# TREATMENT OF SANITARY SEWER OVERFLOW WITH FIXED MEDIA BIOREACTORS

J. Tao, K. M. Mancl, O. H. Tuovinen

**ABSTRACT.** *Fixed media bioreactors (biofilters) are a promising and proven technology used for wastewater treatment in unsewered rural areas. As an on-site treatment system, it can potentially provide high treatment efficiency with a relatively low cost and maintenance. This research expanded the application of fixed media bioreactors and tested their feasibility in the treatment of sanitary sewer overflows (SSO) at high hydraulic loading of 0.2 m/h. Sand, peat, and textile (felt) were used as media to treat simulated 6-h peak flows for a 25-year SSO event in the city of Columbus, Ohio. The influent SSO was a mixture of primary sludge from a wastewater treatment plant diluted with tap water. The efficiency of treatment was measured as changes in the concentrations of biochemical oxygen demand ($BOD_5$), chemical oxygen demand (COD), and total suspended solids (TSS). Sand as a filter medium had the best removal of organic matter with average 84% reduction of $BOD_5$ and 90% of COD. The TSS removal was more than 90% in all media. Peat and felt were somewhat more efficient than the sand in the TSS removal. The media type and influent $BOD_5$ concentration were two major factors that impacted the treatment of $BOD_5$ ($p<0.007$). For the treatment of COD, significant factors were media type, influent concentration, and time course of loading in each SSO event ($p \leq 0.001$).*

***Keywords.*** *Fixed media bioreactor, Sand, Peat, Textile, Sanitary sewer overflow, $BOD_5$, COD, TSS.*

Sanitary sewer overflows (SSOs) contain raw sewage and sometimes occur in unprotected public areas or discharge in public waterways. Overflows can contribute to beach closures, contamination of drinking water supplies, and many other environmental and public health issues. In December 2000, as part of the Consolidated Appropriations Act for Fiscal Year 2001 (P.L. 106-554), the U.S. Congress amended the Clean Water Act by adding Section 402(q), commonly referred to as the Wet Weather Water Quality Act of 2000. The amendment authorized a $1.5-billion grant program for controlling combined sewer overflow (CSO) and sanitary sewer overflow (SSO) (USEPA, 2004). In 2005, the city of Columbus submitted a Wet Weather Management Plan to the Ohio Environmental Protection Agency. The whole plan is expected to generate $2.5 billion in capital improvement projects over the next 40 years for the control of 10-year overflow events. The City has modeled the SSOs for a 10-year and a 25-year event in Columbus. The peak flow is approximately 3 h for a 10-year event. At the same level of flow rate (>17.2 $m^3$/h), a 25-year event has a peak flow of about 6 h (fig. 1).

Large volume of discharge in a short time and various pollution loadings are two characteristics of the SSOs. The U.S. Environmental Protection Agency presented their report to the Congress on the Impacts and Control of CSOs and SSOs in 2004. The report estimated that 23,000 to 75,000 SSO events occur per year in the United States, totaling about 1-3×$10^7$ $m^3$ per year. Stormy, wet weather is the major cause for the large volume of discharge. The principal pollutants in SSO discharges include organic matter [expressed as chemical oxygen demand (COD) and 5-day biochemical oxygen demand ($BOD_5$)], potential pathogens, total suspended solids (TSS), toxic compounds, nutrients, and floating substances. Examples of the levels in SSOs include $BOD_5$ of 6 to 413 mg/L with median about 42 mg/L, TSS of 10 to 348 mg/L with median about 91 mg/L, and about 5×$10^5$ fecal coliforms/100 mL. No data were available for the nitrogen in SSOs (USEPA, 2004).

Technologies for SSO control include end-of-pipe controls, which are used to provide physical, biological, or chemical treatment to excess wet weather flows immediately

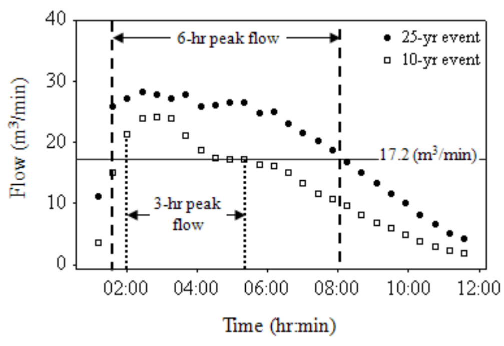


**Figure 1. Modeled flow of SSO events (10 and 25 yr) in Columbus, Ohio (unpublished data from the city of Columbus).**

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prior to discharge from a sanitary sewer system. Treatment can directly reduce the environmental impact of pollutants in SSOs. However, abatement of pollution from the SSOs is one of the most challenging areas in the environmental engineering field (Field and Sullivan, 2001). Conventional treatments have not been widely applied to SSOs partly because of the cost and the difficulty in remote management and control of wastewater treatment. Other factors underlying the lack of treatment include the current condition of existing treatment systems, characteristics of wet weather flows, changes in hydraulic and pollutant loadings, and seasonal variations in temperature and rainfall patterns (USEPA, 2004). Very few research studies have been published on the design of treatment systems for SSOs.

As an onsite wastewater treatment system, fixed media bioreactors can be constructed for single SSO discharge points and respond to the influent quickly and flexibly. They can produce acceptable effluent quality with $BOD_5$ and TSS values below 10 mg/L and operate under variable hydraulic conditions (Roy et al., 1998; USEPA, 2002). Fixed media bioreactors are readily accessible for monitoring and maintenance. In addition, they can be restarted and have stable effluent quality shortly after a long rest time without wastewater loading, which avail themselves to SSO treatment. Therefore, fixed media bioreactors were considered in this study to be an efficient alternative in SSO control.

A variety of materials can be used as media for bioreactors. Sand is the most common material in fixed media bioreactors. Typical effluent concentrations for domestic wastewater treatment in sand bioreactors are ≤ 10 mg/L for both $BOD_5$ and TSS, and N removal is approximately 50% (USEPA, 2002). The design criteria for intermittent sand bioreactors are 0.25-0.75 mm effective size of filter medium, 45-90 cm of depth, and hydraulic loading rates (HLRs) of 0.08-0.2 m/d (USEPA, 1999). Previous research concluded that a 60-cm depth is sufficient for sewage treatment in sand bioreactors and wastewater with HLR > 0.23 m/day can be loaded into sand bioreactors in one dose without clogging (Widrig et al., 1996). However, sand bioreactors may be difficult to apply because of the weight and relatively high cost if a local source of sand cannot satisfy the treatment requirement. Peat and textile are two types of light-weight media developed during the last 15 years. Hu and Gagnon (2006) reported 90% reduction in $BOD_5$, 65% in TSS, and 69% in total N in a 60 cm deep peat biofilter at a 0.16-m/d loading rate of multi-residential wastewater, compared to 96% in $BOD_5$, 31% in TSS, and 74% in total N in a sand column. Roy et al. (1998) used non-woven textile fabrics chips in intermittent biofilters and noted that the effluent $BOD_5$ and TSS levels were typically less than 10 mg/L at HLRs ranging from 0.2 to 0.6 m/d. Leverenz et al. (2001) reported that $BOD_5$ levels in treated wastewater were reduced by 97% and TSS by 95% with a textile filter medium at HLRs of 0.41 and 1.22 m/d.

No reports have been published on SSO treatment using fixed media bioreactors. The objective of this research was to evaluate the treatment of SSO wastewater using this type of treatment system for simulated peak flows of 25-year SSO events. This initial study focused on the removal of organic matter and TSS in simulated SSO wastewater with different fixed media. The treatment standard was chosen as 15 mg $BOD_5$/L, which is the 7-day effluent limit for stream discharge from conventional treatment technologies in Ohio's antidegradation rule (3745-1-05). The experimental data were also analyzed to assess the factors affecting the removal of organic matter.

# Materials and Methods

The fixed media bioreactors were 208-L conical bottom polyethylene tanks mounted on steel stands. The tanks had a diameter of 0.60 m and surface area of 0.28 $m^2$. Each bioreactor had a 0.60-m deep layer of fixed media and a 0.10-m layer of pea gravel, which functioned as an underdrain in the bottom of the tank. The 0.60-m media layers in sand bioreactors were prepared by placing 0.15 m of pea gravel, 0.15 m of coarse sand (effective size ~ 2.5-3.5 mm) and 0.30 m of fine sand (effective size ~ 0.5-1 mm) from the top down. The treatment media in felt bioreactors was a layer of 0.60-m non-woven textile fabric chips (7.5 × 4.5 × 0.7 cm), provided by Wastewater Innovation, Inc. (Batesville, Ind.). Peat bioreactors had 0.60 m of peat provided by Premier Tech Ltd. (Quebec, Canada). The installation densities (mass/volume) in the tank was 0.08 for felt, 0.1 for peat, 1.5 for fine sand, all normalized to 1.0 for water.

A dose tank was constructed from a 114-L polyethylene tank and placed on an elevated stand to allow effluent to discharge by gravity on the top of the bioreactors (fig. 2). No previous bench-scale research has been published on biotreatment of SSO. Physical and chemical characteristic of SSO may vary considerably temporally, which would make

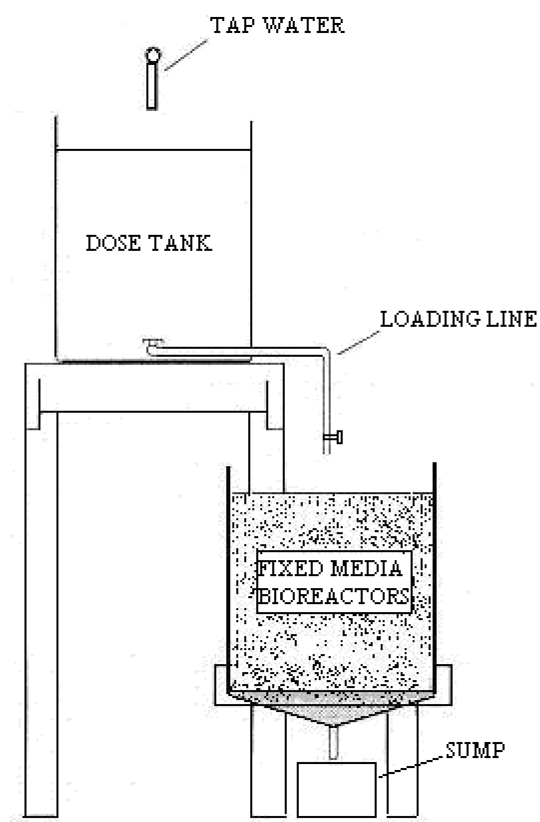


**Figure 2. Diagram of the experimental treatment system used in this study.**

studies of the biological treatment of SSO problematical. With data subject to wide variation, large number of replicates would be needed to yield useful interpretation. To avoid these problems in this initial phase of research, simulated SSO was formulated with a mixture of primary sewage sludge and tap water, previously proven to be an effective simulation of sewage for laboratory-scale sewer system (Peeples and Mancl, 1998). This mixture contains volatile and non-volatile solids, dissolved and particulate organic matter, nutrients and bacteria, all typical components of untreated sewage. The primary sludge sample was from the Southerly Wastewater Treatment Plant (Columbus, Ohio), and it was adjusted to the approximate targeted $BOD_5$ level of 80-100 mg/L with tap water. The target $BOD_5$ level was twice the SSO median level reported by the USEPA.

The wastewater mix was loaded on the bioreactors with 1 dose/h for 6 h to simulate the peak flow of a 25-yr SSO event. The volume per dose was chosen as 0.057 $m^3$ and HLR was 0.20 m/dose, i.e., 0.20 m/h. The total loading for a 6-h SSO event was 1.22 m/event, i.e., 1.22 m/day. After each 6-h loading, the fixed media bioreactors were left exposed in the laboratory and rested until reloading in the next month.

Bioreactor effluents were collected in a sump, sampled, and drained every hour. Every 2 h, samples were pooled and marked as 2-, 4-, and 6-h composite samples, which corresponded with loading in 0-2, 2–4, and 4-6 h intervals. Thus each type of bioreactor had six samples for each day of loading. Organic matter, expressed as $BOD_5$ and COD, in influent and effluent samples was measured for each simulated SSO event during 14 months of research. For the final three months, TSS and soluble $BOD_5$ and COD were also analyzed. Whatman glass microfibre filter disks (grade 934 AH: 1.5 μm) were used to filter suspended solids (weighted as TSS) from the samples. Filtered water samples were used for measurement of soluble $BOD_5$ and COD. The solid $BOD_5$ and COD fractions were calculated by the difference of total $BOD_5$ and soluble $BOD_5$, and the difference of total COD and soluble COD, respectively. The ratios of soluble to solid $BOD_5$ and COD were used for performance evaluation. Standard methods (APHA, 1998) were used for the measurements of $BOD_5$ (section 5210 B and 4500-O C), COD (section 5220 B), and TSS (section 2540 B).

Statistical analysis was conducted using MINITAB 14™. Three factors (medium type, time course of loading during a SSO event, and influent concentration levels) were considered to affect the treatment of organic matter in each SSO event loading. The general linear model (GLM) was used to perform ANOVA for unbalanced data and simultaneously identify if all possible factors had significant effects on the percent removal with p-value $< \alpha = 0.05$. The GLM only indicated if the means of respond (percent removal) were different at varying levels of factors. The Tukey's multiple comparisons were associated with ANOVA and used to compare means of all possible pairs of levels for experimental factors. This method identified levels which were significantly different in the $BOD_5$ and COD removal (p-value $< \alpha = 0.05$).

# Results and Discussion

## Bioreactor Performance

The HLR used in this study was 1.22 m/day, which was 15 to 30 times higher than the HLR recommended by the USEPA (2002) for the intermittent fixed media bioreactors. After each hourly dose, it took 25 to 30 min for the wastewater to flow through the sand bed, but 15 min for the felt bed and peat bed because of different characteristics of media. The percent removal of organic matter at this high HLR is shown in figure 3. The sand presented the best and most stable treatment, removing on average 84% of $BOD_5$ and 90% of COD in the SSO wastewater. The average effluent concentration was 14 mg $BOD_5$/L, lower than the discharge standard of 15 mg $BOD_5$/L. These results indicated that sand bioreactor was an effective treatment system for the SSO at high hydraulic loading. This may be partially related to the longer contact time of wastewater with sand as compared to peat and felt as fixed bed media. Felt and peat were less effective in the removal of $BOD_5$ over the operation days, but they showed steady performance in the treatment of COD. The average effluent concentration was 41 mg $BOD_5$/L with felt and 28 mg $BOD_5$/L with peat. Felt had a higher COD removal, but a lower $BOD_5$ removal than peat.

In the treatment of SSO, fixed media bioreactors functioned as both the primary and secondary process compared with traditional wastewater treatment plant. Therefore, the TSS removal was important to evaluate the performance of bioreactors. All three types of media reduced average > 90% TSS (table 1), indicating that bioreactors have excellent filtration properties at high HLR. Sand had lower removal of TSS than the peat, which was consistent with the results of Hu and Gagnon (2006).

Table 2 lists the ratios of soluble fractions to solid fractions of organic matter. The soluble fraction in organic matter was the ≤ 1.5-μm filtrate. About 50% to 70% $BOD_5$ and 80% to 90% COD in the influent was associated with solids (Ø > 1.5 μm) and the soluble/solid ratios were lower than 1 (table 2). After the treatment, these ratios increased in all three types of filter media (4.0-8.5 for $BOD_5$ and 5.1-8.8 for COD). These results indicated that solid organic matter was efficiently removed by the bioreactors. After the treatment, most organic matter in the wastewater was associated with the soluble fractions and this change may facilitate further treatment of the discharge. The difference of ratios between felt and peat showed a similar pattern with their difference in the treatment of total $BOD_5$ and COD. Lower ratios of soluble/solid fractions in the effluent between felt and peat were consistent with lower removal of $BOD_5$ and COD between them. These data suggested that felt and peat may have different mechanism for the removal of biodegradable organic matter ($BOD_5$) and total organic matter (COD).

## Factor Analysis for Organic Matter Removal

In the GLM/ANOVA, three factors were considered to affect the performance of bioreactors for the treatment of organic matter in a simulated SSO event: the type of medium, time course of loading, and influent concentrations.

As shown in figure 3 and table 3, three types of treatment media differed in the removal of $BOD_5$ and COD. Statistic analysis indicated that the type of medium significantly

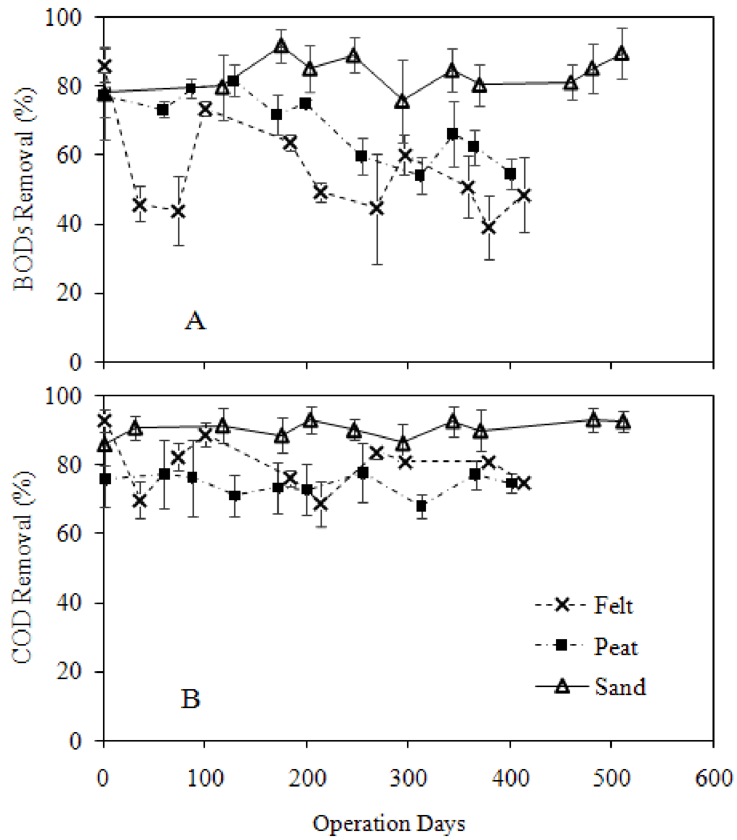


**Figure 3. Treatment of (A) $BOD_5$ and (B) COD with three types of fixed media. Each data point is an average of six samples and error bar presents standard deviation.**

**Table 1. Treatment of TSS (mean ± SD) with fixed-media bioreactors.**

| Media | n | Influent (mg/L) | Effluent (mg/L) | Removal (%) |
|---|---|---|---|---|
| Felt | 18 | 102±3 | 7±2 | 93±3 ab[a] |
| Peat | 18 | 119±22 | 6±3 | 95±2 a |
| Sand | 18 | 117±11 | 12±11 | 90±10 b |

[a] Values followed by the same letter were not significantly different at α = 0.05 using Tukey's multiple comparison.

**Table 2. Average ratios of soluble organic matter to solid organic matter in influent and effluent samples.**

| | Soluble $BOD_5$ / Solid $BOD_5$ | | | Soluble COD/ Solid COD | | |
|---|---|---|---|---|---|---|
| Media | n | Influent | Effluent | n | Influent | Effluent |
| Felt | 18 | 0.6 | 4.0 | 12 | 0.2 | 8.8 |
| Peat | 18 | 0.8 | 8.5 | 12 | 0.2 | 6.2 |
| Sand | 18 | 0.5 | 4.8 | 12 | 0.2 | 5.1 |

affected the percent removal of both $BOD_5$ and COD ($p < 0.001$). Sand showed the highest efficiency in the treatment of organic matter among three types of media.

Time course of loading in a SSO event was a significant factor for the removal of COD ($p < 0.001$), but not for $BOD_5$ ($p = 0.820$). As shown in table 3, the removal of $BOD_5$ did not show marked difference within 2-, 4-, and 6-h loading, which suggested that the duration of a SSO event would not affect the performance of bioreactors in the treatment of $BOD_5$. Fixed media bioreactors performed differently in the removal of COD. The results of composite samples showed that 4- and 6-h loading obtained higher COD removal than 2-h loading. The difference between 4- and 6-h COD removal was not significant.

**Table 3. Summary of $BOD_5$ and COD removal (mean ± SD) for different factors.**

| | Removal (%) | | | |
|---|---|---|---|---|
| Factors | n | $BOD_5$ | n | COD |
| Type of Medium | | | | |
| Felt | 66 | 55±16 a[a] | 60 | 80±8 b |
| Peat | 66 | 68±11 b | 59 | 74±7 a |
| Sand | 66 | 84±9 c | 66 | 90±5 c |
| Time course of loading in a SSO event | | | | |
| 2 h | 66 | 69±14 a | 61 | 78±10 a |
| 4 h | 66 | 68±18 a | 62 | 82±9 b |
| 6 h | 66 | 70±18 a | 62 | 85±8 b |
| Influent concentration level[b] | | | | |
| 1 | 24 | 63±17 a | 24 | 78±9 a |
| 2 | 48 | 68±19 ab | 89 | 80±11 ab |
| 3 | 54 | 66±19 ab | 48 | 83±6 bc |
| 4 | 72 | 71±11 b | 24 | 87±9 c |

[a] Values followed by the same letter were not significantly different at α = 0.05 using Tukey's multiple comparison.

[b] For GLM analysis, influent concentrations of $BOD_5$ and COD were divided into four levels. $BOD_5$: 1: <50 mg/L; 2: 50-80 mg/L; 3: 80-100 mg/L; 4: >100 mg/L. COD: 1, 100-200 mg/L; 2, 200-300 mg/L; 3, 300-400 mg/L; 4, >400 mg/L.

The influent concentrations were 38 to 124 mg $BOD_5$/L and 176 to 470 mg COD/L. Each simulated SSO event had different influent concentration. For effective analysis with GLM, the influent concentrations were grouped into four levels: 1, <50 mg/L $BOD_5$; 2, 50-80 mg/L $BOD_5$; 3, 80-100 mg/L $BOD_5$; and 4, >100 mg/L $BOD_5$. Similarly, the influent COD concentrations were divided also into four levels: 1, 100-200 mg/L COD; 2, 200-300 mg/L COD; 3, 300-400 mg/L COD; and 4, >400 mg/L COD. The results showed that the influent pollution loading impacted the removal of $BOD_5$ ($p = 0.007$) and COD ($p < 0.001$). The summary statistics of percent removal at different levels of influent $BOD_5$ and COD loading are listed in table 3. The only significant difference in $BOD_5$ removal presented between the fourth level (>100 mg/L) and the first level (<50 mg/L). The varying influent concentration < 100 mg $BOD_5$/L did not result in any marked change in the treatment. The treatment for the influent concentration > 100 mg $BOD_5$/L was not different from that for 50 to 100 mg $BOD_5$/L. Therefore, the change of influent concentration had to be at least 50 mg $BOD_5$/L to produce significantly different treatment performance. At the SSO loading rate of 0.2 m/h, this concentration was a change of ≥ 10g $BOD_5/m^2/h$ loading producing significantly different treatment. For COD, each difference of 200 mg/L (level 1 and 3, 1 and 4, and 2 and 4) in influent concentration significantly increased the removal. This loading was 40 g $COD/m^2/h$ at HLR of 0.2 m/h.

## Conclusions

Fixed media bioreactors have extensive capabilities for treatment of different types of wastewater. No previous research was available in the literature for the control of SSO with this technology. The experimental system was developed to investigate the potential of fixed media bioreactors in the treatment of SSO wastewater. Three types of fixed media (felt, peat, and sand) were evaluated at a high hydraulic loading rate of 0.2 m/h. This initial study focused on the treatment of organic matter ($BOD_5$ and COD) and TSS. The loading was designed to simulate the 6-h peak flows in 25-year SSO events of the city of Columbus.

Fixed media bioreactors were designed to combine primary and secondary treatment in the SSO control. The treatment of solids was an important consideration to effectively treat SSO wastewater. All three types of media performed well to reduce TSS, which suggested that this technology can effectively remove solids from the SSO wastewater.

The treatment of organic matter was set as the standard to evaluate the capacity of treatment media. The target of effluent concentration was 15 mg $BOD_5$/L, the 7-day effluent limit for stream discharge from conventional treatment technologies in Ohio's antidegradation rule (3745-1-05). Sand bioreactors showed promising performance in SSO treatment with average effluent concentration of 14 mg $BOD_5$/L. This type of bioreactors also had the most stable treatment of organic matter over extended operation days.

Although peat and felt were not as efficient as sand, they improved water quality of overflow discharge through removing solid fractions of organic matter. Peat and felt have the advantage of being light weight, compressible, and easy to install at a remote or cramped site. The weight of media is an important factor because a light weight fixed media bioreactor could be rapidly deployed to treat spills. In further research, efforts will be made to combine these two media with sand to take advantages of the treatment capacity of sand and the light weight of peat and felt.

Besides treatment media, a factor affecting the treatment of $BOD_5$ in a SSO event was the influent loading. An increase of ≥10g $BOD_5/m^2/h$ loading improved the percent removal. For COD, the time course of loading influenced the extent of treatment. The COD removal increased during a 2- to 4-h SSO event and then it became constant from 4- to 6-h loading. An increase of 40 g COD $/m^2/h$ in the influent resulted in a positive change of COD removal. The positive relationship between the organic matter loading and the percent removal indicated that fixed media bioreactors have potential to achieve higher removal with higher influent concentrations than in this study. Therefore, more data at broader range of influent concentration are needed to test the capacity of SSO treatment using fixed media bioreactors in the future research.

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