Water Res. Vol. 17, No. 7, pp. 813–821, 1983
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0043-1354/83/070813-09$03.00/0

BIOLOGICAL CLOGGING OF SAND AND CHANGES OF ORGANIC CONSTITUENTS DURING ARTIFICIAL RECHARGE

T. OKUBO[1] and J. MATSUMOTO[2]
[1]Nippon Jogesuido Sekkei Co. Ltd, 1-9-15 Kaigan Minato-ku, Tokyo 105 and
[2]Department of Civil Engineering, Tohoku University Sendai 980, Japan

(*Received June* 1982)

Abstract—Biological clogging during artificial ground water recharge is divided into three stages, i.e. aerobic period, transitional period from aerobic conditions to anaerobic conditions and anaerobic period. During the transitional period, the infiltration rate is almost constant or increases slightly because of the transient decrease of microbial accumulation in the sand column. Experimental result shows that the secondary effluent infiltrated through the sand must have SS (Suspended Solids) of $<2\ \mathrm{mg\,l^{-1}}$ and SOC (Soluble Organic Carbon) of $<10\ \mathrm{mg\,l^{-1}}$ to maintain a high infiltration rate during a long inundation period. The gel chromatogram data show that the biological clogging plays an important role in preventing contamination of an aquifer during recharge by polluted water.

INTRODUCTION

Artificial ground water recharge is practiced as a method of conservation of ground water resources. It is reasonable to reuse wastewater through artificial recharge, because artificial recharge is an effective way to increase the ground water storage in an aquifer, to prevent a decrease of ground water level and an invasion of salt water and to reclaim the water quality. For the success of water reclamation by the artificial recharge it is essential to keep a high infiltration rate for a long period of time. For the design and operation of a recharge system it is necessary to understand the mechanism of sand clogging and to predict the optimum inundation period. Factors affecting the clogging can be classified into physical, chemical and biological ones. Biological clogging that threatens to come about when the secondary effluent percolates through the sand is a major problem.

Avnimelech & Nevo (1964), Mitchell & Nevo (1964) and Nevo & Mitchell (1967) reported that biological clogging appeared to be correlated with a decline in the measured oxidation–reduction potential in the sand. De Vries (1972) reported that the loss of infiltration was caused by a sludge layer formed on the soil surface. Wood & Bassett (1975) showed that the growth of anaerobic bacteria in artificial recharge basins affected both the hydraulic conductivity and the chemical quality of recharge water. Okubo & Matsumoto (1979) showed that the initial specific discharge had no effect on the change of hydraulic conductivity in the surface layer. Idelovitch and Michail showed that the main dangers of ground water pollution by seepage of effluents from oxidation ponds appeared to be connected with soluble organics and unoxidized form of nitrogen (Idelovitch & Michail, 1980). These studies have given much information upon biological clogging associated with the ground water recharge. However, the biological clogging process has not yet been clarified for the reason of its complexity. The purpose of this paper is to make clear the biological clogging process and the constitutional change of organic compounds under prolonged submergence, and to predict the change of specific discharge in the recharge system based on the experimental results.

EXPERIMENTAL APPARATUS AND PROCEDURE

A schematic diagram of a sand column used in this study is shown in Fig. 1. The columns are made of polyvinyl chloride, and they are 74 cm in height and 10 cm in diameter. Each column is filled with 10 cm of pea gravel and 40 cm of sand. The sand composed of 0.25–0.42 mm diameter fractions is packed into the column so that the bulk densities range from 1.4 to $1.5\ \mathrm{g\,cm^{-3}}$. The uniformity coefficient of the granular medium is about 1.2. The saturated hydraulic conductivity of column is about $5.0 \times 10^{-2}\ \mathrm{cm\,s^{-1}}$. Hydraulic heads are measured by using piezometers located 1, 4, 12 and 22 cm below the sand surface. The linear distribution of pressure loss shows that the permeability and the porosity are uniform all along the sand bed. The synthetic wastewater is continuously fed into the column by a diaphram metering pump. In order to clarify the effects of initial specific discharge (discharge per unit cross-sectional area of column, q_0), soluble organic carbon (SOC) concentration of influent (C_i) and temperature (T) on biological clogging, the experiments are carried out using the synthetic wastewater mainly composed of glucose. Activated sludge flocs homogenized by an ultrasonic generator are added to the influent synthetic wastewater in order to estimate the effect of organic suspended solids (SS) concentration of influent (S_i) on the clogging.

Three kinds of synthetic wastewater of starch, peptone and skimmed milk were percolated through the sand to investigate the changes of organic constituents. The C/N ratio of 1.44 and the organic carbon concentration of wastewater resemble that of a secondary treated effluent (Ohgaki *et al.*, 1978). Chemical oxygen demand (COD), total organic carbon (TOC), glucose and volatile fatty acid are determined. Gel chromatography was used to determined the apparent molecular weight (MW) of organic

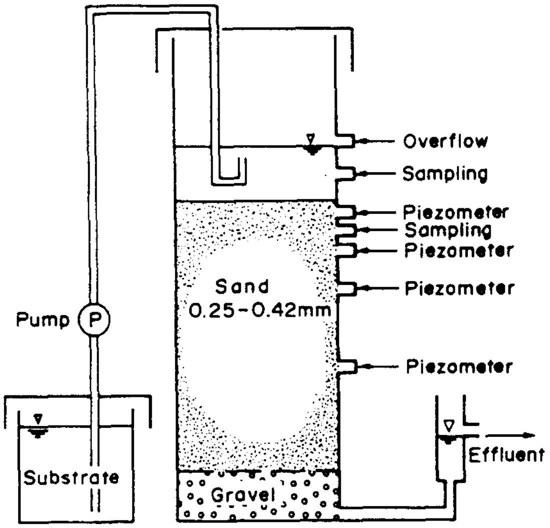

Fig. 1. Schematic diagram of sand column.

constituents, using Sephadex G-15 (Pharmacia, Sweden) as a separation medium.

BIOLOGICAL CLOGGING PROCESS

The biological clogging process is discussed on the basis of changes in the infiltration rate, water quality and head loss; and, on the basis of growth characteristics of microorganisms.

The variation of infiltration rate at an influent glucose concentration of $54\,\text{mg}\,\text{l}^{-1}$ is shown in Fig. 2. The infiltration rate is defined as the discharge per unit area of cross section and therefore equivalent to the specific discharge. Figure 3 shows the variations in infiltration rate at the inundation of starch, peptone and skimmed milk. The synthetic wastewater of starch, peptone and skimmed milk is infiltrated at the same carbon concentration as the inflitration of glucose. The change of infiltration rate can be divided into three stages on the basis of changes in the water quality, head losses and hydraulic conductivity during inundation period as follows: (1) The infiltration rate decreases rapidly with the reduction of dissolved oxygen (DO) due to aerobic microbial growth for the first 10 days (aerobic period). (2) The infiltration rate is almost constant or increases slightly for the next 10 days. The DO concentration at 2 cm depth of the sand becomes less than $1\,\text{mg}\,\text{l}^{-1}$ on the 14th day. The aerobic microbial growth is limited by the lower DO level during this period (transitional period). (3) The infiltration rate decreases rapidly after the 21st day as biological clogging develops under anaerobic conditions. The soluble COD at the 2 cm depth becomes higher than that of the influent because the anaerobic degradation of microbial products occurs in the surface layer. However, the soluble COD of the effluent is stable during 3 months of infiltration (anaerobic period).

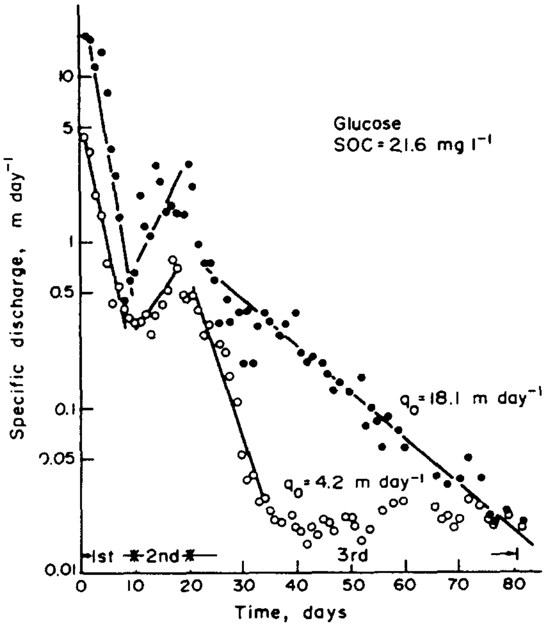

Fig. 2. Variation of infiltration rate in infiltration of glucose.

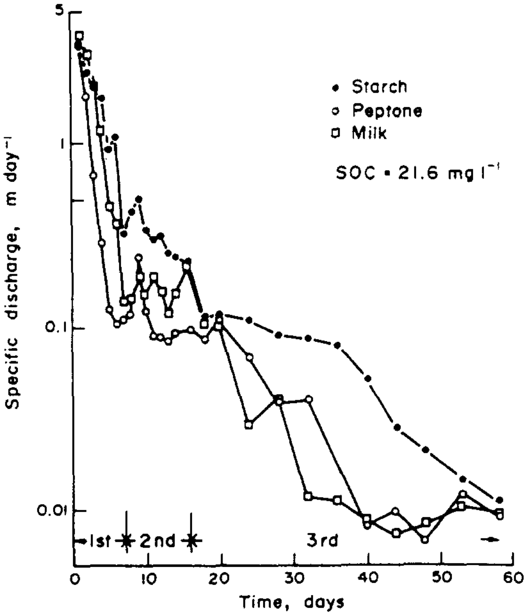

Fig. 3. Variation of infiltration rate in infiltration of three kinds of substrate.

The head losses at the 1, 4, 12 and 22 cm depth increase rapidly for the first 10 days. Head loss at 1 cm depth is almost constant between the 10th and the 18th day, and it decreases slowly on and after the 19th day. The decrease of head loss may be due to the anaerobic degradation in the clogging surface layer. Figure 4 shows the variation of TOC at the infiltration of starch, peptone and skimmed milk. The ($\text{TOC}_{\text{inf}} - \text{TOC}_{\text{eff}}$) concentration transiently decreased on the 10th day because the aerobic microbial activity is suppressed by the low DO conditions. The results of TOC removal suggest that there is a transition of oxidation-reduction conditions during this period.

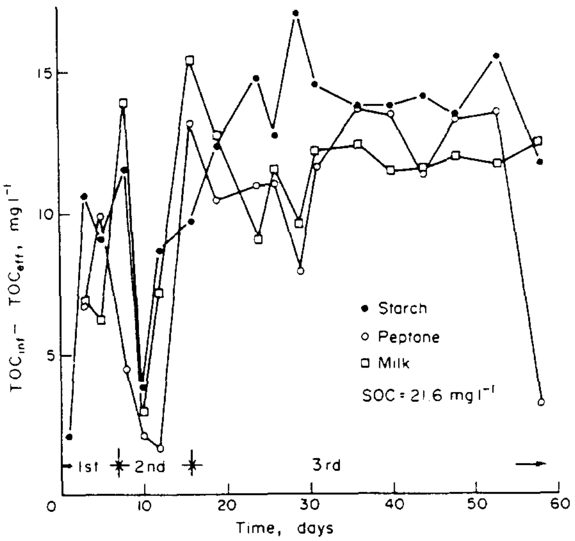

Fig. 4. Variation of TOC removal during inundation period.

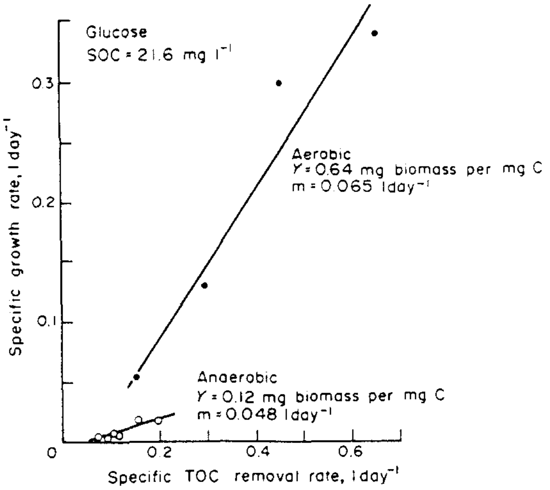

Fig. 6. Relationship between specific growth rate and specific TOC removal rate.

Figure 5 shows the change of microbial dry weight in the column during the inundation period. This experiment is performed using the small columns. The columns are 15 cm in height and 2.6 cm in diameter. The synthetic wastewater of glucose is infiltrated into the same 14 columns and the dry weight of microorganisms in the column is measured every second day during inundation period. The dry weights of microorganisms in the column increases rapidly and the effluent DO from the column decreases with the time for the first 7 days. The dry weight decreases transiently after the aerobic microbial growth and increases slowly after the 15th day. The transient decrease of microbial weight may be caused by the degradation of aerobic microorganisms under anaerobic conditions of the column. The infiltration rate increases transiently during the transitional period as stated previously because the dry solids of microorganisms in the surface layer decreases during this period. It is obtained from the data of Fig. 5 and the cross-sectional area of the column that the dry weight of microorganisms per cross-sectional area on the 35th day is 4.1 mg cm^{-2}.

Figure 6 shows the growth yield coefficients (Y) and the maintenance costants (m) during aerobic and anaerobic period of biological clogging process at the influent glucose of 54 mg l^{-1}. The growth yield coefficient of the aerobic period is 5 times as large as that of anaerobic period.

The microbial growth characteristic at the low DO of the influent is examined by a similar experimental procedure. The DO of influent wastewater was

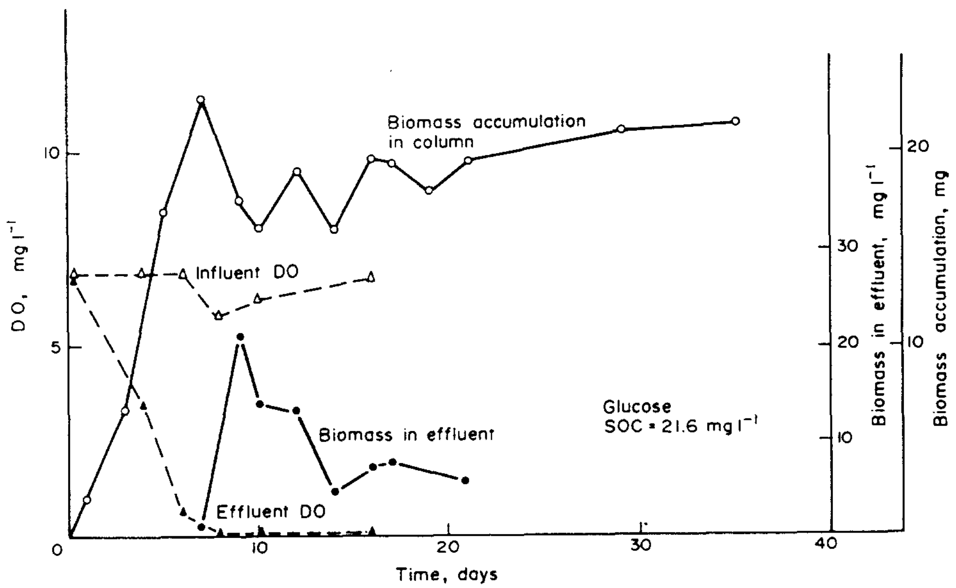

Fig. 5. Change of microbial dry weight in the column.

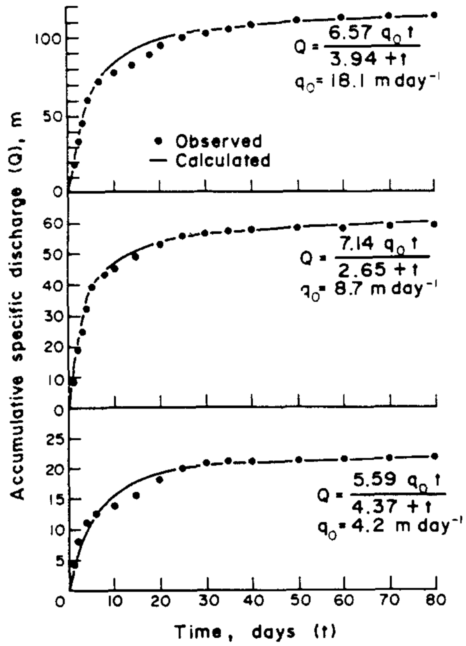

Fig. 7. Changes of accumulative specific discharge.

reduced by bringing N_2 gas into contact with the influent. The growth yield coefficient is 0.35 mg dry solids/mg C at the influent DO of less than 0.8 mg l^{-1}, which is half of the value during aerobic period. The results show that the biological clogging develops more slowly at lower influent DO. However, the organic matter of wastewater is not completely degraded and the degradation rate of the organic compound is usually slower under the low DO conditions.

The microbial accumulation in the surface layer of column is 3.9 mg cm^{-2} as a dry solid on the 28th day of inundation when the infiltration capacity is very small. Both sets of microbial growth data show that the infiltration rate is very slow at an microbial accumulation per unit cross-sectional area of more than 4.0 mg cm^{-2} as a dry solids weight (Okubo & Matsumoto, 1981a). This value may be useful in evaluating biological clogging by the data of yield coefficient and organic matter removal.

The biological appearance of the surface layer of column is observed microscopically during the inundation period. Filamentous fungi are predominant in the column at the first stage of the biological clogging process followed by active growth of rod-shaped acidogenic bacteria. At the third stage of anaerobic period, ciliate appears in sight and the species in the sand become more variable with the development of biological clogging.

FACTORS AFFECTING BIOLOGICAL CLOGGING

Effect of initial specific discharge (q_0)

The accumulative specific discharge (Q) is plotted with time at q_0 of 4.2–18.1 m d^{-1} in Fig. 7. A limit of Q for the increasing inundation period is higher at a greater initial specific discharge. After the 30th day of infiltration, the accumulative specific discharge is almost constant in the three columns. It has been previously shown that the change of accumulative specific discharge could be evaluated by the following equation (Okubo & Matsumoto, 1981b).

$$Q = \frac{K_1 q_0 t}{K_2 + t}. \tag{1}$$

Where Q is the accumulative specific discharge (m), q_0 is the initial specific discharge (m d^{-1}), K_1 and K_2 are the parameters and t is the time (d). The K_1 value is a limit of Q/q_0 for an increasing inundation period of t while the K_2 value is an inundation period at which Q/q_0 is half the maximum. There is a successful agreement between the observed data and the calculated results by data fitting as shown in Fig. 7. As to the relationship between the two parameters and q_0, the important result is that the two parameters of K_1 and K_2 are not dependent upon q_0.

Effect of influent SOC concentration (C_i)

It is shown by many workers that the growth rates of microorganisms depend upon the concentration of the constituents in the nutrient medium. The algebraic description of this dependence is most commonly expressed by the Monod equation. It is accepted that this equation can depict the general variation of the growth rate with substrate concentration. As the biological clogging is caused by the microbial growth, the influent SOC concentration is one of the most important factors influencing the biological clogging. Figure 8 shows the change of accumulative specific discharge at the different SOC concentrations of influent. There is a successful agreement between the observed data and the calculated results determined by curve fitting. As to the relationship between the K_1 and K_2 values and C_i, an approximation is made with the following expressions:

$$K_1 = 349\, C_i^{-1.32} \tag{2}$$

$$K_2 = 195\, C_i^{-1.32} \tag{3}$$

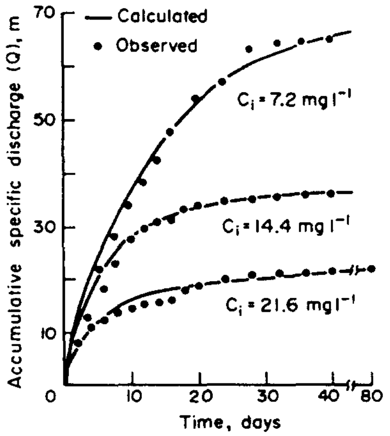

Fig. 8. Effect of influent SOC concentration.

It is clear that the K_1 and K_2 values decrease in inverse proportion to the 1.32 powers of C_i and that they are influenced more significantly at lower influent SOC concentration.

Temperature effect

Figure 9 shows the change of accumulative specific discharge at the different column temperature. The influent SOC concentration of wastewater used in this experiment is about 21.6 mg l^{-1}. The corresponding curves in Fig. 9 show good agreements between the observed data and the calculated results except the case of 5°C. The effect of temperature on biological clogging is estimated by using the temperature coefficient, θ, in the same manner as that used in *Phelps* relationship.

The experimental relationship between the K_1 and K_2 values and the temperature is obtained as follows:

$$K_{1,T^\circ C} = K_{1,20^\circ C} \times 1.0608^{-(T-20)} \tag{4}$$

$$K_{2,T^\circ C} = K_{2,20^\circ C} \times 1.0608^{-(T-20)} \tag{5}$$

where $K_{1,T^\circ C}$ and $K_{2,T^\circ C}$ are the K_1 and K_2 values at T°C. The two equations of (4) and (5) determined here are in a good agreement with the experimental results.

Effect of influent organic suspended solids (S_i)

Secondary treated effluent from the treatment plant contains suspended organic matter which cannot be removed in the sedimentation process. Organic suspended solids in secondary effluent may have a significant impact on the sand clogging. In order to estimate the effect of influent organic SS concentration on clogging, synthetic wastewater, of which the organic SS concentration ranges from 1.4 to 14.6 mg l^{-1}, is percolated through the sand column at 20°C.

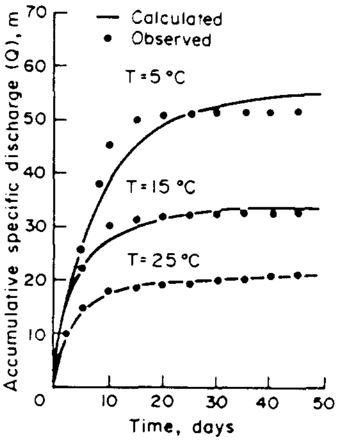

Fig. 9. Effect of temperature.

The change of accumulative specific discharge at different organic SS concentrations is plotted against time in Fig. 10. There is a good agreement between the observed data and the calculated results. Equation (1) may be used to evaluate the clogging caused by the organic suspended solids. Figure 11 shows the relationship between the K_1 & K_2 values and the influent organic SS concentration.

The following equations are determined by linear regression analysis:

$$K_1 = \frac{K_{1,S_i=0}}{1 + 18.5\exp(-5.7\,S_i)} \tag{6}$$

$$K_2 = \frac{K_{2,S_i=0}}{1 + 87.3\exp(-10.7\,S_i)} \tag{7}$$

where S_i is the influent organic SS concentration

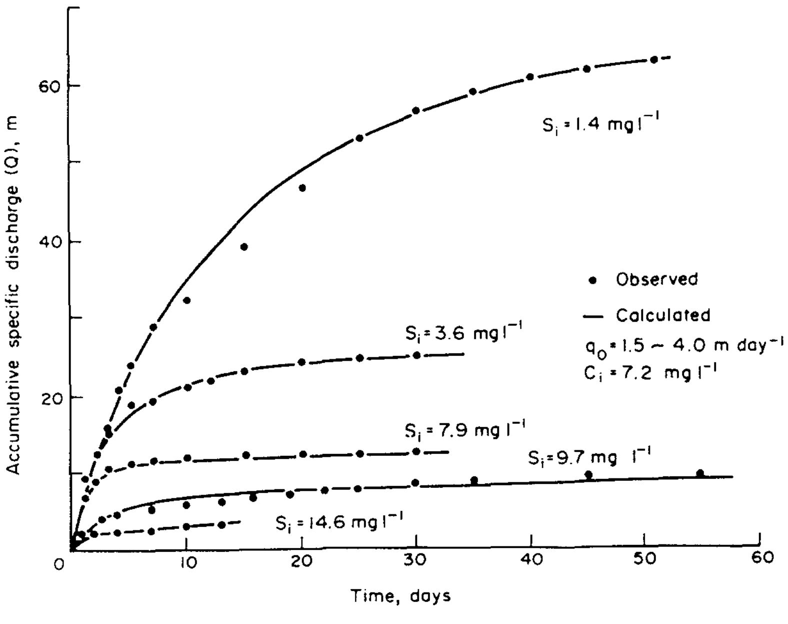

Fig. 10. Effect of influent SS concentration.

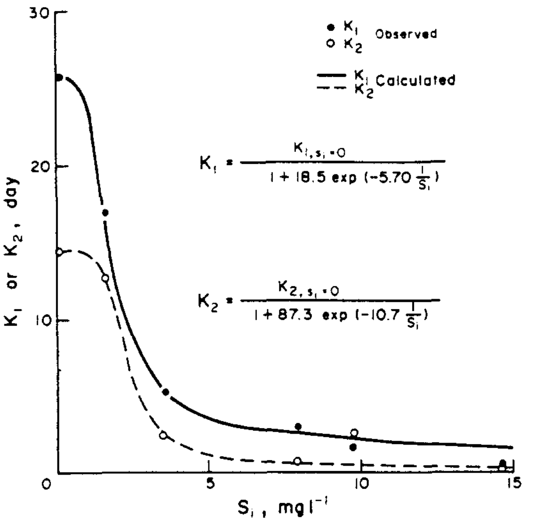

Fig. 11. Relationship between K_1 and K_2 values and S_i.

(mg l^{-1}) and $K_{1,S_i=0}$ and $K_{2,S_i=0}$ are the K_1 and K_2 values at $S_i = 0$, respectively. The K_1 and K_2 values decrease with the increase of influent SS concentration. The effluent SS concentration of the sand column is observed to be nearly constant, that is about 2 mg l^{-1}, in this experiments (Okubo & Matsumoto, 1980). At low SS concentration of the influent, the accumulation of SS stored in the surface layer is small because large part of the influent SS may be discharged from the column outlet. The K_1 and K_2 values decrease at higher SS concentrations than 2 mg l^{-1}. It is likely that the deposited matter stored in the sand surface layer is useful to remove the organic SS imposed upon the sand column. It is impossible to infiltrate secondary treated effluent containing a lot of organic suspended matter through the sand layer for a long inundation period. The organic suspended matter of the secondary effluent must be removed by a physical or chemical treatment process such as a rapid filtration process before the application of the secondary effluent to the recharge system.

Prediction of accumulative specific discharge

Based on experimental results, the accumulative specific discharge Q is expected to express itself as a function of q_0, C_i, T, S_i and time t. If the five variables are independent of each other, the accumulative specific discharge can be estimated by the following equations:

$$Q = \frac{K_1 q_0 t}{K_2 + t} \tag{8}$$

$$K_1 = \frac{349 \times 1.0608^{-(T-20)} C_i^{-1.32}}{1 + 18.5\exp(-5.70/S_i)} \tag{9}$$

$$K_2 = \frac{195 \times 1.0608^{-(T-20)} C_i^{-1.32}}{1 + 87.3\exp(-10.7/S_i)} \tag{10}$$

where Q is the accumulative specific discharge (m) and t is time (d). It is important to predict the K_1 value related to the maximum accumulative specific discharge during artificial recharge. Figure 12 shows the predicted value of K_1 at 20°C. The K_2 value must be evaluated in order to determine an alternating schedule of flooding with drying periods. Figure 13 shows the calculated results of K_2 value. Equations (8)–(10) may be used to design the artificial recharge system and to determine the optimum inundation period.

BEHAVIOUR OF ORGANIC CONSTITUENTS

As stated previously, the biological clogging process is divided into the three stages and the organic constituents of effluent may be different at each stage during the inundation period. The change of organic constituents is examined using gel chromatography. Sephadex G-15 is used as a separation medium (Pharmacia, Sweden), and distilled water and 0.1 N NH_4OH are used as eluents (Kamei & Tambo, 1977). A sample of sand column effluent is filtered through a 0.45 μm Millipore filter. The filtered sample is concentrated by rotary evaporation at 40°C and adjusted to a pH between 7 and 8. The TOC concentration and the absorbance at the wave length of 220 and 260 nm are measured in order to get the apparent molecular weight distribution of all organic carbon in the sample.

Figure 14 shows the chromatograms of sand column effluent on the 1st, 7th and 30th days of the inunda-

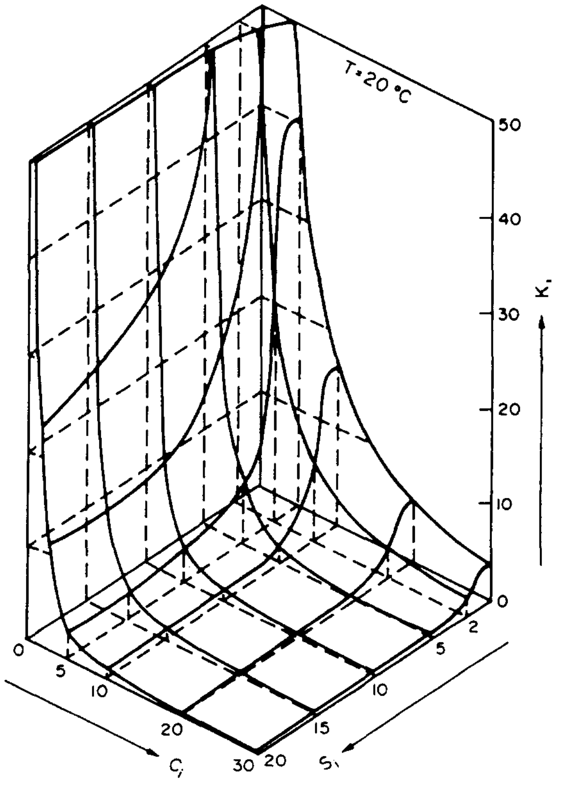

Fig. 12. Prediction of K_1 value at 20°C.

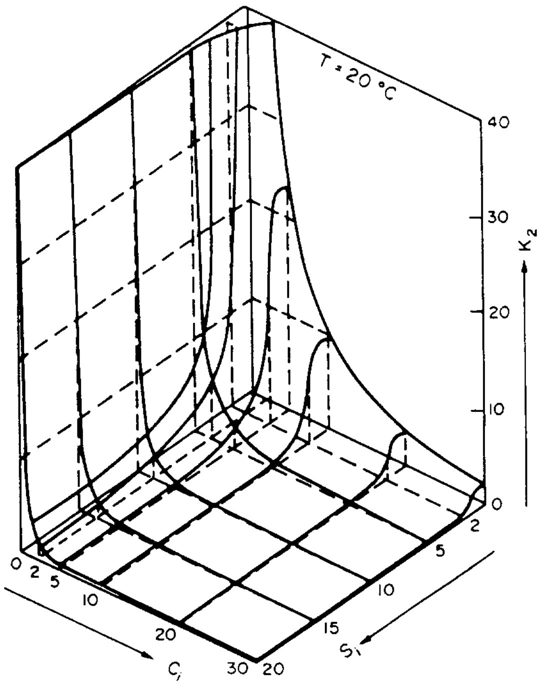

Fig. 13. Prediction of K_2 value at 20°C.

tion period. The 1st day chromatogram has a TOC peak at the 35th fraction of water elution (WF 35) and no absorptions at the 220 and 260 nm levels. This chromatogram is similar to that of influent glucose. The chromatogram on the 7th day shows the ultraviolet absorptions at the WF 35, and the organic compounds at the WF 35 may be volatile fatty acids, such as acetic acid, caused by microbial degradation of glucose. The low molecular weight compounds at WF 43 increase during infiltration whereas the higher molecular weight compounds at WF 19 seem to appear in sand column effluent on the 30th day. The appearance of high molecular weight compounds in the course of inundation may be caused by the degradation of aerobic microorganisms products under anaerobic conditions.

Figure 15 shows a comparison among the three kinds of chromatograms obtained in the infiltration of starch, peptone and skimmed milk in the latter half of inundation. These apparent molecular weight distributions are similar even when the influent of different organic constituents is applied to the sand column. Microorganisms can break down the organic compounds to a certain extent in the latter half of inundation because the detention time in the sand layer in-

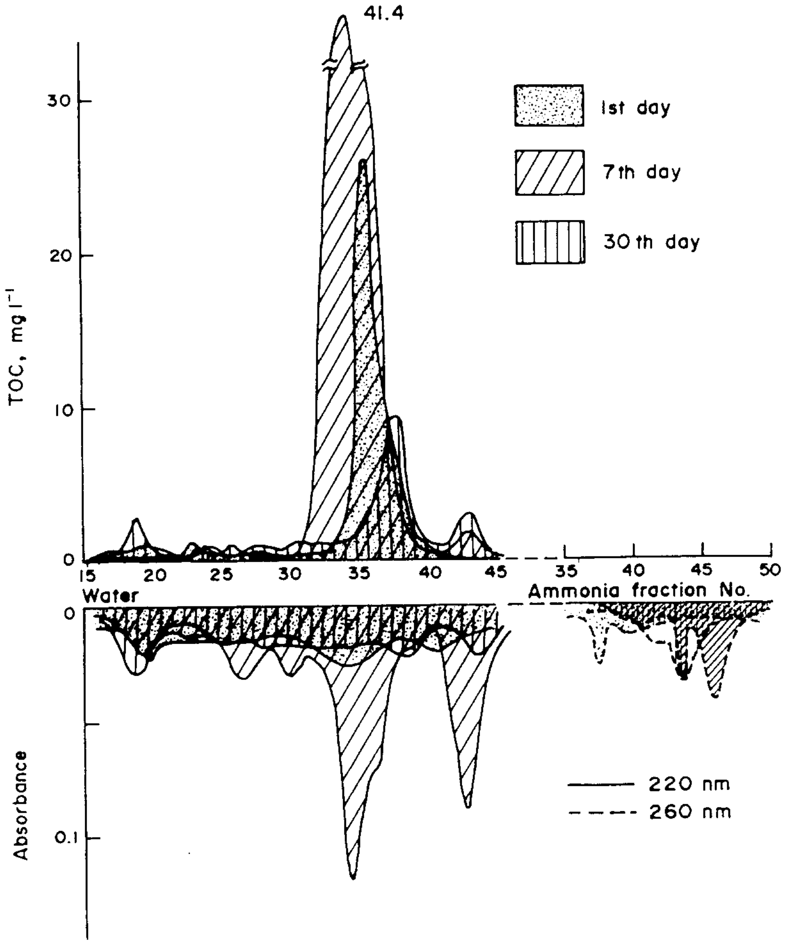

Fig. 14. Chromatograms in infiltration of glucose.

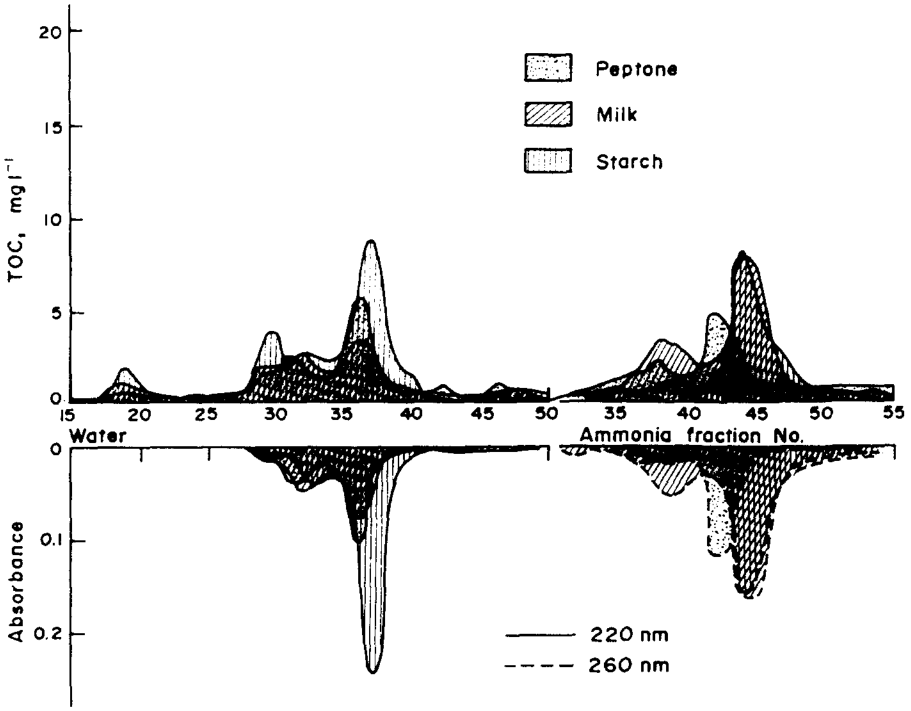

Fig. 15. Comparison among the three kinds of chromatograms in the latter half of inundation.

creases with the development of biological clogging. On the other hand, only part of the organic constituents are metabolized in the first half of inundation because of a short detention time and a large specific discharge in the aerobic period.

CONCLUSIONS

1. The biological clogging process is divided into three stages, i.e. aerobic period, transitional period from aerobic conditions to anaerobic conditions and anaerobic period. The infiltration rate decreases rapidly due to aerobic microbial growth during the aerobic period, and it is almost constant or increases slightly during the transitional period because of the transient decrease of microbial accumulation in the column. The infiltration rate decreases rapidly during the anaerobic period because of anaerobic microbial growth.

2. The effects of influent soluble organic carbon concentration, initial specific discharge, temperature and influent organic SS concentration on the sand clogging are made clear. The equation which can predict the change of accumulative specific discharge is derived from the experimental results. The secondary effluent infiltrated through the sand must have SS of $<2\ \mathrm{mg\ l^{-1}}$ and SOC of $<10\ \mathrm{mg\ l^{-1}}$ in order to maintain a high infiltration rate during a long inundation period.

3. As a result of changes in the organic constituents during the inundation period, only part of the influent organic constituents are metabolized in the first half of inundation because of a short detention time and a large specific discharge in the aerobic period. In the latter half of inundation, microorganisms are able to break down the influent organic compounds to a certain extent because the detention time in the sand layer increases with the development of biological clogging.

The chromatograms of the effluent show the similar TOC distributions in the anaerobic period of the biological clogging process even when the different organic compounds are applied to the sand column.

Acknowledgement—This work was financially supported by the Special Research Project "Environmental Science" of the Ministry of Education, Culture and Science, Japan.

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