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A MATHEMATICAL MODEL OF BIOLOGICAL CLOGGING OF SOIL-SAWDUST MEDIA

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The present study investigates how sawdust material affects the biological clogging and the transport properties of porous media. The decrease in porosity and hydraulic conductivity of a saturated porous media due to bacterial growth is commonly referred to as biological clogging. A one-dimensional model for biological clogging was used to study the progress of biological clogging in soil-sawdust column experiments. A model was developed simulating solute transport in soil-sawdust experimental columns including biological clogging processes. To simulate the biological clogging effects, the changes in porosity are calculated by converting biomass into volume, which directly reduces the porosity. The biomass growths are formulated using the Double Monod kinetic equation. Results from laboratory soil-sawdust experiments were used as data to verify the simulation results. The experimental results showed that the hydraulic conductivity in the columns decreased over time. Such decreases in the hydraulic conductivity are due to clogging of the soil pores by bacterial growth. The results from this study show that it is generally possible to simulate the laboratory experimental results with a mathematical numerical model. A detailed comparison between the experimental and the simulation results showed that good agreement was obtained. This study also shows that sawdust materials are promising materials for improving the hydraulic conductivity and removal of pollutants from wastewater.

INTRODUCTION

The decrease in porosity and hydraulic conductivity of a saturated porous media due to bacterial growth is commonly referred to as biological clogging (Baveye et al., 1998a). Biological clogging may reduce the success of bioremediation because contaminated parts of a porous media can clog due to bacterial growth and rates of degradation can decrease (Baveye et al., 1998b). Most of the studies on biological clogging were investigated in column experiments. Numerous studies reported a significant reduction of hydraulic conductivity due to biological clogging (Thullner et al., 2002; Thullner et al., 2004; Seki et al., 1996; Seki and Miyazaki, 2001; Seifert and Engesgaard, 2007). Gupta and Swartzendruber (1962) conducted a column experiment with sand and observed that the hydraulic conductivity decreased remarkably when the bacterial number exceeded 4×10^5 per gram of sand by the dilute plate counting method. Taylor and Jaffe (1990) conducted a column experiment with a constant influx. Reduction in hydraulic conductivity by three orders of magnitude was observed. Seki et al. (1996) carried out a series of column experiments and reported that reduction in hydraulic conductivity was observed with an increase of biomass. In addition to these column studies, Thullner et al. (2002) investigated bacterial growth and its influence on hydraulic properties of pore networks. They observed that the hydraulic conductivity decreased by at least two orders of magnitude.

Numerical models developed on the basis of a mechanistic understanding of all physical and microbiological activities that affect bacterial growth and distribution are important tools for interpreting experimental results.

Cunningham et al. (1991) measured the hydraulic conductivity and biofilm thickness of sand and glass beads. They simulated their data using the Kozeny-Carman equation. Vandevivere and Baveye (1992) calculated bacterial density from the phospholipids content. They reported that the volume of bacterial cells was 2.4%, 4.8%, 8.5% respectively of pore volume, when the hydraulic conductivity decreased a tenth, hundredth, and thousandth of the initial volume. Seki and Miyazaki (2001) developed a mathematical model for estimating hydraulic conductivity decrease due to biological clogging of porous media. They proposed a mathematical model with nonuniform bacterial distribution. Baveye and Valocchi (1989) reported three models for the distribution of bacteria in porous media, first the biofilm approach with uniformly distributed bacteria, second a micro-colony approach with a nonuniform distribution, and third a macroscopic approach where the bacteria are considered a bulk average bacterial volume with no description of the geometry.

A number of studies on contaminant removal from water using sawdust as a matrix have been reported (Shukla et al., 2002; Schipper and Vukovic, 2000; Schipper et al., 2005; Zavala et al., 2004). Sawdust can be used for the removal of nitrate from water. For example, denitrification walls amended with sawdust are effective in nitrate removal (Schipper and Vukovic, 2000). The denitrification wall was constructed by digging a trench that intercepts groundwater. The excavated soil was mixed with 30% of sawdust as a carbon source and then returned to the trench. Nitrogen levels in the wall and in the surrounding groundwater were monitored for one year. Successful nitrate removal from groundwater was demonstrated. Another report (Ajmal et al., 1998) showed that the efficiency of the removal of copper from river water using sawdust was 63%, and it was thus concluded that the sawdust is an excellent adsorbent for copper removal from aqueous solution.

The problem with bacterial growth and decrease in porosity and hydraulic conductivity of saturated porous media due to biological clogging have not been reported in the literature for columns amended with sawdust.

This study discusses a simulation model of the biological clogging progress in soil-sawdust column experiments. In the present study, our previous research (Eljamal et al., 2007) on the simulation of solute transport and bioremediation processes was used as basis for developing the model to include biological clogging possesses. To simulate the biological clogging effects, the changes in porosity are calculated by converting biomass into volume, which directly reduces the porosity. The model is able to calculate the spatial variation of hydraulic conductivity. The bacterial growths are formulated using the Double Monod kinetic equation. Results from laboratory soil-sawdust experiments were used as data to verify the simulation results of the model.

THEORETICAL BACKGROUND

Transport Model

The fundamental one-dimensional partial differential equation governing the advective-dispersive solute transport of contaminants considering reaction part in the porous media can be written as (Bear, 1972).

$$\frac{\partial C_{mob}}{\partial t} = \frac{\partial}{\partial y}\left(D_L \frac{\partial C_{mob}}{\partial y} \right) - v' \frac{\partial C_{mob}}{\partial y} + S_i \,, \; D_L = \alpha_L v' + D_M \tag{1}$$

where C_{mob} is the concentration of solute in the mobile phase, D_L is the longitudinal dispersion coefficient, α_L is the longitudinal dispersivity, D_M is the molecular diffusion coefficient, v' is the average pore velocity, t is the time, y is the distance, and S_i is the chemical source-sink term representing the changes in mobile phase concentration of species due to chemical or biochemical reaction in the porous media.

Bacterial Growth Model

The bacterial growth is considered in the model only in the bio phase. The model defined four functional bacterial groups (X1, X2, X3, and X4). Bacterial group X1 uses oxygen under aerobic conditions and nitrate as electron acceptor under anaerobic conditions. Under anaerobic conditions bacterial groups X2, X3, and X4 use Mn (IV), Fe (III), and sulfate as an electron acceptor respectively. The growth of different groups of bacteria in the bio phase is formulated by the Double Monod kinetic equation:

$$\frac{\partial X}{\partial t} = v_{\max} \frac{C_1}{K_{s1} + C_1} \cdot \frac{C_2}{K_{s2} + C_2} X \tag{2}$$

where v_{max} is the maximum growth rate, C_1 is the primary substrate concentration in bio phases, C_2 is the secondary substrate concentration in bio phases, K_{s1} is the primary substrate half-saturation constant, K_{s2} is the secondary substrate half-saturation constant, and X is the total of bacterial concentration.

Biological Clogging Model

In order to simulate biological clogging effects, we have adopted the macroscopic approach, which makes no assumptions about the bacterial growth distribution. The changes in porosity are calculated by converting bacterial growth distribution along the depth into volume, which directly reduce the porosity. The fraction of total volume occupied by bacterial growth can be written as (Hirano et al., 1998).

$$V = \frac{(1-\varepsilon_0)\rho_m Q_s}{\rho_s (1-f_\sigma)} \tag{3}$$

And the bacterial growth which reduces porosity is

$$\varepsilon = \varepsilon_0 - V \tag{4}$$

The hydraulic conductivity is assumed to be a function of porosity. In the model the relation between hydraulic conductivity and porosity is formulated by the Kozeny-Stein equation:

$$\frac{K}{K_0} = \frac{\left(\varepsilon_0 - \dfrac{(1-\varepsilon_0)\rho_m Q_s}{\rho_s (1-f_\sigma)}\right)^3}{\varepsilon_0^3 \left(1 + \dfrac{\rho_m Q_s}{\rho_s (1-f_\sigma)}\right)^2} \times \left(\sqrt{\frac{\rho_m Q_s}{3\rho_s (1-f_\sigma)} + \frac{1}{4}} + \frac{\rho_m Q_s}{3\rho_s (1-f_\sigma)} + \frac{1}{2}\right) \tag{5}$$

where V is the total volume of bacterial growth, ε_o is the initial porosity before filtration, ε is the porosity after filtration, Q_s is the volumetric fraction of clogged or deposited material ($Q_s = A\,X$), A is the rate constant of deposition, X is the bacteria concentration, ρ_m is the density of soil-sawdust material, ρ_s is the density of clogged or deposited material, f_σ is the secondary porosity of the deposited material, K is the hydraulic conductivity of the clogged porous medium, and K_o is the hydraulic conductivity of the clean porous medium.

Model Structure

The one-dimensional model was developed for the purpose of simulating the biological clogging. The model solves a system of equations that consists of a solute transport equation and bacterial growth equation coupled with a biological clogging equation. The equations are solved numerically using the method of characteristics and finite differences (Jinno, 2001; Momii et al., 1997). By applying the method of characteristics, the advective and dispersive transport equations are solved for each species. By applying the finite difference method, the sub models of reaction and clogging are solved with the concentration changes from the transport part. The general procedure performed in solute transport with biological clogging model for a typical simulation run is illustrated in Figure 1.

APPLICATION

Column Experiment

The column experiment was carried out using acril resin glass columns of 45 cm height and 10 cm internal diameter. The wire mesh and the filter paper were placed at the bottom of each column as shown in Figure 2. The top and the bottom of the column were closed using glass transparent resin plates with tubes inserted for flow inlet and flow outlet.

The columns were packed to a height of 30 cm with soil and sawdust. The first column was packed with 100% soil while the second column was packed with a 50-50 mixture of sawdust and soil. The secondary wastewater was constantly fed to the top of the two columns for 56 days.

Materials

Secondary treated municipal wastewater from the Wajiro wastewater treatment plant of Fukuoka city, Japan was applied to the two columns.

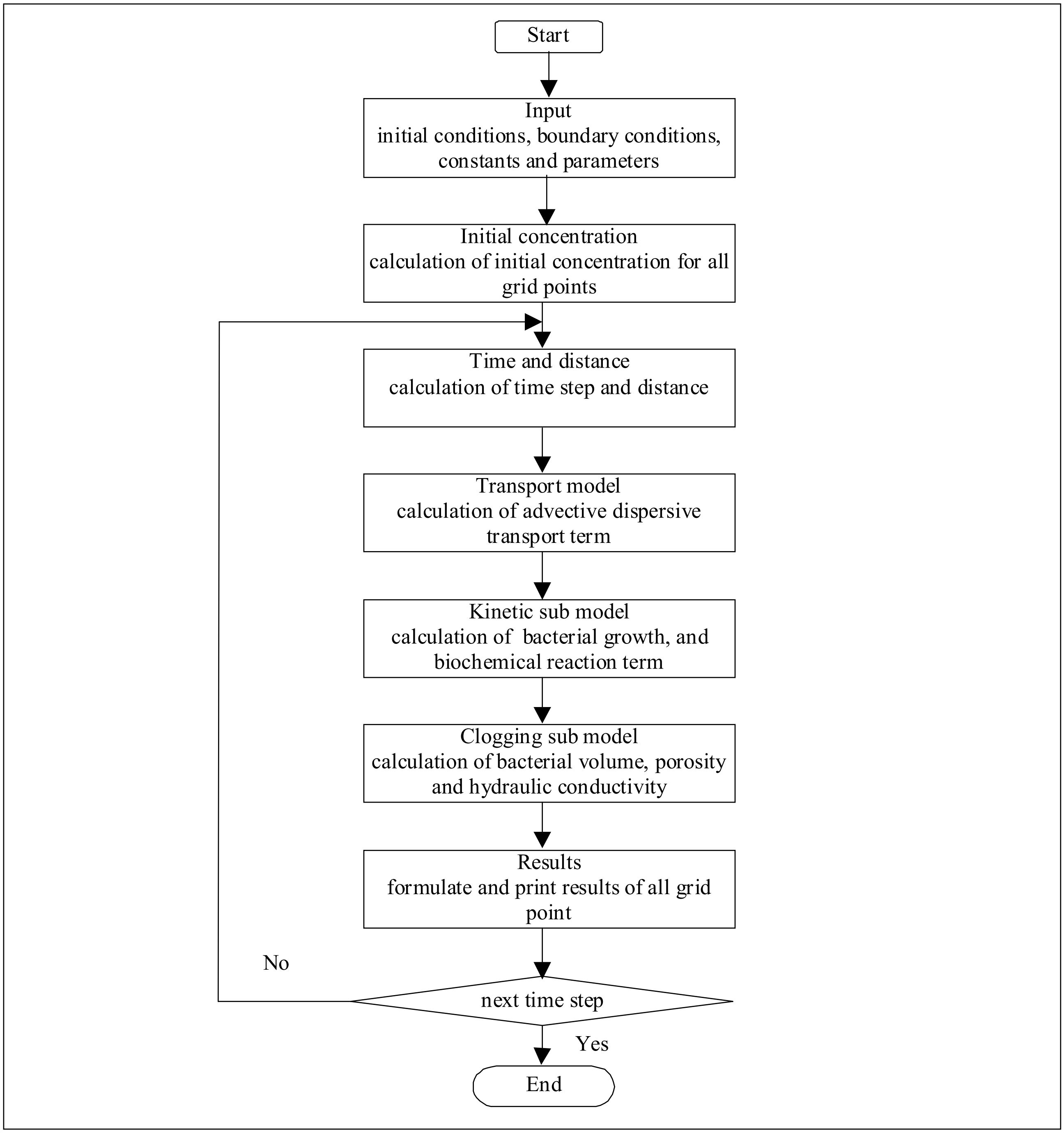

Figure 1. Flow chart of solute transport with biological clogging model.

The soil was collected from actual paddy field in Fukuoka city and sawdust was collected from local wood factory in Fukuoka city. Table 1 shows the chemical concentration of the injection wastewater and the chemical components of paddy soil and sawdust.

Model Parameters

The model of biological clogging is highly complex, as it involves a large number of parameters. Hydraulic parameters and biochemical parameters were taken from several studies related to biological clogging modeling and simulations of solute transport with bioremediation (Hirano et al., 1998; Kildsgaard and Engesgaard, 2001; Fabritz, 1995; Guerra et al., 2004; Lensing et al., 1994; Schreiber et al., 2004; Schäfer et al., 1998). In order to illustrate the potential application of the

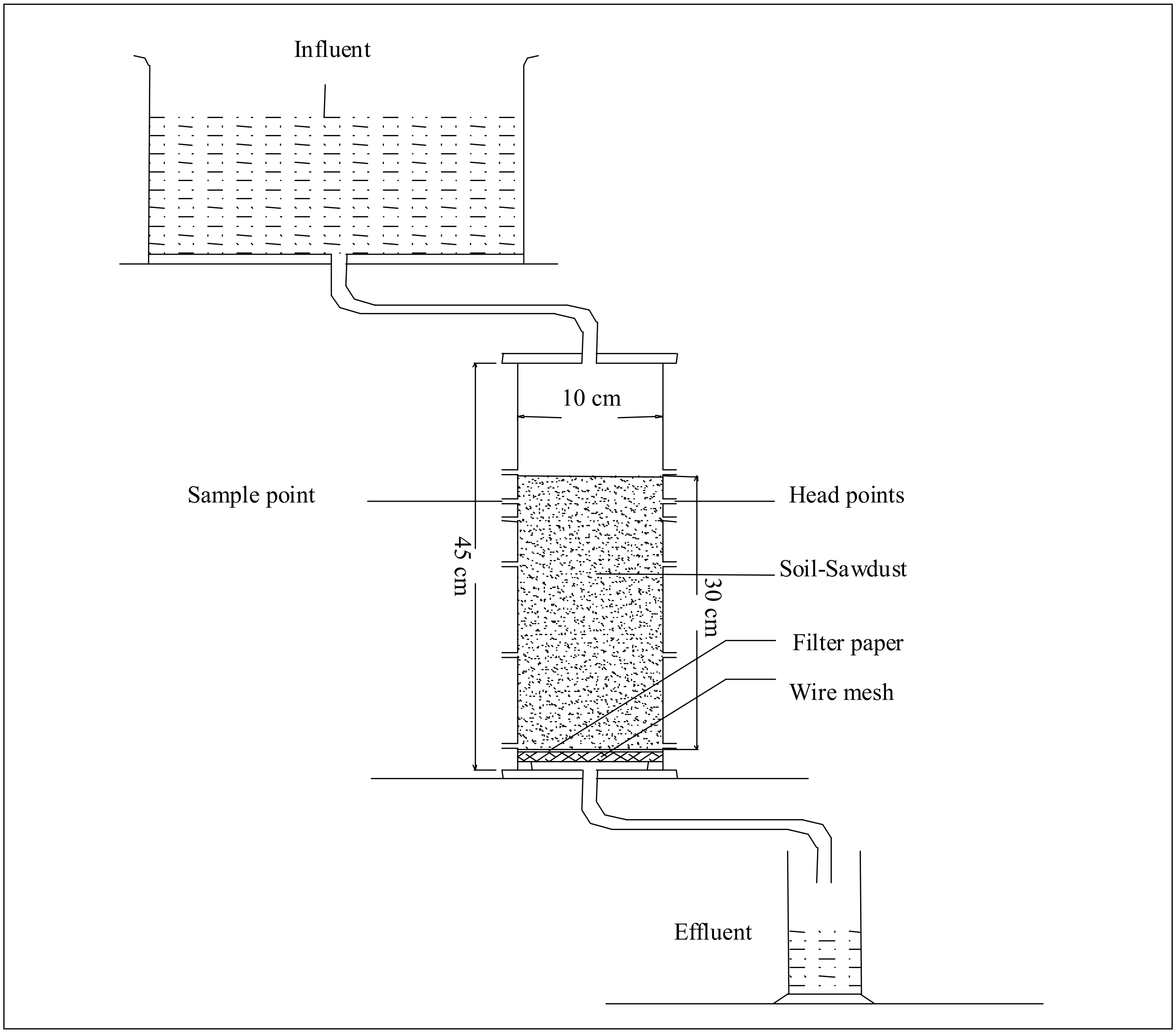

Figure 2. Schematic set-up of laboratory column experiment.

developed model, the column experiment was simulated. The parameters were adjusted to obtain the best fit of the model to the experimental data.

The discretization, and clogging parameters are presented in Table 2. The discretization is chosen such as it meets numerical stability and accuracy criteria (Courant number = $(v\Delta t)/\Delta x \leq 1$, grid number = $\Delta x/\alpha_L \leq 2$). The pore water velocity of the columns was calculated based on measured data. The initial and boundary conditions were selected depending on the experimental setup, injection wastewater analysis and chemical components of raw materials.

RESULTS AND DISCUSSION

Bacteria Growth

The growth of microbial biomass has the ability to reduce the effectiveness of the columns while appreciable quantities of nutrients are still present. The problem with bacterial growth is that it reduces the hydraulic conductivity of the columns, producing more resistance to flow through the columns. Figures 3 and 4 show the results of simulated schematic of bacterial growth with time at different depths for soil and soil-sawdust columns. Initially the bacteria tend to be acclimated

Table 1. Chemical components of materials.

Soil			Sawdust		
Chemical species	Units	Content	Chemical species	Units	Content
Fe_2O_3	%	7.5	pH (H_2O)	-	5.1 (20.1)
MnO_2	%	0.16	T-P	mg/kg	40
Al_2O_3	%	16.1	K	mg/kg	478
SiO_2	%	43.7	NH_4	mg/kg	7.1
Ig-loss	%	5.9	C/N	-	259
C	%	1.57	T-C	%	44.1
H	%	0.58	T-N	%	0.17
N	%	0.14			
Wastewater					
Na	mg/L	95.2	TOC	mg/L	5.6
K	mg/L	14.5	Cl	mg/L	161
Ca	mg/L	40.3	NO_3-N	mg/L	10.5
Mg	mg/L	9.2	SO_4	mg/L	40
Fe^{2+}	mg/L	0.13	PO_4-P	mg/L	0.172
Mn^{2+}	mg/L	0.137			

Table 2. Discretization and clogging parameters.

Parameter	Function	Value
L	column length	30 cm
d	column diameter	10 cm
Δx	distance between grid points	0.5 cm
Δt	time step size	30 sec
ε_0	Initial porosity	0.3
ρ_m	density of the clogged material	1 g/cm^3
ρ_s	density of the soil material	2.65 g/cm^3
f_σ	secondary porosity of the clogged bacteria material	0.985
K_0	hydraulic conductivity of the clean porous medium	0.151 cm/s
A	rate constant of deposition	0.01

to the new environmental conditions (pH, temperature, nutrients, etc.). Then the living bacteria population increases rapidly with time at an exponential growth in numbers, and growth rate increasing with time. After that with the exhaustion of nutrients and build-up of waste and secondary metabolic products, the growth rate has slowed to the point where the growth rate equals the death rate.

Hydraulic Conductivity

The variation of bulk hydraulic conductivity during the experiment is shown in Figure 5. The figure shows the comparison of the experimental result with the simulation result for bulk hydraulic conductivity. The simulation result for bulk hydraulic conductivity correlated fairly well with the bulk hydraulic conductivity in the experiment. The bulk hydraulic conductivity was calculated from the measured hydraulic head gradients based on Darcy's Law. The experimental results showed that the hydraulic conductivity of the two tested materials decrease with time. This

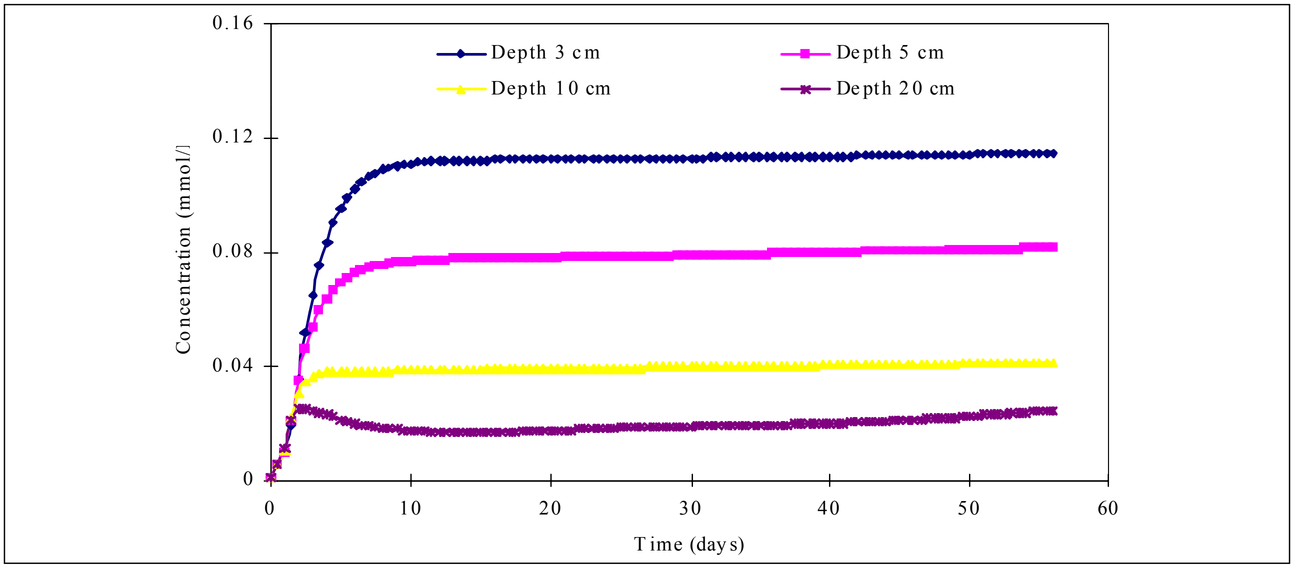

Figure 3. Bacterial growth versus time at different depth for the column packed with soil.

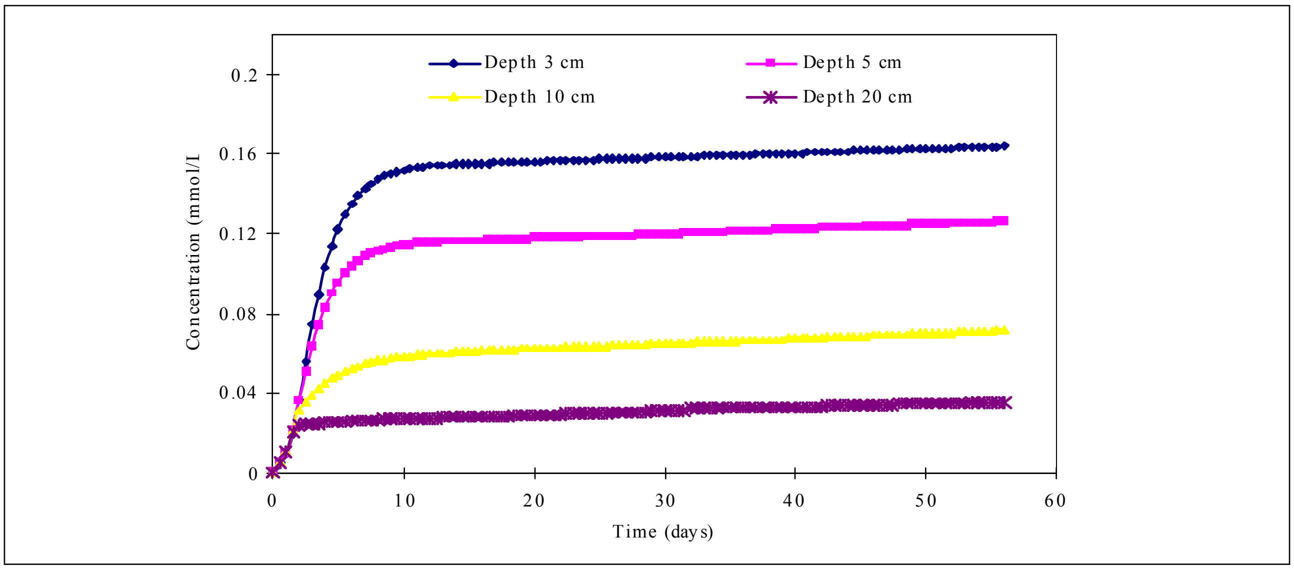

Figure 4. Bacterial growth versus time at different depth for the column packed with sawdust.

reduction may possibly be due to clogging of the soil pores as a result of bacterial growth. The results show also that higher hydraulic conductivity is obtained for the soil-sawdust mixture than for the pure soil, which may be due to the higher particle size of sawdust and sawdust degradation during the running time.

Figure 6 shows the hydraulic conductivity distribution along the two columns after 5 days. The model simulation results show that the top 10 cm of soil-sawdust are most important for reduction of hydraulic conductivity. Hydraulic conductivity reduced at the top of column due to the higher growth of aerobic bacteria at this location.

Figure 7 shows the effect of the volumetric fraction *Qs* on the hydraulic conductivity ratio. The increase of the value of total volumetric fraction causes a decrease in the hydraulic conductivity ratio. Moreover, the figure shows a rapid decrease in hydraulic conductivity ratio for the column packed with soil and a smooth decrease in hydraulic conductivity ratio for the column packed with soil-sawdust, which is due to the higher particle size of sawdust and its degradation. Figure 8 also shows the reduction of hydraulic conductivity as a function of porosity. The simulation result showed that the decrease in porosity causes a decrease in the hydraulic conductivity.

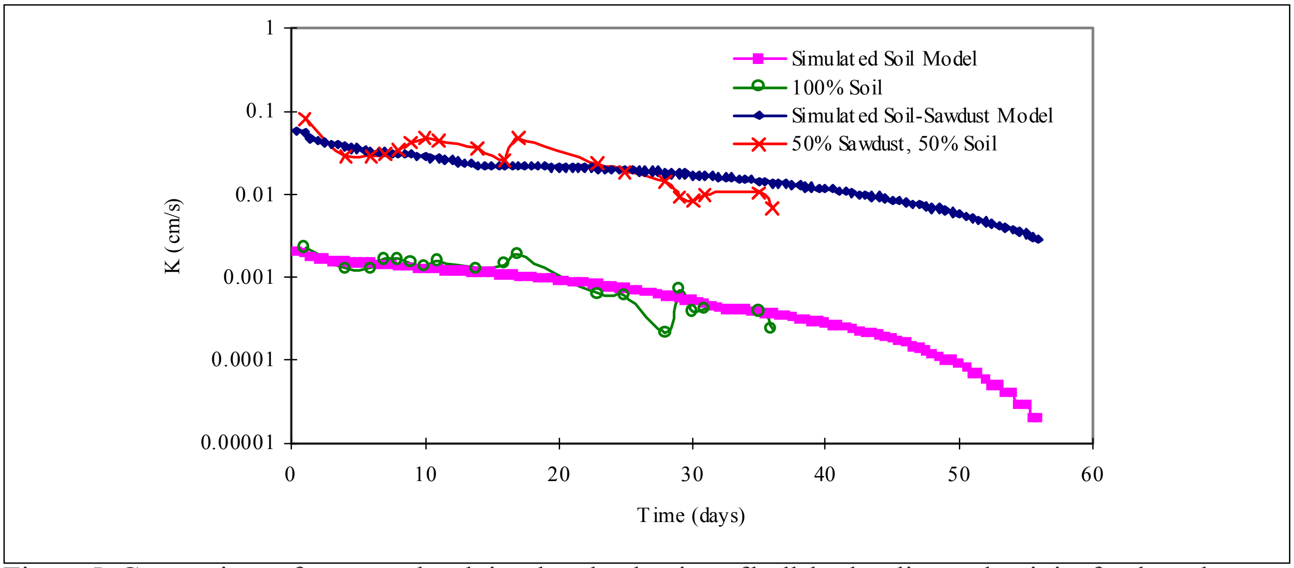

Figure 5. Comparison of measured and simulated reduction of bulk hydraulic conductivity for the columns.

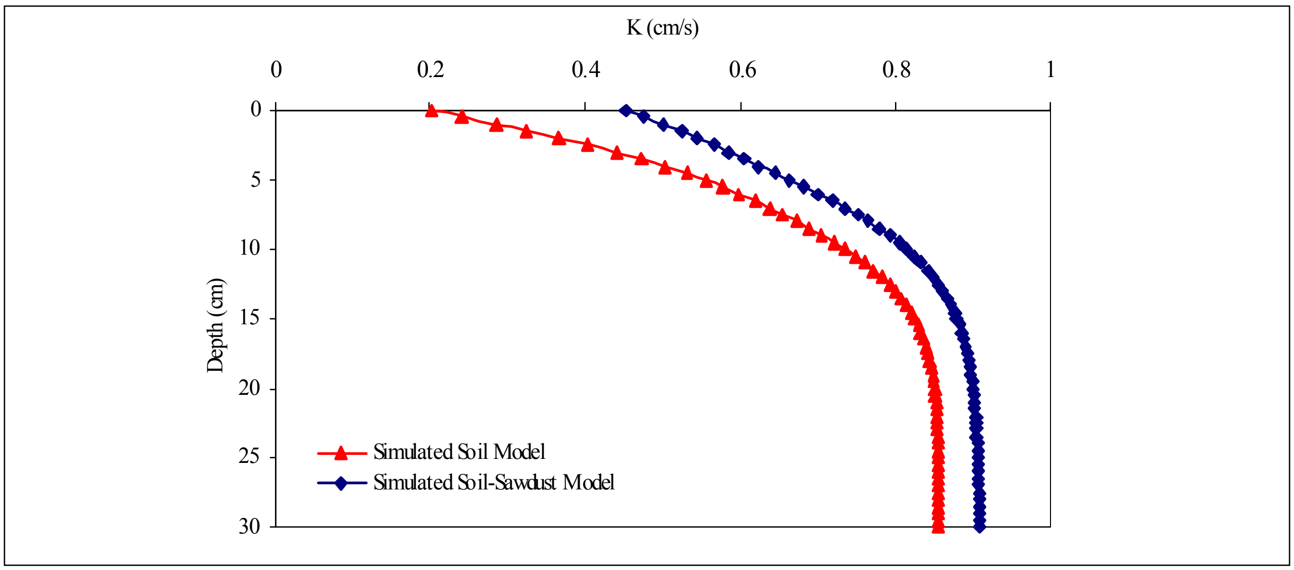

Figure 6. Hydraulic conductivity distribution along the two columns after 5 days.

Volumetric Fraction and Porosity

Figure 9 shows the volumetric fraction of clogged or deposited material as a function of time. The volumetric fraction Q_s was calculated by converting bacterial growth into volume using the rate constant of deposition. The simulation result showed that the volumetric fraction of the two columns increase with time. This increase was due to bacterial growth inside the columns. Figure 10 shows the variation of porosity with time. The simulation results showed that the porosity of the columns decrease with time. The decrease in porosity of a saturated porous media due to deposited material as a result of volumetric fraction increases. The simulation result showed there was significant increase in the porosity when sawdust was used.

CONCLUSION

The results from this study show that it was generally possible to simulate the laboratory experimental data with a mathematical model. A detailed comparison between the experimental data and the simulation results show a good agreement.

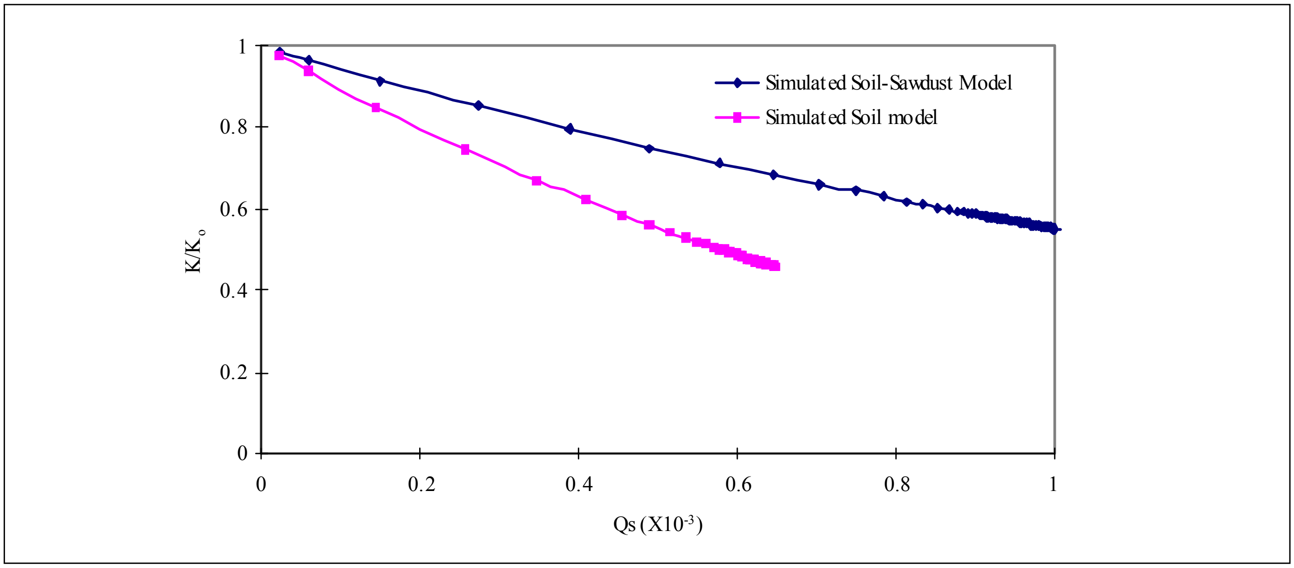

Figure 7. Hydraulic conductivity ratio versus volumetric fraction of bacteria for the columns at depth 5 cm.

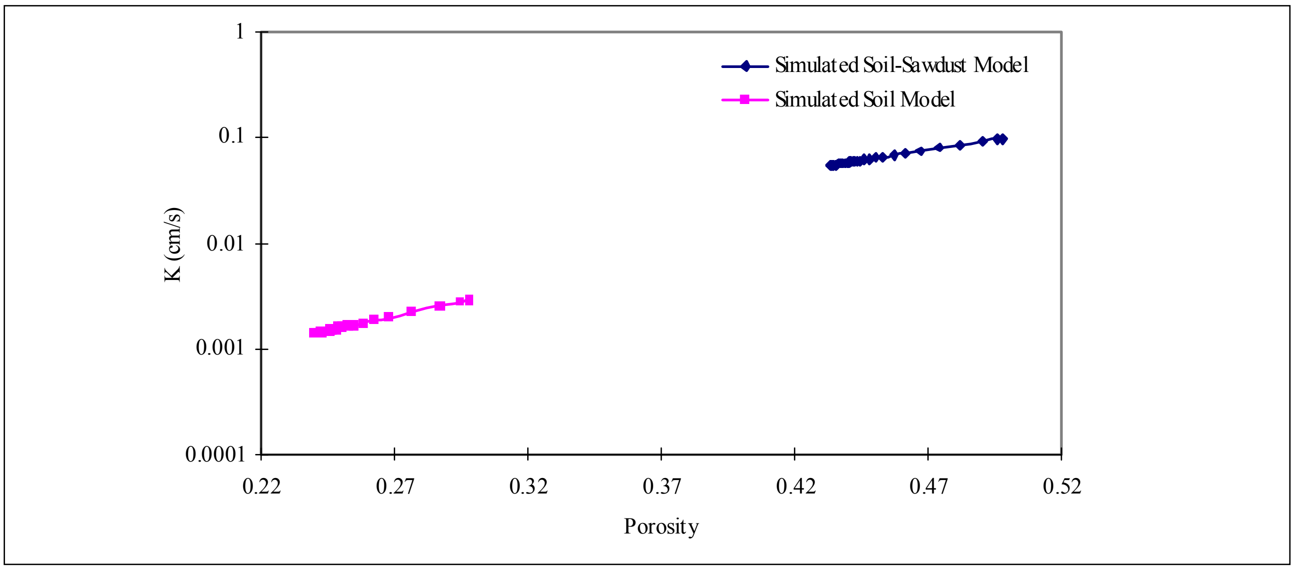

Figure 8. Hydraulic conductivity versus porosity for the two columns at depth 5 cm.

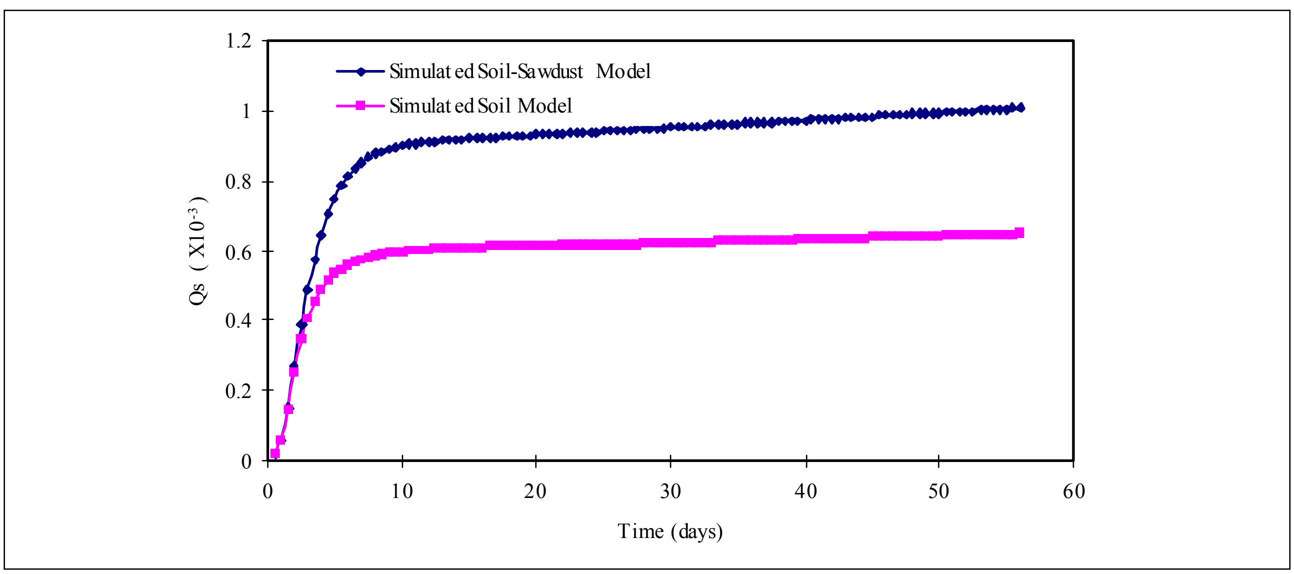

Figure 9. Volumetric fraction versus time for the two columns at depth 5 cm.

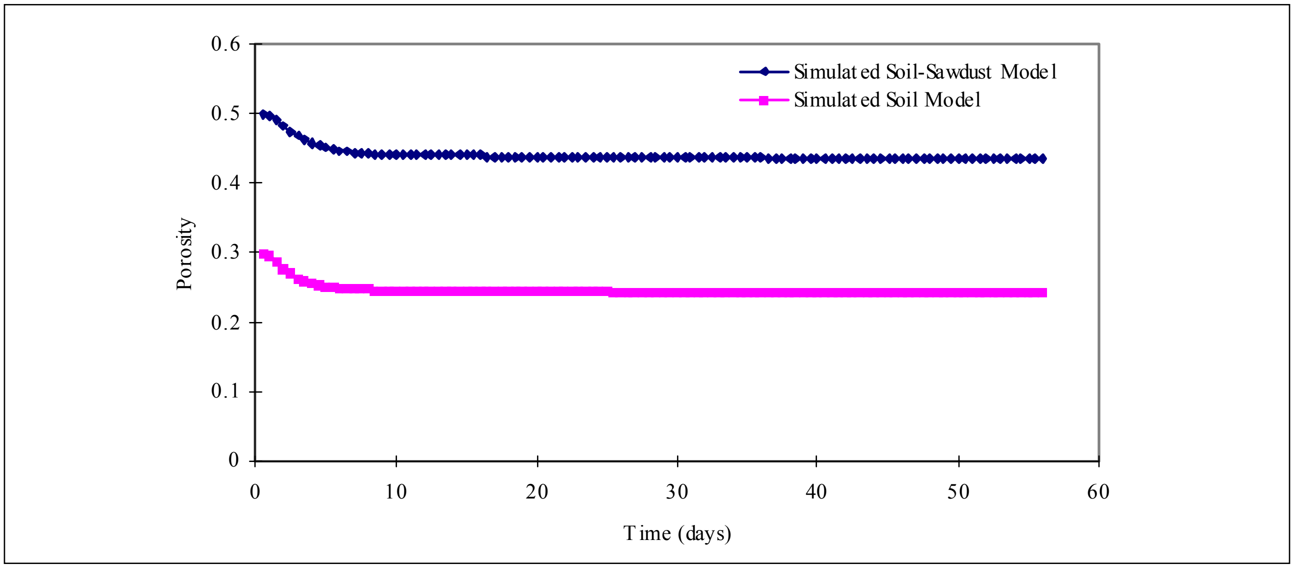

Figure 10. Porosity versus time for the two columns at depth 5 cm.

A mathematical model was developed for estimating hydraulic conductivity decrease due to biological clogging of soil-sawdust columns. Simulation and experimental results show that the hydraulic conductivity of the columns decreased with time, which may be due to the rapid increases in the microbial population when food and energy are available.

The results from the laboratory column experiments showed a higher hydraulic conductivity is obtained when sawdust was used as a carbon source than for the pure soil, which may be due to the higher particle size of sawdust and sawdust degradation during the running time.

Sawdust materials have proven to be promising materials for increasing the hydraulic conductivity and enhance the bioremediation processes in porous media.

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