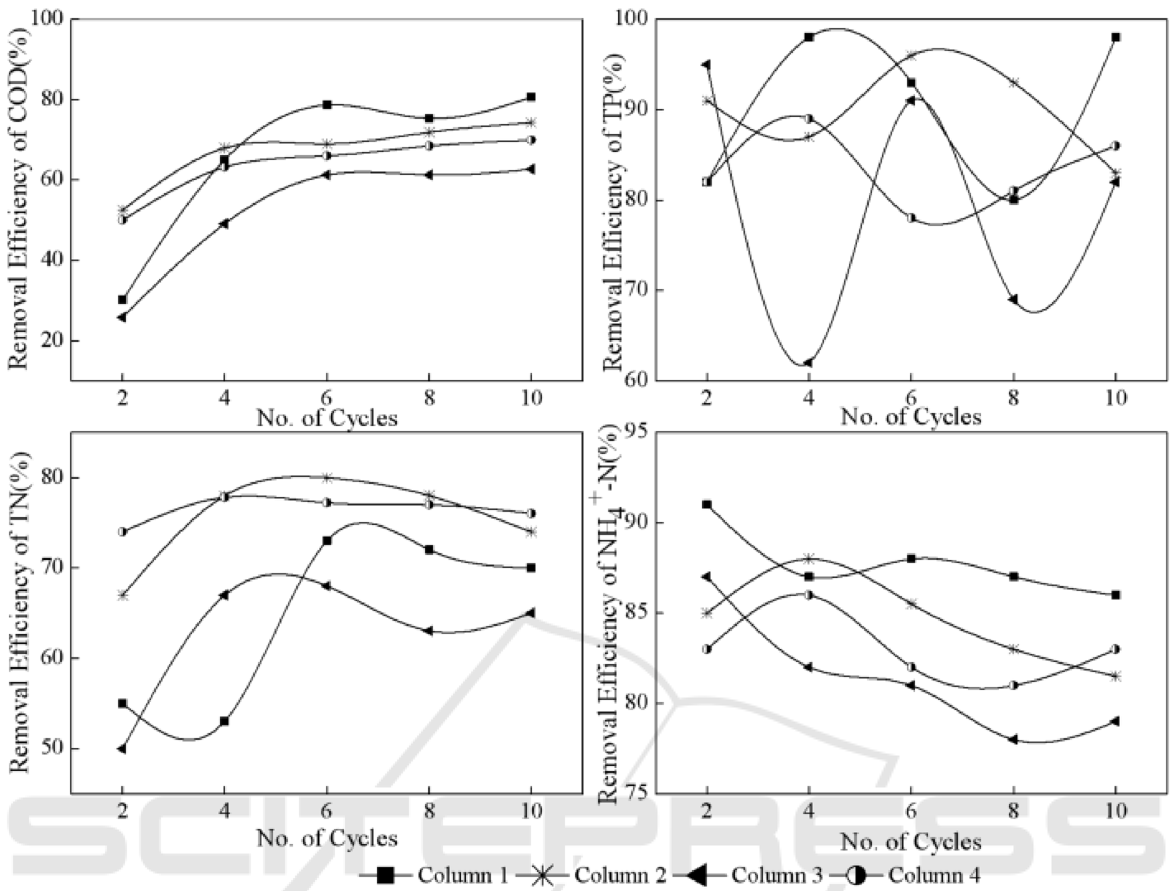


Figure 5. Removal efficiency of pollutants under different hydraulic load cycles.

The nitrogen in the test water was mainly in the form of NO_3^- and NH_4^+. The concentration of NH_4^+ was 5 mg/L. The removal mechanism of TN by CRIS could mainly be attributed to the combined effects of nitrification and denitrification considering the characteristics of influent. It can be seen from Figure 5 that the removal efficiency of TN was better in column 4 and 2. The long submerging time in column 4 and 2 may prevent the transport of oxygen in the topsoil layer and make the denitrification fully performed, which resulted in the higher removal efficiency of TN. The above results showed that the smaller the submerging-drying ratio was, the more favorable performance of TN removal could be achieved.

It can also be seen from Figure 5 that under different hydraulic load cycles, the removal efficiencies of TP in CRIS were all over 60%. However, the removal efficiencies were varied significantly during the whole operating time which required further study in details.

4. Conclusions

CRIS was an effective strategy for the pollutants control of urban runoff. The best and cost-effective permeability coefficient (0.166 cm/min) and high pollutant removal efficiency (> 70%) were obtained when the ratio of sand : soil : zeolite was 47.5% : 47.5% : 5%.The pollutants removal in the surface layer (0 - 30 cm) of CRIS was significantly higher than that in the deeper layer (50 - 80 cm). Higher pollutants removal were obtained at the hydraulic load cycle of 2 hours submergencing and 10 hours drying. Under such conditions, the removal rates of COD, NH_4^+ N, TN, and TP reached 80%, 85%, 65%, and 90%, respectively. The adsorption and degradation of pollutants on multi-medium surface biofilm were the main mechanisms for the efficient pollutants removal in

CRIS and the variation of aerobic environment was important to the removal of COD and nitrogen.

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