Accumulated Organic Matter Degradation and the Function of Porous Media during Enhanced Sewer Self-purification

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ABSTRACT
This study aims to clarify the function of different porous media layers during accumulated organic matter degradation with enhanced sewer self-purification by porous sponge media. To do so, intermittent flow and low continuous flow were applied to channels containing sponge media while maintaining similar volumetric flow rates per channel. Accumulated organic matter, in the form of margarine, was placed underneath the sponge media. Aerobic activity related to organic matter degradation was monitored for 32 days followed by test sponge oxygen consumption and biomass density evaluation. Porous sponge media of different pore cell radii and thicknesses were tested under the described conditions. Findings for intermittent flow showed that although the top layers did not have direct contact to accumulated organic matter, they contributed 33–70% to the total aerobic activity related to organic matter degradation. A lower contribution of 12–42% was found for the top layers for channels subjected to low continuous flow. For all channels, higher biomass density was found for the bottom layer directly in contact with accumulated organic matter. Findings show that while the bottom layer may have higher contribution to organic matter degradation, the upper media layer contributes significantly to aerobic activity during enhanced sewer self-purification.

Keywords: sewer self-purification; porous media; wastewater treatment

INTRODUCTION
Enhanced sewer self-purification is an emerging technology that can positively impact wastewater management by removing organic pollutants in flowing wastewater [1–5]. Application to upstream sewers is of interest because upstream sewers are thought to comprise a large portion of the sewer system. Enhancing sewer self-purification largely relies on the promotion of both biomass growth and retention inside the sewer pipe, with emphasis on attached biomass [6,7]. Researchers have found that sewer self-purification can be enhanced through modifying the inner surface of the sewer pipe to promote microbial growth and retention [5–9]. Of the modifications used, porous plastic sponge media have recently shown promising results [5,7].

Accumulated organic matter degradation is a challenge in enhanced sewer self-purification. Organic matter is anticipated to accumulate at the bottom of the porous media where access to oxygen in the sewer headspace-gas is less. Upstream sewers connected to buildings have both low [10] and intermittent flow [11]. During intermittent flow shown in Fig. 1A, a part of the wastewater is retained in the media after flow. The retained water volume may not fully occupy the media thus, leaving intermittently submerged media layers where biomass activity occurs. During low continuous flow shown in Fig. 1B, a low flow of wastewater would contact only the bottom part of the media. Similarly, biomass activity may be heavily concentrated in the media layer where wastewater flows continuously. It is of interest whether the porous media layer that is not in contact with accumulated organic matter or wastewater has significant contribution to the aerobic degradation of accumulated organic matter.

With the given narrative, the aim of this paper is to clarify the function of different porous media layers during accum-
mulated organic matter degradation with enhanced sewer self-purification. Specifically, to investigate the contribution of porous media layers on aerobic activity related to accumulated organic matter degradation during intermittent flow and low continuous flow. Here, function means the contribution of the media to the aerobic activity related to organic matter degradation. To do so, biofilm was developed in the porous media, which was placed over accumulated lipids, by applying intermittent and continuous flow over a period of 32 days. Then, biomass oxygen consumption and biomass density of different media layers were evaluated to assess the contribution of each media layer to the aerobic activity. Further, porous sponge media of different pore cell radii and thicknesses were assessed to clarify whether water retention plays a role in enhancing aerobic activity to different media layers depending on the type of flow. Lipids, as margarine, was used as a model substrate because it can remain solid at the operating temperature.

MATERIALS AND METHODS

Reagents

The following analytical grade reagents were obtained from FUJIFILM Wako Pure Chemical Corporation, Tokyo, Japan: KCl, CaCl\(_2\), NH\(_4\)Cl, MgSO\(_4\)-7H\(_2\)O, K\(_2\)HPO\(_4\), MnSO\(_4\), NaOH, and concentrated H\(_2\)SO\(_4\). Ultrapure water prepared with a MilliPoreSigma™ Milli-Q™ Advantage A10 (Fisher Scientific, New Hampshire, USA) was used for all preparations that required aqueous matrix. The margarine sample was obtained from a local grocery store.
solution was prepared as previously described by Smolders et al. [12]. The dissolved oxygen (DO) concentration of the nutrient feed was between 7.5–8.5 mg L\(^{-1}\). Air pump, A2, was operated at the same time as feed pump, P3, to replenish the headspace-gas in the airtight channel. The exhaust gas was released at an outlet in the water seal during air pump operation. Oxygen consumption rates were evaluated similar to the method described by Sotelo et al. [13]. Measurements were taken 6 times a day at 240-minute intervals. The oxygen consumption rate was expressed as mass of oxygen consumed per sponge media area per day.

**Inoculation**

Microorganisms were introduced to the test sponge via inoculated substrate sheets which were prepared as follows. First, substrate sheets were prepared by applying 6 g of melted lipid sample (approx. 15 g COD in the channel where 1 g margarine = 2.43 g as chemical oxygen demand (COD)). Each sheet was then inoculated with microorganisms via an inoculation sponge (0.3 cm depth, 7 cm width, and 40 cm length) (Sekisui Chemical Co., Tokyo, Japan). The inoculation sponges had been seeded with return sludge from a municipal wastewater treatment plant. Each substrate sheet was fixed on top of the inoculation sponge and placed inside an open channel (48.5 cm length, 7 cm width, and 6 cm depth) as shown in Fig. 2B. A plastic sheet (7 cm wide, 30 cm length) was placed 10 cm downstream from the inlet side between the inoculation sponge and the substrate sheet. This was done to minimize substrate transfer between the inoculation sponge and substrate sheet. Nutrient feed was supplied by a recirculation pump from a recirculation tank for 5 minutes every 30 minutes at a rate of 240 mL min\(^{-1}\) feeding approximately 1.2 L per cycle. The nutrient feed contained per liter of tap water: KCl 73.3 mg, CaCl\(_2\)·2H\(_2\)O 44 mg, NH\(_4\)Cl 166.7 mg, MgSO\(_4\)·7H\(_2\)O 367 mg, K\(_2\)HPO\(_4\) 24 mg, and 20 µL of trace metal solution. Incubation was conducted for 24 hours at 25 ± 1°C. Afterwards, the inoculation sponges were removed. Inoculated substrate sheets were then individually placed underneath a blank test sponge in separate airtight channels.

**Function of sponge media during different flow**

The channels were divided into two groups, I and C, with each group having a different flow pattern. For group I, diluted nutrient feed was supplied for 5 minutes every 240 minutes at a flow rate of 240 mL min\(^{-1}\) via a feed pump, P3. For group C, diluted nutrient feed was supplied continuously at a flow rate of 5 mL min\(^{-1}\) via another feed pump, P3. The volumetric loading per channel was the same at 7.2 L d\(^{-1}\). Here, I denotes intermittent flow and C denotes continuous flow.

Four channels containing different test sponges were observed per group. The four channels were labelled S1, S2, L1, and L2. In this nomenclature, S denotes sponge type BCC-2.
with smaller pore radius of 0.6 mm, and L denotes sponge type BCD-2 with larger pore radius of 0.9 mm. The numbers 1 and 2 denote the thickness of the sponge in centimeter. All the test sponges were 7 cm wide and 40 cm long. Test sponges in each channel was divided into top and bottom layers where the top layer was the upper depth and the bottom layer was the lower depth of the test sponge sheets. For test sponges in S1 and L1, the top and bottom layers were 0.5 cm thick, together forming a 1 cm thick sheet. Similarly, test sponges in channels S2 and L2 had top and bottom layers which were 1 cm thick, together forming a 2 cm thick sheet. Each test sponge was placed on top of an inoculated substrate sheet and aerobic activity was monitored for 32 days with different flow. The retained water height and flowing water height during operation were measured with a ruler.

To simplify the subsequent discussions, channels operated under intermittent flow (Group I) will be termed as I-S1, I-S2, I-L1, and I-L2, respectively. Similarly, channels operated under continuous flow (Group C) will be named as C-S1, C-S2, C-L1, and C-L2.

### Biomass analysis

#### Biomass extraction

Biomass was manually extracted from the whole of the top and bottom test sponge layers by scraping and suspending in ultrapure water after assessing biomass oxygen consumption. Manual biomass extraction was repeated as needed. The extracted biomass was subjected to total biomass density analysis immediately after extraction.

#### Biomass density analysis

The biomass density in the top and bottom test sponge layers was estimated based on the nitrogen content in the extracted biomass [14]. Here, biomass density means the amount of biomass per volume of test sponge media. The amount of organic nitrogen was evaluated in each test sponge layer after a full experimental run of 32 days.

Each extracted biomass sample was resuspended in a volume of water and 2 mL of the suspension was placed in a separate reaction tube. To the reaction tube, 7 mL of 1 N NaOH was added and mixed. The reaction tube was closed and incubated in a 100 ± 1°C oven for 1 hr then, taken out and cooled to room temperature. After cooling, 1 ml of 5N H₂SO₄ solution was added and mixed to each tube. The mixture was analyzed for total nitrogen (TN) concentration using a TN analyzer (TOC-V with TNM-1, Shimadzu Corporation, Kyoto, Japan). The TN concentration was multiplied by 8.07 to obtain biomass concentration, assuming biomass composition to be (C₅H₇NO₂) [15]. The biomass concentration was multiplied by the volume of the suspension and divided by the volume of the test sponge to get the biomass density.

### RESULTS

#### Water retention and flow in the sponge media

Table 1 shows the summary of the water heights and top surface condition of the test sponges for each channel.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Flowing water height (cm)</th>
<th>Retained water height (cm)</th>
<th>Surface condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-S1</td>
<td>1</td>
<td>1</td>
<td>Wet</td>
</tr>
<tr>
<td>I-S2</td>
<td>2</td>
<td>2</td>
<td>Wet</td>
</tr>
<tr>
<td>I-L1</td>
<td>1</td>
<td>&lt;1</td>
<td>Wet</td>
</tr>
<tr>
<td>I-L2</td>
<td>2</td>
<td>1</td>
<td>Dry</td>
</tr>
<tr>
<td>C-S1</td>
<td>0.75</td>
<td>-</td>
<td>Dry</td>
</tr>
<tr>
<td>C-S2</td>
<td>0.75–1</td>
<td>-</td>
<td>Dry</td>
</tr>
<tr>
<td>C-L1</td>
<td>0.5</td>
<td>-</td>
<td>Dry</td>
</tr>
<tr>
<td>C-L2</td>
<td>0.5</td>
<td>-</td>
<td>Dry</td>
</tr>
</tbody>
</table>

For Group I channels, the full volume of the test sponge was filled with water during flow. Water was discharged from the media when flow stopped, while part of the water was retained inside the test sponge. Retained water heights did not change significantly after discharge. The water heights retained in channels I-S1 and I-L1 were almost the same as the test sponge thickness. Retained water height for channel I-S2 was slightly lower than the test sponge thickness. The test sponge in channel I-L2 had an approximate retained water height of 1.0 cm with most of the top surface dry to the touch. That is, the top surface under the influent tube was the only wet area. The top surface of test sponge in channel I-S2 was wet to the touch.

Water heights in Group C channels were also measured. As the applied flow rate was constant, the water height was also constant. The water height in channel C-S1 was about 0.75 cm with a wet top surface. The test sponge in channel C-S2 had a water height of 1.0 cm from the influent side and decreased to about 0.75 cm at the discharge side. Test sponges in channels C-L1 and C-L2 had flowing water height of about 0.5 cm. For channels C-S2, C-L1, and C-L2, the top surface of the test sponges was dry.
Oxygen consumption rates during different flow patterns

The oxygen consumption rates per sponge area of each channel operated under intermittent and continuous flow patterns are shown in Fig. 3. The oxygen consumption rates for the last 3 days of channel C-S2 could not be evaluated because of sensor failure.

For the Group I channels, the areal oxygen consumption rates ranged between 0.60–2.12 gO₂ m⁻² d⁻¹ for channel I-S1, 0.77–1.47 gO₂ m⁻² d⁻¹ for channel I-S2, 1.17–1.73 gO₂ m⁻² d⁻¹ for channel I-L1, and 0.90–1.10 gO₂ m⁻² d⁻¹ for channel I-L2. For Group C channels, the oxygen consumption rates ranged 2.17–5.18 gO₂ m⁻² d⁻¹ for channel C-S1, 1.90–4.60 gO₂ m⁻² d⁻¹ for channel C-S2, 2.23–4.27 gO₂ m⁻² d⁻¹ for channel C-L1, and 1.73–3.17 gO₂ m⁻² d⁻¹ for channel C-L2. The final rates for Group I channel gathered at day 32 were 1.10 gO₂ m⁻² d⁻¹ for channel I-S1, 1.0 gO₂ m⁻² d⁻¹ for channel I-S2, 1.50 gO₂ m⁻² d⁻¹ for channel I-L1, and 1.20 gO₂ m⁻² d⁻¹ for channel I-L2. For group C channels, the final rates were 3.35 gO₂ m⁻² d⁻¹ for channel C-S1, 3.55 gO₂ m⁻² d⁻¹ for channel C-L1, and 2.80 gO₂ m⁻² d⁻¹ for channel C-L2. The final recorded rate for channel C-S2 was 2.40 gO₂ m⁻² d⁻¹. Results showed that aerobic activity was generally higher for sponges L1 and L2 than S1 and S2 regardless of flow pattern. A decreasing rate trend was also found with increased test sponge thickness.

Rates varied over time however, certain trends can still be found. Oxygen consumption rates for channel I-S1 showed a decreasing trend over time. On the other hand, there were no significant changes in oxygen consumption rates for channels I-S2, I-L1, and I-L2. Group C channels C-S1 and C-S2 showed a decreasing trend until day 15 and until day 8 for channels C-L1 and C-L2. Afterwards, rate increase was observed until the end of the observation period. The higher
rates during the first week of operation may be due to the following: presence of readily soluble components in the substrate sheet and initial propagation of microorganisms with available surface. Results showed that Group C channels had higher oxygen consumption rates. Rates were found to be similar for channels operated with the same flow pattern.

**Test sponge analysis**

**Contribution to oxygen consumption**

The areal oxygen consumption rate of each dewatered top test sponge layer was evaluated at the end of the 32-day observation period and the results are presented in Fig. 4. Oxygen consumption rates ranged between 0.65–0.80 gO₂ m⁻² d⁻¹ for smaller pore cell radius sponges (S1, S2) and 0.40–1.00 gO₂ m⁻² d⁻¹ for larger pore cell radius sponges (L1, L2). The contribution of the top layers to the rates of the full sponge at the end of operation was 33–70% for Group I channels and 12–42% for Group C channels. The estimated contribution is thought to be valid because the top test sponge layers were not filled with water during operation, except for test sponges in channels I-S1 and I-S2, as shown in Table 1. Hence, the percentages for test sponges in channels I-S1 and I-S2 may be overestimated as the top layers were filled with water during operation. The oxygen consumption rate for the top layers of Group C channels were generally higher than those found for Group I channels except for S1. However, top test sponge layers from Group I channels showed a higher percentage of contribution to the overall aerobic activity than those in Group C channels.

**Biomass density**

The biomass density from the top and bottom layers of each test sponge was evaluated and the results are shown in Fig. 5. Values ranged between 0.00–0.14 mg cm⁻³ for top layers, 0.44–1.75 mg cm⁻³ for bottom layers, and 0.25–0.95 mg cm⁻³ when the biomass density for the full test sponge was considered. Biomass content for the top layer of channel C-S2 was below detection limit. Biomass density was higher for bottom layers when compared with their corresponding top layers for all flow patterns. For test sponges with smaller pore cell radius (S1, S2), values were higher for Group C channels than Group I channels. The opposite was true for test sponges with larger pore cell radius (L1, L2). The evaluation of biomass density for the full test sponge showed similar trends to those found for the bottom layer.

**DISCUSSION**

**Interpretation of oxygen consumption rates**

The aerobic degradation of accumulated organic matter was studied by using lipids as a model substrate. Lipid, in the form of margarine, was used because of its low solubility in water and its ability to remain solid inside the channels at the operating temperature.

Oxygen consumption rates per sponge area were evaluated to assess the aerobic activity related to accumulated organic matter degradation. Detected oxygen consumption was thought to be due to degradation of the lipid substrate because the consumption of an electron acceptor is strongly related to the consumption of an electron donor. The only available electron donor comes from the lipid substrate, including lipids assimilated as biomass. Oxygen consumption by nitrification was thought to be minimal.

Although aerobic degradation of organic matter was focused on, anaerobic degradation was also thought to occur in each channel. A faint smell of rotten eggs, indicative of hydrogen sulfide, was detected during air recirculation inside the channels. However, further contribution of anaerobic processes to accumulated organic matter degradation was no longer focused on.
Function of porous media during different flow

In the following sections, the function of the porous media that is directly and not directly in contact with accumulated organic matter during different flow is discussed focusing on the implications of additional media volume above the accumulated organic matter. The portion of the media that is directly and not directly in contact with the accumulated matter was previously shown in Fig. 1. Succeeding discussions are based on findings when intermittent and low continuous flow were applied.

Porous media during intermittent flow

Significant aerobic activity and biomass growth were found for top layers although they were not in direct contact with the accumulated lipid substrate, as shown in Fig. 4 and Fig. 5, respectively. The top test sponge layers contributed 33–70% of the final oxygen consumption rates. As shown in Fig. 5, the biomass contribution from the top layers was between 3–12% of the total. The findings highlight the significant contribution of the top media surface to aerobic activity related to accumulated organic matter degradation.

Areal expression of the oxygen consumption rates (Fig. 3) showed that the mass of oxygen consumed per channel was similar. The similarity indicated that most of the aerobic activity, and biomass growth, may have been concentrated around the lipid substrate contained in the substrate sheet. However, the percent contribution of the top layers shown in Fig. 4, especially for L2, indicate that majority of the aerobic activity was on the top layer although the top layer did not directly access the accumulated substrate. This means that oxygen could not effectively penetrate to the bottom layer and instead, aerobic degradation of accumulated organic matter was concentrated on the top layer which experienced intermittent flow and water discharge. The findings open the question on what caused the aerobic activity to the top layer.

Intermittently submerged top layers, emphasized by top test sponge layers in I-L1 and I-L2, played a key role during intermittent flow. It was described that when flow occurred, the full sponge media was filled with water. At this time, mixing due to turbulence occurred inside the media which allowed organic material transport from the bottom layer to the top layer. Water was discharged from the media when flow stopped. When discharge stopped, some water was retained in the media through capillary action. Previously submerged top layers were then fully exposed to the headspace-gas. However, mechanisms other than turbulence may have also contributed to the organic matter transport to the top layers such as biological material transport.

It is shown in Fig. 3 and Fig. 5 that test sponges which have a larger pore cell radius (L1, L2) had higher aerobic activity and biomass density than those with smaller pore cell radius (S1, S2). The difference may be due to the retained water in the media after flow. The pore cell radius affected the retained water volume in the media through capillary action such that the larger the pore cell radius, the lower the retained water height [16]. Sponges with larger pore cell radius (L1, L2) retained water less which led to increased aerobic condition in the top layer. Increased aerobic condi-

Fig. 5  Biomass density in Top and Bottom test sponge layers and then the full media volume (TB) in Group I (□) and Group C (■) channels containing BCC-2 1 cm (S1) and 2 cm (S2) thick test sponge, and BCD-2 1 cm (L1) and 2 cm (L2) thick test sponge.
tion may have led to increased biomass growth and ability to oxidize organic matter.

Slight decrease in aerobic activity when media thickness was increased from 1 cm to 2 cm can be explained by the increased retained water height influenced by capillary action for both types of test sponges. Retained water was higher for test sponge with smaller pore cell radius (S1, S2) where the resulting retained water height was the same as the test sponge thickness for both 1 cm and 2 cm thicknesses used. When flow stopped, Sotelo et al. [17] suggested that diffusive oxygen mass transfer occurred and was negatively affected by increased retained water height.

**Porous media during continuous flow**

During low continuous flow, lower aerobic activity was observed when the test sponge thickness was increased from 1 cm to 2 cm and when pore cell radius was decreased. Observations in **Table 1** suggest that flowing water height during operation was less than the media height and that water mostly flowed at the bottom layer. The flowing water height was affected by the pore cell radius of the media through capillary action where smaller pore cell radius resulted to a higher flow height [16].

The flow height was not significantly affected by increased media thickness as indicated by the similar flow height between S1 and S2 and L1 and L2. However, slightly lowered aerobic activity was observed with increased media thickness which means that the additional media thickness hindered oxygen mass transfer to the bottom layer.

Aerobic activity related to organic matter degradation was concentrated in the bottom layer near the accumulated organic matter during low continuous flow. This is supported by the lower percentage of contribution of the top media layers to the aerobic activity (Fig. 4) and the higher biomass density of the bottom media layers (Fig. 5 **Bottom**). This finding indicates that the media layer that cannot be reached by the flowing water height could be detrimental to aerobic accumulated organic matter degradation when low continuous flow is expected.

**Effect of flow**

Areal oxygen consumption rates were higher for Group C channels than Group 1 channels. The difference in the oxygen consumption rates could be explained by the difference in oxygen mass transfer mechanism to the biofilm grown in the test sponge. When intermittent flow was applied in this study, diffusive mass transfer occurs during the almost 4-hr duration when there was no flow. During long extents without flow observed in the intermittent flow pattern applied, diffusive mass transfer occurs. The very surface of the media is continuously supplied with oxygen but, as water flow does not occur, oxygen is consumed only on the surface without being transported inside the sponge [17]. On the other hand, during flow, oxygen is transferred more effectively to the biofilm via convective mass transfer in porous media [18]. This means that the biomass can obtain more oxygen, and is more aerobically active, during continuous flow.

**Relevance on enhanced sewer self-purification**

Enhanced sewer self-purification using porous media is affected by the flow frequency, flow rate, and physical structure of the media used [5,13,14]. Flow frequency and rate cannot be controlled because sewer pipes only experience flow when wastewater-generating activities occur [11]. Hence, the media structure should be considered during the design phase. The choice of media structure is dependent on the predominant sewer pipe flow regime.

Upstream sewer pipes, or lateral sewer lines which are directly connected to buildings, have highly intermittent flow [19]. By studying household appliance use, researchers have described that long periods without flow predominate in upstream sewer pipes [11,20,21]. A high flow rate is expected at the influent side of the pipe during flow events, followed by water retention as discharge continues. If porous media is applied, the media would be fully submerged and then subsequently dewatered. In such situations, our findings indicate that the use of thick, large pore cell radius media would be beneficial to enhance sewer self-purification.

Dynamic flow from the upstream sewer lines would dissipate to slow, almost continuous wastewater flow. For enhanced sewer self-purification, the current findings suggest that it would be advisable to use thin porous media that has smaller pore cell radius for pipes near the trunk line. However, long-term studies need to clarify whether pore cell radius and thickness would still have significant effects on the aerobic activity when surface clogging occurs.

**CONCLUSIONS**

The function of porous media under different flow patterns during accumulated organic matter degradation was studied. The following conclusions were drawn:

1. Accumulated organic matter degradation was observed with oxygen supply during flow and with exposure of the media to headspace-gas during continuous and intermittent flow. Continuous flow enhanced aerobic
activity as Group C channels consistently exhibited higher rates as shown in Fig. 3.

2. The bottom layer near accumulated organic substrate have higher contribution to aerobic degradation regardless of flow pattern and it was likely due to the higher biomass density for the bottom layers as shown in Fig. 5.

3. The top layer which was not in direct contact to accumulated organic matter had different functions depending on flow pattern.

3.1 With intermittent flow, most of the aerobic activity came from the top layers as shown in Fig. 4, which implies that the top layers functioned to enhance aerobic activity after dewatering occurred.

3.2 With low continuous flow, the absence of flow to the top layer caused lower contribution to aerobic activity related to accumulated organic matter degradation.

This study highlighted the effect of excess media space above accumulated organic matter during enhance sewer self-purification when intermittent and low continuous flow are applied. Pilot studies incorporating these findings are advisable when considering the performance evaluation of enhanced sewer self-purification by porous media.

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