Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2013.767217

51 (2013) 6592–6600
October

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An effective method for decentralized wastewater treatment: addition of polyurethane foam to subsurface wastewater infiltration system

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Received 30 October 2012; Accepted 13 January 2013

ABSTRACT

Subsurface wastewater infiltration system (SWIS) is widely used in the treatment of wastewater, which is very effective in purification of the sewage and improving its quality, but it is known to be prone to clogging. A laboratory-scale research was therefore proceeded to solve the clogging problem in this study. The experimental results showed that it could significantly enhance the ability of anti-clogging with the addition of polyurethane foam content of 6‰ (mass mixture ratio) to the soil column (R3), which was proved to be the optimum composition and worked successfully with a hydraulic loading less than 26 cm/d for over 4 months. The saturated permeability of the soil columns increased along with the increasing concentration of polyurethane foam. The average removal efficiencies for chemical oxygen demand, NH_3–N, TN, and TP were 85, 98, 62, and 99%, respectively, at a hydraulic loading value less than 30 cm/d treated by R3 column. The saturated permeability rate of the control column (R1) was only 1.8 cm/d leading to the clogging after operation of SWIS for 20 weeks, while other three columns (columns 2, 3, and 4 have different packing volumes of polyurethane foam: 3, 6, and 8‰) were not clogged with the saturated permeability rate of 17.3, 46.3, and 84.1 cm/d, respectively.

Keywords: Subsurface wastewater infiltration system (SWIS); Wastewater; Saturated permeability; Polyurethane foam; Clogging

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1. Introduction

The discharge amount of wastewater in China exceeded 65.21 billion tonnes in 2011 [1]. The application of municipal sewage treatment plants were limited to the high cost of capital construction and operation [2]. As a result, lack of water resources affects the future development and the people life in the country seriously [3]. Furthermore, groundwater is of critical shortage due to the overuse by residents and the environmental pollution [4]. In order to seek alternative methods to conventional systems, those with minimum or null energy cost, simple operational

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and maintenance procedures and high treatment efficiency when faced with large fluctuations in the influent load are preferentially considered.

The subsurface wastewater infiltration system (SWIS), as one of land treatment systems, is an ecological process used for decentralized domestic wastewater treatment, especially in villages, small towns or scattered residential areas. Compared with the conventional methods, such as activated sludge method and biofilm processes, SWIS has better performance in the removal of organic substances and phosphorus. In addition, it is of lower cost of construction and operation, simple management and maintenance [5–7].

In recent years, many studies that were focus on the SWIS have been carried out, such as construction styles of the SWIS [8], filled soil [9], hydraulic loading rate, nitrogen and phosphorus removal effect [4,9,10], and eco-environmental response assessment [11,12]. However, soil leach-fields are prone to clogging which generally causes failure in SWIS because of the reduced permeability rate, leading to the bad quality of effluent. Clogging mainly includes physical clogging and bio-clogging. Physical clogging generally produces due to the suspended solids (SS) in sewage, but septic tanks always removed most of the SS. Bio-clogging is frequently resulted from the excessive growth of bacteria, which blocks the flow paths in soil matrix [13], microbial cell mass and extracelluar polymeric substances on the surface of the soil which made the soil pores narrow and then blocked [14,15]. The probability of bio-clogging increases along with the operation time of SWIS and the quantity of sewage treatment. A lot of studies that were focused on the efficiency of soils and soils added with other materials into the SWIS to avoid clogging were carried out [16–18]. As was known to all, the liquid could move in the interstices of insulation or other porous material as a result of surface tension through the capillary action. Usually, polyurethane foam is used as a suspension filler in the sewage treatment for its characteristics of its big porosity, large water amount, large specific surface area, good flexibility, strong water absorption, and corrosion resistance. Furthermore, the polyurethane foam is conducive to microbial adhesion and growth. In this study, the hydrophobic polyurethane foam was chosen as additive in the SWIS to improve the soil porosity and permeability.

Therefore, the objective of this study was to evaluate the potential utility of polyurethane foam adding to padding to prolong the lifespan of SWIS in order to resolve the bio-clogging problem as well as its mechanism. The effects of laboratory scale SWIS on pollutants removal were also investigated by the quality of the effluent.

2. Materials and methods

2.1. Wastewater and materials characteristics

The pre-treated wastewater was delivered from a septic tank of Shanghai Jiao Tong University campus, Shanghai, China. During the entire operation period, the characteristics of the pre-treated wastewater exhibited both diurnal and seasonal variations mainly due to the sewage system especially in wet weather and changes in student populations during weekends and holidays. The ranges of major water quality indices of pre-treated wastewater were shown in Table 1.

Brown soil was used for the SWIS, which was sampled 20 cm below the soil surface, with total organic matter 4.2 g/kg, TN 0.61 mg/kg, and TP 2.1 mg/kg, respectively. The polyurethane foam was obtained from local market in Shanghai, China (in density: 25–45 kg/m^3; in pore diameter: 0.1 μm-2 mm). Polyurethane foam was processed to smaller cubic pieces with the size of about 1 cm^3 before mixing with soil and other materials equably.

2.2. Laboratory-scale system setup

Four parallel sets of column laboratory-scale systems made of organic glass with a height of 120 cm and a radius of 15 cm were manufactured. The indoor temperature was maintained over 10℃ during the experimental period. Column 1(R1) which was set as control system has no polyurethane foam added, columns 2, 3, and 4 (R2, 3, and 4) have different packing volumes of polyurethane foam, the components of which were shown in Table 2. The experimental setup of the SWIS was shown in Fig. 1, which has three layers: distributing water layer, treatment layer and filtration layer. The three layers have different functions. The wastewater distribution layer is gravel for distributing influent water uniformly. The treatment layer is composed of soil, sand, iron ore, and polyurethane foam. These materials are mixed equably. Iron ore was used to enhance the TP removal efficiency.

Table 1
Properties of the pretreated wastewater

Property	Unit	Value
NH_3–N	mg/L	34 ± 9
TN	mg/L	46 ± 13
TP	mg/L	4.6 ± 3
COD	mg/L	300 ± 39
BOD_5	mg/L	180 ± 22
SS	mg/L	95 ± 21
pH	/	6.8 ± 0.7

Table 2
Element and ratio in treatment layer of the soil columns (mass ratio)

Column	Polyurethane foam	Soil (%)	Sand (%)	Iron ore (%)	Porosity (%)
R1	0	60.0	37.0	3.0	38.0
R2	3‰	59.8	36.9	3.0	43.0
R3	6‰	59.6	36.8	3.0	51.0
R4	8‰	59.5	36.7	3.0	58.0

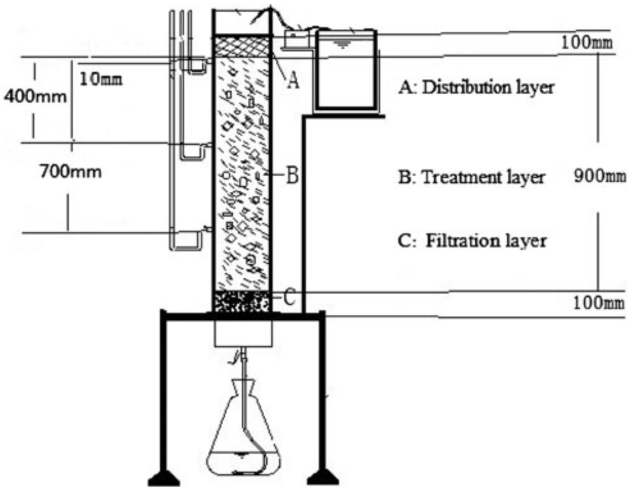

Fig. 1. Schematic diagram of soil column.

Sand is the main transporting medium because of its favorable permeability. The filtration layer is composed of sand used as filter media to removing the SS in the effluent from treatment layer. The optimal packing volume of polyurethane foam of the soil columns was determined by the removal efficiencies of NH_3–N, chemical oxygen demand (COD), TN, TP at different hydraulic loading values.

The performance of the pollutants removal at different packing volumes of polyurethane foam in the SWIS was evaluated in column R1, R2, R3, and R4. Sampling was conducted for about one year. The influent and effluent samples were collected at regular intervals, stored at 4˚C and analyzed within 24 h.

2.3. Analytical methods

The measurement of soil porosity in this study was following the method reported by Wang [19]. COD, BOD_5, TN, NH_3–N, and TP of the water samples were analyzed according to the Standard Methods [20]. Potassium dichromate method was used for COD determination; Colorimetric method was used for NH_3–N, TN was analyzed by Kjeldahl method, and TP was analyzed by the ammonium molybdate method. The formation mechanism of clogging layer was examined under a light microscope (OLYMPUS BH-2, Japan) to detect the morphology of the clogging layer. Statistical analysis was carried out with Micro Cal Origin 7.0 (Origin Lab).

3. Results and discussion

3.1. Effect of hydraulic loading on the pollutant removal efficiencies

The wastewater after pre-treated by septic tank was of about 300 mg/L COD and 180 mg/L BOD_5. During the experiment operation period, hydraulic loading values of 5.0, 10.0, 15.0, 20.0, 25.0, and 30.0 cm/d were presented to test its effect on the pollutants removal efficiencies. As seen from Fig. 2, the hydraulic loading had obviously negative influence on the COD, nitrogen and phosphorus removal in the SWIS. The effluent concentrations of COD, TN, NH_3–N, and TP increased along with the rise of the hydraulic loading.

In the SWIS, organic matters are firstly absorbed by the padding and then degraded by microbes that were native-born through fermentation and/or respiration and finally mineralized as a source of energy or assimilated into biomass [21]. Therefore, the removal efficiency of COD always gradually decreased because of the adsorption saturation. In this study, the effluent COD concentration increased dramatically from 8.6 to 11.4 mg/L under a hydraulic loading value of 5.0 cm/d to 37.5–48.8 mg/L under a hydraulic loading value of 30.0 cm/d. The COD removal efficiencies which decreased along with the increase in the hydraulic loading values for all the four soil columns were the highest, when the hydraulic loading was 5 cm/d with the COD removal rate of 97.2, 96.8, 96.4, and 96.1% for R1–R4 soil columns, respectively. These results indicated that higher hydraulic loading values lead to the lower soil available porosity with the worse capacity of reoxygenation (Fig. 2(a)). Because the oxygen was insufficient in the soil columns result from the aerobic degradation, and it was not added when the SWIS operated at a high hydraulic loading value, so

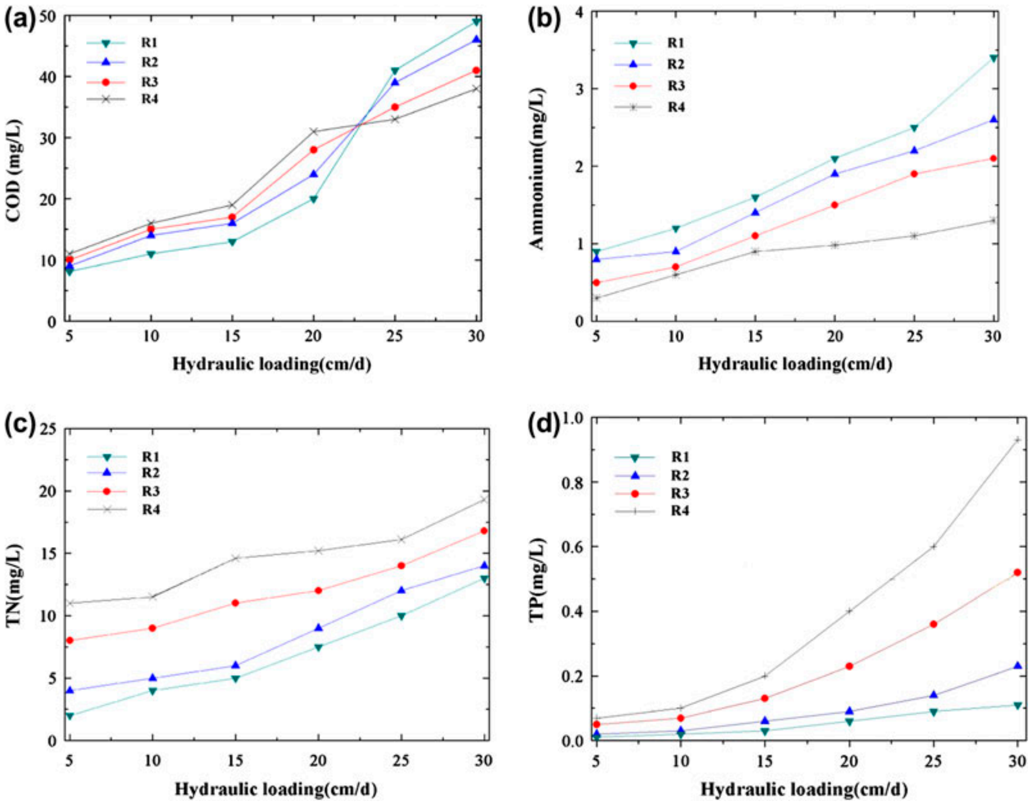

Fig. 2. Effect of hydraulic loading on the pollutants removal. (a) Effluent COD concentration; (b) effluent ammonium nitrogen concentration; (c) effluent TN concentration; and (d) effluent TP concentration.

the capacity of reoxygenation was weak. The COD concentration in effluent increased from R1 to R4 orderly, when the hydraulic loading values were less than 20 cm/d. On the other hand, the concentration of COD in effluent decreased from R1 to R4 orderly when the hydraulic loading values were larger than 20 cm/d. The porosity of the columns R1–R4 has direct relationship with the additive amount of polyurethane foam (Table 2). The soil columns which have more polyurethane foam were of higher resistance to hydraulic loading, especially for column R4, which could have a resistance to hydraulic loading value of 30 cm/d. These observations confirmed that hydraulic loading could affect COD removal by the following reasons: Firstly, increasing hydraulic loadings means shortening hydraulic retention time (HRT), so organic matters are not fully degraded, leading to the lower removal efficiency of COD. However, the lower porosity in columns resulted in the worse permeability, and this will extend the HRT, as a result of this, the organic matters will be degraded better; Secondly, increasing hydraulic loadings lead to stronger shock to media surfaces, this will also decrease COD removal efficiencies.

NH_3–N is the main form of nitrogen in the sewage, and it could be removed well in the application of two procedures, including nitrification and denitrification [22]. The effect of hydraulic loading on the NH_3–N removal was obvious, when the initial concentration of NH_3–N in the sewage was about 35 mg/L (Fig. 2(b)). The removal rates of NH_3–N were between 89 and 98% in the four soil columns, and the concentration of NH_3–N in effluent was lesser than 5.0 mg/L in the whole experimental period. The average concentration of NH_3–N increased from 0.9 mg/L under the hydraulic loading value of 5.0 cm/d to 3.4 mg/L under the hydraulic loading value of 30.0 cm/d in column R1. According to other three soil columns (R2, R3, and R4) for NH_3–N removal, similar trends could be seen in Fig. 2(b). The NH_3–N removal efficiency when the sewage was treated by R4 column was better than other three columns ($p < 0.05$). The concentration of NH_3–N in effluent decreased along with the increasing of the packing volume of polyurethane foam at the same hydraulic loading. As shown in Table 2, the porosity of the columns increased from 38 to 58%, when the packing volume of polyurethane foam in the four soil columns increased from 0 to 8‰.

The ability of reoxygenation in SWIS was enhanced because of the increasing porosity values [19], and nitrification reaction was promoted which could translate NH_3–N into NO_3–N [23,24]. Deterioration of nitrification reaction was obvious caused by soil clogging, leading to the great elevation of NH_3–N concentration in the effluent in column R1. In a word, the removal efficiency of NH_3–N in column R4 was the best of the four soil columns ($p < 0.05$).

Correspondingly, the average effluent TN concentration increased from 2.2–11.2 mg/L to 13.2–18.6 mg/L, when the hydraulic loading value increased from 0.0 to 30.0 cm/d in columns R1–R4 (Fig. 2(c)). The average removal rate of TN was greater than 75% in R1 and R2 columns during the whole experiment period. While according to the R3 and R4 columns, the average removal rate of TN was only about 62%, for denitrification reaction must be in an anoxic/anaerobic system. The effluent TN concentration from R4 column would reach about 20 mg/L, when the hydraulic loading was 30 cm/d, and the R1 column had the best removal efficiency for TN of all the four columns ($p < 0.05$) (Fig. 2(c)). It could be concluded that the TN removal efficiency in the columns with lower permeability at the same hydraulic loading was better, and the same conclusion was also reported by Fan et al. [25].

According to some previous researches, nitrogen could be removed by volatilization, adsorption, plant uptake, and nitrification–denitrification in a SWIS [26–28]. In this study, pH in the SWI system was found to be 7.0–8.5. As a result, the nitrogen was eliminated through volatilization was negligible [28]. Some report revealed that NH_3–N could be adsorbed on matrix, but could also be released easily when water chemistry conditions changed [29]. Therefore, nitrification which is coupled with denitrification is the major removal process in the SWIS.

With respect to the TP removal, short-term and long-term storage are the main removal mechanisms in the SWIS [30]. Good effect of TP removal was obtained by all the four soil columns with the TP initial concentration of 10 mg/L and hydraulic loading 5–30 cm/d in influent (Fig. 2(d)). It could be seen that the SWIS could absorb as high as 99% of the total incoming phosphorus for R1 and R2 columns with a hydraulic loading of 5–30 cm/d, which was much higher than that reported by both Molle et al. [31] and Kadam et al. [32]. On the contrary, the TP removal efficiencies for R3 and R4 were a little worse ($p < 0.05$), and the effluent TP concentration even reached about 1.0 mg/L (Fig. 2(d)). Brooks et al. [30] also revealed that there was a positive correlation between phosphorus removal efficiency and the SWIS surface area. In this study, TP removal efficiency decreased with the increasing of the hydraulic loading values, for the higher hydraulic loading lead to the lower values of HRT. According to the above results, hydraulic loading of 25 cm/d for R3 column was the optimal choice to achieve high effluent quality and hydraulic efficiency in this SWIS (Fig. 2(d)).

3.2. *Effect of the influent pollutant concentration on its removal efficiency*

The concentration of pollutants in domestic wastewater may affect the quality of effluent after treated by the soil columns greatly. The higher degree of the sewage pollution is the worse efficiency of pollutant removal with the same hydraulic loading [33,34].

The SWIS was conducted at an range of influent COD concentration between 100 and 700 mg/L with a hydraulic loading value of 26 cm/d. Results showed that an excellent removal rate of COD at 85–96% throughout the normal operation period was seen in Fig. 3(a). The residual COD concentration was between 9 and 50 mg/L. As to conventional technology of treating wastewater, the organic substance is removed in an anaerobic tank and then followed by soil filter. Onsite wastewater treatment system containing a septic tank, and SWIS is capable of removing nearly all the biodegradable organic compounds [5]. The concentration of COD in effluent from all the four soil columns increased along with the increasing influent COD concentration and its removal rate was very high when the influent concentration of COD was less than 300 mg/L (Fig. 3(a)). On the contrast, when the influent COD concentration exceeded 300 mg/L, the columns with lower porosity (R1 and R2) had worse effect on the treatment of sewage than that treated by R3 and R4 ($p < 0.05$), for most of the organic substances must be degraded in oxygen-rich systems. Nevertheless, the soil columns with higher porosity (R3 and R4) had better effect on the treatment of sewage even if the influent COD was of high concentration. In the SWI system, most dissolved organic matters are removed by the combination of physical (i.e. sedimentation, absorption, filtration, and trapping) and biological degradation processes. In general, the surface layer of the soil filter was considered biologically active because of the presence of a large quantity of bacteria, protozoa, and metazoan. Hence, biodegradation of organic substances occurred mainly in this oxygenated section. When wastewater from distributing layer flowed into infiltration zone, most of organic pollutants were scattered under the role of the capillary force and gravity, then degraded in aerobic zone.

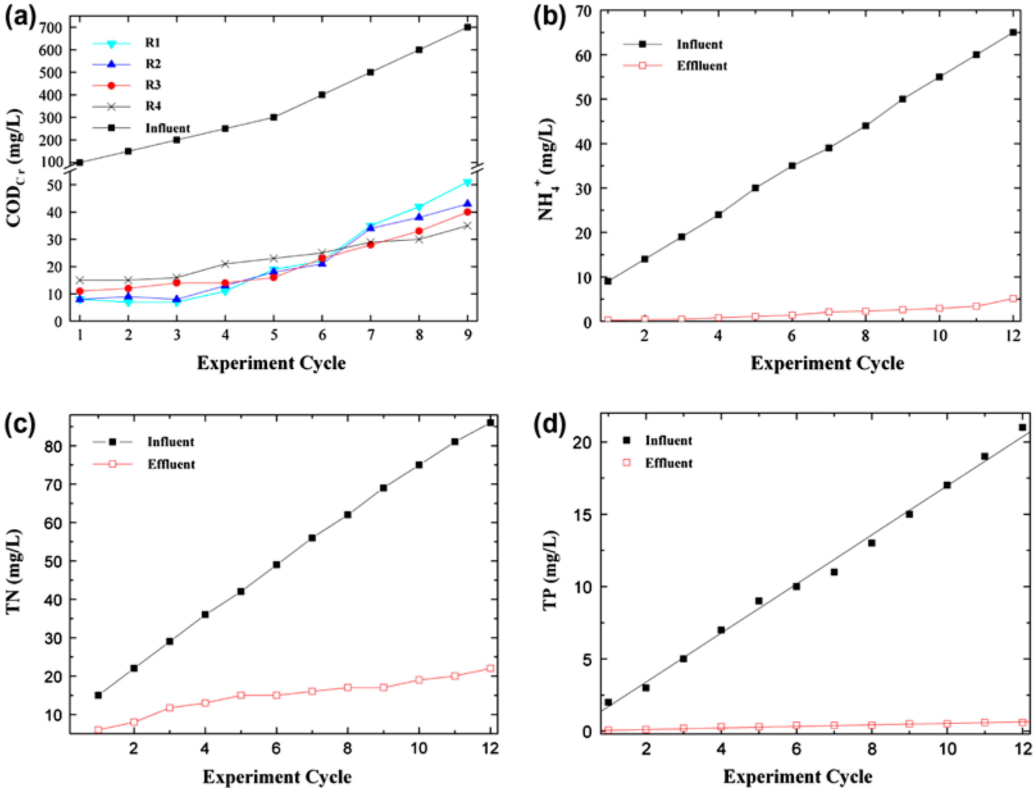

Fig. 3. Variations of effluent pollutants at different experiment cycles. (cycle: contain four weeks). (a) The removal effect of COD; (b) the removal effect of ammonia nitrogen; (c) the removal effect of TN; and (d) the removal effect of TP.

During the increasing process of the pollution loading, the soil columns of R1 and R2 were both blocked for three and five times, respectively, while the columns of R3 and R4 were not air-clogged at all during the whole experimental period. The R3 column was chosen for the optimum composition of the treatment system during the following experiments, as its quality of effluent was better than that from R4 column when the hydraulic loading was less than 400 mg/L (Fig. 3(a)).

The pollutant removal performance experiments were performed under the optimal conditions in column R3. When the influent NH_3–N concentration ranged from 10 to 60 mg/L, the effluent NH_3–N concentration was lower than 4 mg/L with the hydraulic loading of 26 cm/d (Fig. 3(b)). Because most of NH_3–N in sewage was transformed into nitrate and nitrite in the system, NH_3–N concentration decreased. Most of the NH_3–N was removed by nitrosobacteria and nitrobacterium. The average removal rate of NH_3–N was greater than 98% in R3 column system, with a remarkable increase compared with other reports [23,35].

When the influent TN concentration ranged from 20 to 80 mg/L, the effluent TN concentration was lower than 25 mg/L with a hydraulic loading value of 26 cm/d (Fig. 3(c)). The effluent TN concentration rose along with the increasing of the influent TN concentrations. Because the COD concentration decreased when the sewage flowed from the upper to the lower of the soil column, as a result, the denitrification bacteria at the lower soil layer were lack of carbon source, leading to the bad effect on the removal of TN [36,37].

When the influent TP concentration was between 2 and 20 mg/L, the effluent TP concentration was lower than 0.5 mg/L with a hydraulic loading value of 26 cm/d (Fig. 3(d)), complying to the GB18918-2002 1 A discharge standard in China. It was showed that TP removal rate could reach between 98 and 99.5% throughout the entire study period. The main mechanism of TP removal in the SWIS is generally through physicochemical absorption by the soil as well as by nutrient uptake in this study. With regard to the former studies, minerals such as Ca, Al, and Fe oxides serve as important binding sites and their presence in considerable amounts would enhance the phosphorus sorption capacity, resorption rate, and the permeability of the soil filter. Therefore, a significant basis for the selection of soil media is the presence of high levels of Ca, Al, and Fe oxides. In this study, iron ore was chose to adsorb the phosphorus, and it was indicated that the soil filter applied exhibited high capacity for adsorption of phosphorus.

3.3. Formation mechanism of the clogging layer

The saturated permeability rate quickly dropped when the soil columns R1–R4 ruined for the first 1 week, and the results were seen in Fig. 4. After that, it decreased gradually in the following 10 weeks, which was similar to that reported by Reddi et al. [38]. The saturated permeability rate of column R1 was only 1.8 cm/d leading to the clogging after operation for about 20 weeks, while the saturated permeability rate of columns R2, R3, and R4 were 17.3, 46.3, and 84.1 cm/d, respectively. It could be concluded that the higher packing volume of the polyurethane foam was, the higher saturated permeability rate was after operated for the same time.

Fig. 5 showed that the hydraulic heads (for three points along the column, see Fig. 1) against processing time of experiment column R1 after operation for 20 weeks. It was clear that the hydraulic head in the 10 mm place apart from the treatment layer did not change within 48 h during the course of the experimental period, while other hydraulic heads measured in the 400 or 700 mm place apart from the treatment layer gradually declined until the pressure of the soil column became zero. Because of the upper-level resistance of the soil column treatment layer, the head loss of the sewage from the surface layer flowing to the treating layer 400 mm apart from surface layer was the highest, while the head loss at the place 700 mm apart from surface layer was lower. Similar results were also reported by Van Cuyk et al. [33]. When the clogging of soil column happened, the unsaturated status of the treating layer changed into the saturated status, leading to the reduction of reoxygenation ability [39], as a result of this, the quality of effluent deteriorated because of the increasing COD concentration (Fig. 5). This indicated that a clogging layer was gradually developing at the interface between the distribution layer and treatment layer (Fig. 6).

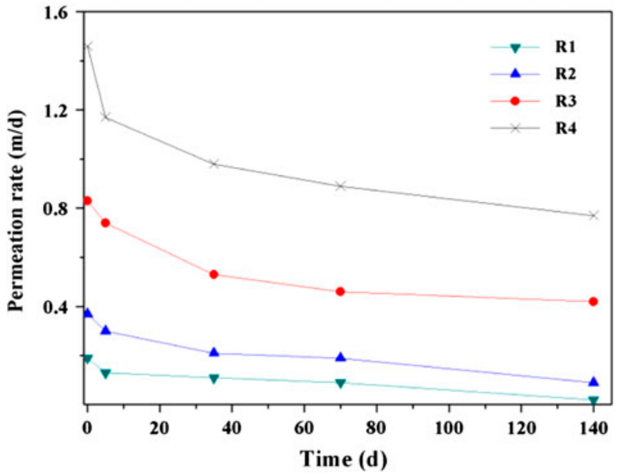

Fig. 4. Changes of permeability in R1–R4 columns during the process.

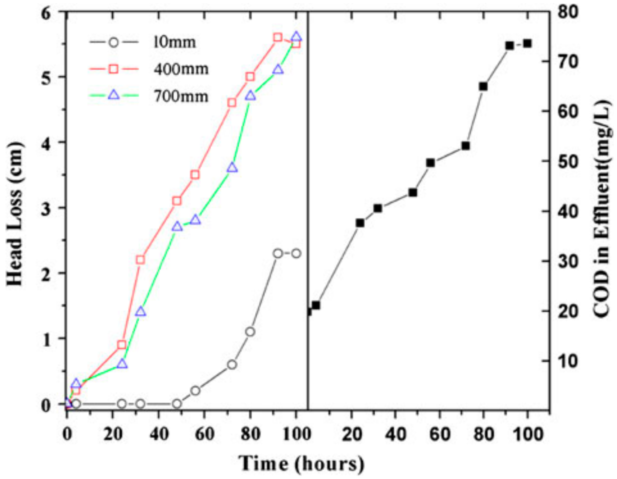

Fig. 5. Hydraulic head loss and COD changes during the clogging process.

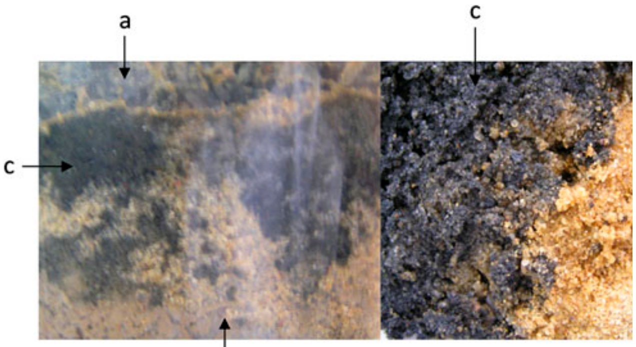

Fig. 6. Bio-clogging on the surface of treatment layer in column R1. (a) Distribution layer; (b) treatment layer; and (c) clogging layer.

4. Conclusions

The soil columns with 6‰ polyurethane foam, 59.6% soil, 36.8% sand, and 3% iron ore were the optimal parameters for the SWIS operation when total hydraulic loading was less than 26 cm/d operated for over 4 months. Under the optimized conditions, the average removal efficiencies for COD, NH_3–N, TN, and TP were 85, 98, 62, and 99%, respectively. Both of the hydraulic loading and the concentration of the influent pollutants had negative effects on the removal of the pollutants. The above results provided an effective way to enhance the ability of anti-clogging with the addition of polyurethane foam to SWIS.

Acknowledgment

This study was financially supported by the Shanghai Science and Technology Commission (No. 11dz1211203).

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