Paper No. 994074
An ASAE Meeting Presentation

HYDRAULIC CONDUCTIVITY REDUCTION DUE TO PONDED HOG MANURE

by
C. P. Maule, T.A. Fonstad, S.K. Vanapalli, and G. Majumdar
Department of Agriculture and Bioresource Engineering
University of Saskatchewan, Saskatoon, CANADA

Written for Presentation at the
1999 ASAE/CSAE-SCGR Annual International Meeting
Sponsored by ASAE/CSAE-SCGR
Toronto, Ontario
July 18-22, 1999

Summary

An experimental research program results are presented in this paper to study the effect ponded hog manure on soil hydraulic conductivity. The specific concerns addressed are related to the contribution of the manure 'seal' and pore clogging towards flow reduction and its permananance. Seven different soils with a varying clay content from 9 to 33% were studied using 20 cm soil column tests in a low-temperature (5-6°C) environment.

The soil hydraulic conductivity measured with water head ranged between 3×10^{-8} and 132×10^{-8} m/s. Fresh hog manure was ponded on these soil columns for 634 days and hydraulic conductivities were measured. The hydraulic conductivity decreased rapidly to about 0.1×10^{-8} m/s irrespective of the type of soil tested for the entire period of study, except during the time of failure of the cooling system. Visual studies indicated that a black seal developed at the manure-soil interface of all columns. The seal increased downwards at a rate of 0.3 mm/month into the soil.

The hydraulic conductivities of various soils at different depth intervals, indicated that most, if not all, of the reduction in hydraulic conductivity occurred at the seal layer. Manure particles within the soil pores were found from thin section and SEM studies. The formed seal was removed and the hydraulic conductivities were measured again for all soils with a prepared chemical solution of similar ionic concentration as that of manure. The hydraulic conductivities of all soils increased to that of 'pre-manure' conditions. The results of this study suggest that the hydraulic conductivity reduction from ponded hog manure is mainly related to the development of a seal at the manure-soil interface.

Keywords:
Earthen hog manure storage structures, hydraulic conductivity, sealing/clogging effects.

Hydraulic Conductivity Reduction due to Ponded Hog Manure; Can we count on it?
by
C. P. Maule, T.A. Fonstad, S.K. Vanapalli and G. Majumdar
Department of Agriculture and Bioresource
University of Saskatchewan, 57 Campus Drive
Saskatoon, S7N 5A9
SK, CANADA

INTRODUCTION

Earthen manure lagoons offer an economically viable means of storing manure as compared to concrete or steel tanks. Ground water contamination is, however, a likely problem if improper soil materials are used or if proper construction techniques are not practiced. Manitoba Agriculture (1994), Ontario Ministry of Agriculture, Food and Rural Affairs (1994), Saskatchewan Agriculture and Food (1992) and the United States Soil Conservation Service (1993) regulations governing earthen manure storage lagoons construction are based upon maintaining a minimum seepage rate through the earthen material. These regulators recommend the use of soils with a clay content of 15% or higher that have a plasticity index, I_p, greater than 10%. These soils are to be compacted such that the resulting maximum effective pore diameter is 0.45 µm and capable of developing a soil-manure seal to reduce seepage. The desired hydraulic conductivity of the earthen material, generally in the form of a liner is required to be lower than 1×10^{-9} m/s. A detailed background related to the above recommended standards is available in the literature (Barrington et al. 1987a,b; Barrington and Broughton 1988; USDA Technical Note 716 (Soil Conservation Service, 1993)).

Several investigators reported seepage reduction due to clogging and sealing of soils by animal manure and also by other organic liquids. These studies provided an insight towards understanding of the clogging and sealing mechanism. In the present study, the term 'clogging' is referred to as the lodging of manure particles within soil pores whereas 'sealing' is due to the formation of a manure layer on the soil surface.

Davis et al (1973) studied the infiltration rate of a pond holding liquid dairy manure. The hydraulic conductivity of a newly constructed pond decreased from 1×10^{-5} m/s to 6×10^{-8} m/s when the pond filled with water for two days was replaced with liquid dairy manure. Culley and Phillips (1982), Miller et al (1985), and Rowsell et al (1985) investigated the sealing effects due to liquid cattle manure. These studies show that an effective seal was formed and infiltration rate reduced to 1×10^{-8} m/s in various soils. Barrington et al (1987) using column tests with liquid hog manure showed that the final hydraulic conductivity of the soil columns approached values of 1×10^{-9} m/s for soils with varying textures. The hydraulic conductivity values decreased approximately by two orders in magnitude for all types of soils irrespective of the manure type.

Chang et al (1974), deTar (1979), Rowsell et al (1985) and Barrington et al (1987) demonstrated that the sealing mechanism in soils under ponded manure conditions is a physical blocking of pores by the particulate material in the manure. However, other researchers demonstrated that clogging under ponded conditions involving organic materials (but not necessarily manure) can be due to microbial activity and polysaccharide accumulation resulting in the reduction of flow through soils (Allison 1947; McCalla 1950; Avnimelech et al. 1963; Mitchell and Nevo 1963; Chang et al., 1974; Nicholaichuk, 1978; and McConkey et al. 1990).

Other investigators whose studies used ponded organic liquids reported that sealed soils, if allowed to dry, could recover to initial hydraulic conductivity values or higher within 8 to 125 days with water applied after drying (De Vries 1972, and Chang et al., 1974). The increase in hydraulic conductivity was reportedly caused by the aggregation of the soils by the microbial biproducts.

More studies are necessary to better explain the mechanism and the durability of the reduction in flow with ponded organic liquids. The study reported in this paper is an attempt to further investigate flow reduction due to ponded hog manure with respect to the following specific questions:

1. How much is the flow reduced?
2. Does texture have an effect upon flow reduction?
3. Does length of time of manure ponding have an effect upon flow reduction?
4. Is the flow reduction due to a seal and/or clogging within the soil?
5. What is the durability of the seal or clogging?
6. What is the effect upon flow rates upon seal removal?

The flow rates and hydraulic heads were measured on seven soils from Saskatchewan using soil columns for more than 600 days with ponded hog manure to answer the above questions. Hydraulic conductivities of the entire soil columns were measured and the individual layers were calculated. Visual analysis were also conducted with closeup photography through the acrylic walls of the columns, and with thin soil sections. It is expected that the studies presented in this paper would be useful for providing better guidelines in the location, design, and construction of earthen hog manure storage structures to assist in providing a cost-effective hog industry.

MATERIALS AND METHODS

SOIL PROPERTIES AND SETUP OF SOIL COLUMNS

Seven different soils of Saskatchewan were collected from subsoil materials at depths 3 m below natural ground level (Table 1). Three replicates of columns for each soil sample were prepared and packed into transparent acrylic cylinders that were 121 mm in diameter and 900 mm in length (Figure 1a). An acrylic base with a tube connector fitting was attached to the bottom to collect outflow. A 30 mm base of coarse sand was first established at the bottom of the soil columns. The soil, that had been air dried, ground, and sieved to remove particles greater than 2 mm size, was compacted into the acrylic cylinder in four 50 mm layers with a water content equivalent to optimum moisture content. The total thickness of the soil layers was 200 mm. The total compactive effort for all the soils ranged between 90 and 92% of Standard Proctor's energy for each layer resulting in bulk densities between 1.50 and 1.83 Mg/m^3. Low compactive efforts were used to simulate field compaction conditions that can be easily achieved by simple excavation equipment. The soil surface of each compacted layer was scarified with a wire brush such that flow properties of the compacted soil are not influenced by any discontinuities within the sample. The column design as shown in Fig. 1a is after Barrington and Broughton (1988).

Three manometers were installed by horizontal insertion of 8 mm diameter stainless steel tubes with 2 mm diameter drilled holes along the length. The steel tubes were pushed into the column to about 80 mm from the wall of the cylinder, at the soil surface and at 25 mm and 100 mm beneath the soil surface (Fig. 1a). The prepared columns were stored temperature-controlled room at approximately 6° C to minimize biological effects at the manure-soil interface. This value of temperature also represents year-round average for shallow groundwater systems in Saskatchewan. At various time intervals during the 634 days testing period, a set of replicates of each soil were disassembled for chemical, visual and microscopic analysis.

Table 1. Physical, mineralogical, packing, and chemical properties of soils used in column study (Fonstad, 1996)

Soil #	Sand (%)	Clay (%)	E clay (%)	SA (m^2/g)	CEC (Cmole/kg)	Ip (%)	γ_d (Mg/m^3)	Efv (μm)	pH	EC (mS/cm)	Na^+ (mg/L)	SAR
1	20	33	70	46	21.3	35	1.50	0.19	7.9	6.0	489	3.8
2	34	24	60	32	17.9	7	1.57	0.24	7.7	3.4	152	1.5
3	42	12	20	6	5.8	9	1.80	0.31	8.1	4.5	185	1.5
4	47	17	35	33	6.9	7	1.83	0.22	7.8	4.3	121	1.0
5	41	14	60	36	8.5	15	1.76	0.29	7.8	3.8	64	0.5
6	55	13	70	43	8.2	4	1.62	0.42	7.9	1.3	56	1.1
7	75	9	80	31	6.4	NP	1.58	0.64	8.1	2.2	170	2.7

E clay is expanding clay, expressed as a percentage of clay fraction (expanding clay percentage was approximated from X-ray analysis done by A. Mermut, University of Saskatchewan, Saskatoon).
SA is the Surface Area of the clay fraction.
CEC is the Cation Exchange Capacity of the entire soil.
Ip is the plasticity index and γ_d is the dry density
Efv is Effective Void Diameter (Barrington and Broughton, 1988).
EC is the Electrical Conductivity of the saturated paste extract. EC and Na^+ were determined from the saturated paste extract of the soil and corrected for the saturated moisture contents of the columns.
SAR is the Sodium Adsorption Ratio of the saturated paste extract.

EXPERIMENTAL PROCEDURE FOR MEASUREMENTS

The soil columns were first saturated for a period of two weeks with tap water. The saturated hydraulic conductivity of the entire soil column was then measured under steady state conditions using a constant head of water under the conditions shown in Fig. 1a.

Fresh hog manure from local pen gutters with a total N of 6100 mg/L, dissolved solids of 15,800 mg/L, and an electrical conductivity (EC) of 39 mS/cm was added on the saturated soil columns after removing the water. Shortly after adding manure, the column setup had to be modified to prevent soil desaturation and air entry through the manometers. Figure 1b shows the modifications in the design. The columns were monitored for manometer levels and effluent flow rates. Raw supernatant from the liquid hog manure stored in 20 L pails at 6°C was applied to the top of the column to maintain a constant head at 600 mm.

One set of soil column replicates of each soil type were disassembled for chemical, visual and microscopic analysis on days 185, 406, and 634. The acrylic soil columns were carefully cut open. Care was taken to ensure minimal disturbance of the soil columns. One longitudinal half of the soil column was sectioned at various depth intervals and then used for chemical analysis while other longitudinal half was used for the preparation of thin sections.

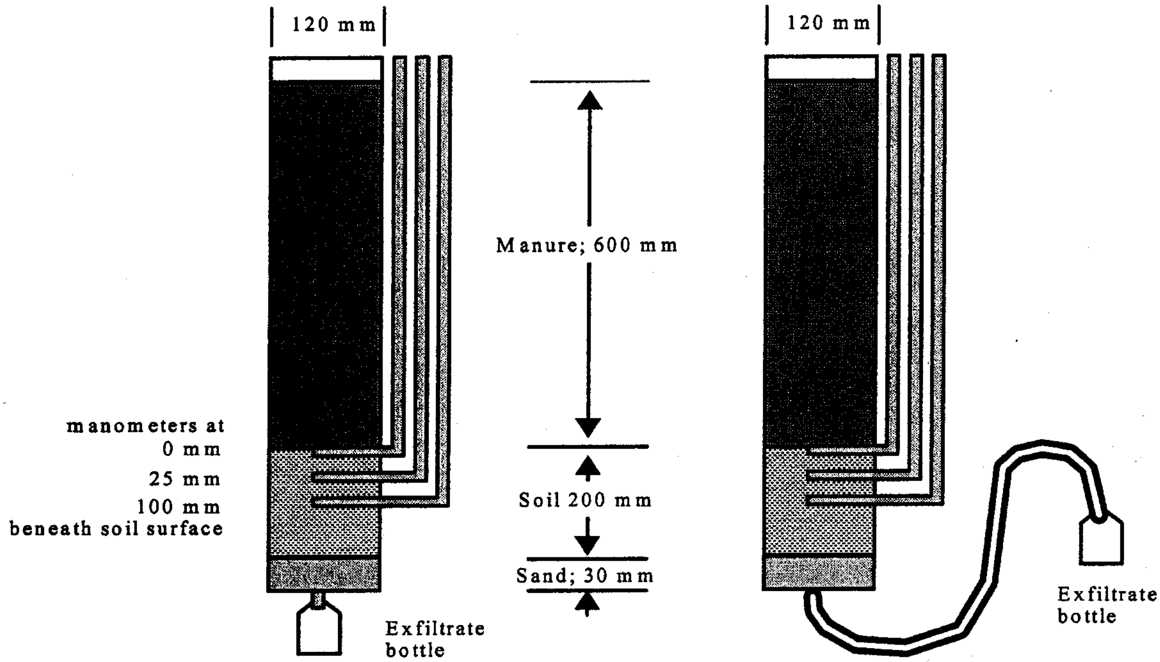

Fig. 1a. Original setup of columns

Fig. 1b. Modified column setup used for duration of manure seepage study

Figure 1. Modified column setup used for duration of manure seepage study

The relative importance that the manure seal had upon flow reduction relative to internal clogging of soil pores was studied by removing the seal from the soil surface on selected columns at the end of the study (day 634). The manure was removed from the column and then the seal was removed using a scraper such that the soil surface itself was exposed without too much soil being removed. A chemical solution with a similar ionic strength of manure was immediately added to these soil columns and hydraulic conductivity was measured. This was done to ensure that there was no sudden change in the soil matrix ionic strength and composition. The prepared chemical solution had an electrical conductivity, EC, of 20.7 mS/cm and the following makeup: KCl (4.0 g/L), NaCl (2.0 g/L), $CaCl_2.H_2O$ (2.0 g/L), and $(NH_4)_2SO_4$ (6 g/L). Monitoring of manure EC in the column during the last 200-300 days indicated that the EC was between 20 and 25 mS/cm.

DETERMINATION OF HYDRAULIC CONDUCTIVITY

The saturated hydraulic conductivity, K_{sat}, of the entire soil layer length (i.e., 200 mm) wirh the manure seal was determined under steady seepage conditions using Darcy's law. The hydraulic gradient was determined based upon the ponded manure depth (i.e., about 600 mm) and by assuming that the sand base had negligible resistance for the fluid passing through it. This hydraulic conductivity is referred to as the total hydraulic conductivity, K_{tot}. It was possible to determine the K_{sat}, of the four different layers with manometer measurements. The four layers are designated as L_1, L_2, L_3 and L_4 and their hydraulic conductivities are K_1, K_2, K_3, and K_4 respectively. The effective hydraulic conductivity of the entire column, K_{eff}, was calculated using the Eq. 1.

$$K_{eff} = \frac{(L_1 + L_2 + L_3)}{\left(\frac{L_1}{K_1} + \frac{L_2}{K_2} + \frac{L_3}{K_3}\right)} \quad [1]$$

where:

L_1 = manure seal at the soil surface;
L_2 = between the soil surface and a depth 25 mm;
L_3 = between the manometers at 25 mm and 100 mm; and
L_4 = interval between the manometer at 100 mm and the bottom of the soil at 200 mm.

The thickness of the manure seal was measured visually through the acrylic columns. Comparison of K_{tot} to K_{eff} and the K_{sat} of individual layers was useful to determine the effect of surface sealing and pore clogging upon overall flow reduction.

VISUAL AND MICROSCOPIC ANALYSIS

Thin sections studies were undertaken to evaluate pore structure, seal formation, and clogging. The steps in the preparation of thin sections consisted of sample air-drying, impregnation with a resin, cutting a block out of the soil with a diamond saw, then grinding and polishing so that the final section, as mounted on a glass slide was 65 x 85 mm and 30 μm thick.. Two vertical thin sections were prepared; one from the top of the core and the other from the bottom of the core. Further details related to sample preparation and thin sectioning is available from Majumdar (1996).

The differences in color of the soil and the soil-manure interface at different time intervals were captured by 35 mm camera using a close-up lens. The photographs were digitized and measurements were taken of seal thickness and seal development relative to reference marks to determine the change in thickness between measurements. It was attempted to have at least three separate measurement points for each column. Thin soil sections were examined with a 30X Zeiss Polarized microscope and photographic enlargements. Small soil samples, about one cm^3 in volume, were taken from within the soil column at the manure-soil interface for scaning electron microscopic (SEM) analyses from Soils #1, # 4 and #7 at the time of column disassembly after 185 days. More details with respect to the above experimental procedures are available in Majumder (1996).

RESULTS AND OBSERVATIONS

SOIL HYDRAULIC CONDUCTIVITY WITHOUT MANURE

The average column hydraulic conductivity values measured with water varied from 2.6 x 10^{-8} m/s to 131.8 x 10^{-8} m/s (Table 2). There was a close agreement within the three column replicates. The test results suggest that saturated hydraulic conductivity was largely a function of clay content (Table 1). None of the seven soils tested had a hydraulic conductivity less than 1 x 10^{-9} m/s required by many of the regulatory agencies (British Columbia, 1991and 1992; Manitoba 1993; Ontario 1994; Quebec (Gangbazo et al. 1989); Minnesota (Brach et al. 1992); USDA SCS, 1993).

Table 2. Hydraulic conductivity values at various depth intervals within soil columns for water and manure (K values are x 10^{-8} m/s).

Interval	Fluid	Soil # 1	2	3	4	5	6	7
Entire column	Water	2.6	28.1	16.3	43.1	51.3	20.4	131.8
25-100 mm depth	Water	3.4	50.3	22.4	39.6	94.7	60.0	545.2
Entire column	Manure	0.085	0.102	0.085	0.110	0.116	0.096	0.099
Seal	Manure	0.024	0.003	0.003	0.003	0.003	0.004	0.003
0-25 mm depth	Manure	0.161	0.740	0.082	1.019	1.200	0.172	0.736
25-100 mm depth	Manure	0.254	2.698	3.871	3.698	1.573	1.048	6.077
100-200mm depth	Manure	0.187	5.451	2.778	2.836	5.308	3.606	4.061

Hydraulic conductivity values are the average of 3 replicate columns.
Hydraulic conductivity values for manure is the average of measurements taken on a weekly basis.

HYDRAULIC CONDUCTIVITY OF THE SOILS WITH PONDED MANURE

The flow reduced rapidly within the first hour of application of hog manure and within 48 hours there was no fluid in the manometers. It was concluded that the column had desaturated with air entering through the manometers due to the presence of a low permeability layer at the soil surface. A very thin black layer resting was visible at this stage on the soil surface. The system was resaturated on the third day with water. This was achieved by increasing the head at the outlet to a greater pressure than the ponded manure at the soil surface. The outlet tube was then lowered to a new configuration after the manometers were re-established with water for the remainder of the study period (Fig. 1b). A period of 35 days were required for resaturation and stabilization of manometer levels in the new flow position.

The hydraulic conductivity values for all soils dropped to about 0.1 x 10^{-8} m/s within 3 to 6 weeks of ponding manure and varied within half an order of magnitude of this value for the remainder of the study period (Tables 2 and 3). The drop was regardless of the natural hydraulic conductivity with water, whether it was high as with the sandy material (Soil #7) or low as with the clay rich material (Soil #1, Table 1). This behavior is consistent with the research studies of other investigators (Culley and Phillips, 1982; Rowsell et al., 1985; and Barrington et al., 1987a, b).

The manure seal, which varied in depth from 3 to 8 mm, had the smallest hydraulic conductivity with a typical value of 0.003 x 10^{-8} m/s (Table 2). The 0-25 mm depth interval had the next lower hydraulic conductivity values under ponded manure head. This value is generally one to three orders greater in magnitude than the 'seal' hydraulic conductivity value. However, this value is also about 5 to 10 times smaller than deeper soil intervals. The hydraulic conductivity values were always lower for ponded manure conditions in comparison to water at all soil intervals (Table 2).

There was a seven hour failure in the cooling system on day 76 and a one day failure on day 276 causing the room temperature to rise from 6° C to 20-22° C. In both cases, air bubbles were found in the outflow tubes were removed. The hydraulic conductivity values increased in the period following the increase in temperature. The average hydraulic conductivity of all the columns during the days 81 to 102, rose from 1.1 x 10^{-9} m/s to 1.5 x 10^{-9} m/s and then decreased back to their original values within 10 days. For the day 276 failure, the average hydraulic conductivity of all the columns increased from less than 0.10 x 10^{-8} m/s to about 0.36 x 10^{-8} m/s (compare day intervals 59-269 to that of 276-319 in Table 3). Some columns did not recover to their pre-heating hydraulic conductivity values until day 400. The hydraulic conductivity increased during days 599-634, likely due to control room warming as there were several people working during this period (Table 3).

Table 3. Hydraulic conductivity of the soils with ponded manure at different time intervals (K values are x 10^{-8} m/s).

Day	No of	Soil #							
(Interval)	replicates	1	2	3	4	5	6	7	Mean
38-185	3 Reps	0.09	0.10	0.09	0.11	0.12	0.10	0.10	0.10
59-269	2 Reps	0.06	0.09	0.09	0.10	0.12	0.11	0.09	0.10
276-319*	**2 Reps**	**0.24**	**0.21**	**0.25**	**0.65**	**0.48**	**0.61**	**0.08**	**0.36**
327-403	2 Reps	0.08	0.08	0.09	0.21	0.16	0.20	0.08	0.13
421-593	1 Rep	0.06	0.07	0.04	0.07	0.07	0.05	0.06	0.06
599-634*	**1 Rep**	**0.18**	**0.17**	**0.06**	**0.12**	**0.09**	**0.09**	**0.21**	**0.13**

Reps are the number of replicate columns measured during each time period.
*Days 276-319 and 599-634 are periods during which hydraulic conductivities were higher (Results are shown in bold)

EFFECT OF SEAL REMOVAL UPON HYDRAULIC CONDUCTIVITY BEHAVIOR

The effect of removing the manure seal from the soil surface (i.e., day 634) and replacing the ponded manure with a chemical solution resulted in increase of hydraulic conductivities back to values originally measured with water (Table 4).

Table 4. Hydraulic conductivity of selected columns at different stages (K values are x 10^{-8} m/s).

Stage	Interval	Fluid	Soil # (Column number)		
	Mm		Soil #3 **(9)**	Soil #5 **(15)**	Soil # 6 **(18)**
Stage I	200	Water	9.13	57.75	21.94
Stage II	Seal + 200	Manure	0.19	0.64	0.01
Stage III	200	Chemical	18.67	65.06	21.00
Stage I	25-100	Water	19.82	50.04	61.23
Stage II	25-100	Manure	0.46	2.71	1.50
Stage III	25-100	Chemical	24.97	57.82	68.54

(Stage I) : Hydraulic conductivity of the soil columns with water
(Stage II) : Manure was ponded replacing water for a period 634 days in the soil columns (i.e., after Stage I).
(Stage III): A chemical solution was ponded after removing manure and manure-seal (after day 634).

VISUAL AND MICROSCOPIC OBSERVATIONS OF SOIL-MANURE INTERFACE

A layer of black amorphous material was observed to develop upon the soil surface in the first sixteeen hours of the experimental study. The outflow from the columns slowed considerably during this sixteen hour period. Similar observations associated with decreases in hydraulic conductivity of soil columns were reported by other investigators (Barrington and Jutras, 1985; Rowsell et al., 1985; Barrington et al., 1987). Within 36 hours, columns with Soils # 3 to #7 had distinct black lines with a thickness less than 1 mm on the soil surface. However, columns with Soils #1 and #2 had diffuse black material just forming on the soil surface. Photographs taken of the soil surface at various intervals showed that the seal thickness increased with time during the entire study period. The growth of the seal appeared to be extending into the soil, rather than becoming thicker on top of the soil surface. Measurements from scanned images of the photographs over a period of 1.5 years indicated that the black layer thickness increased at a near constant average rate of 0.33 mm per month, without considering the first three month period. The regression equation for this relationship with $r^2 = 0.9998$ is given below:

$$T = 0.0111D + 1.269 \qquad [2]$$

where: T is the thickness of the black layer in mm, and D is the number of days since manure was ponded on the soil surface.

The formed black layer was fragile and could be separated from the underlying soil upon disassembly of the columns. This black layer was observed to disappear upon drying and was likely absorbed into the mineral soil matrix (Majumdar 1996). Just above the seal layer there were identifiable plant parts that formed a manure mat. These observations were from thin section analysis with an optical microscope and scanning electron microscopic analysis. The seal itself could not be thoroughly investigated with these two techniques due to the limitations in drying pre-treatment methods. Organic particles and coatings within the pores of the soil were found using both these techniques. The presence of organic particles in sandy soils was observed to be more common and frequent. It was also found that organic particles protrude deeper into coarse-grained soils in comparison to fine-grained soils (Majumdar 1996).

DISCUSSION

Experimental results of the research study have shown that reduction in hydraulic conductivity occurs simultaneously with the formation of the manure seal. The hydraulic conductivity values recovered to original values that were measured with water once the seal was removed. This phenomenon clearly shows that the reduction in hydraulic conductivity values are associated with the manure seal formation rather than due to the clogging of the soil pores with manure solids. The unplanned heating events during the study appeared to have disrupted the integrity of the seal for short periods following the rise in temperatures in the control room. These events resulted in a large increase in flow rates which may be due to the softening of the manure seal, seal disruption by gases, and reduced viscosities of the fluids.

The hypothesis that the seal is the primary controlling factor in reduction of hydraulic conductivity can also be verified with the use of a two layered flow system using Equation 1. The two layers are the manure seal and the soil layer whose hydraulic conductivity values as measured with water are summarized in Table 2. Table 5 summarizes the comparisons of calculated effective hydraulic conductivity value, K_{eff}, for various manure seal layer and soil layer thicknesses.

Table 5. Comparison of calculated effective hydraulic conductivities for a two layer system for the seven different soils.

Item	Hydraulic Conductivity	Manure seal layer D_1 (mm)	Soil layer D_2 (mm)	#1	#2	#3	#4	#5	#6	#7
				Hydraulic conductivity x 10^{-8} m/s						
1.	K_{water}	0	200	2.6	28.1	16.3	43.1	51.3	20.4	131.8
2.	K_{manure}	3*	200	0.09	0.10	0.09	0.11	0.12	0.10	0.10
3.	K_{eff}	3	200	1.01	0.20	0.20	0.20	0.20	0.27	0.20
4.	K_{eff}	8	200	0.51	0.08	0.08	0.08	0.08	0.10	0.08
5.	K_{eff}	8	1000	1.40	0.37	0.37	0.37	0.38	0.49	0.38

D_1 is the thickness of manure seal layer; D_2 is the soil thickness

* Average manure seal thickness due to 170 days of manure ponding from seven soil columns tested

K_{water} is the measured hydraulic conductivity of the soil column with water (from Table 2)

K_{manure} is the measured hydraulic conductivity of the soil column ponded with manure (from Table 2)

K_{eff} is the calculated effective hydraulic conductivity for a two layer system using Equation 1.

With the exception of soil #1, the effective hydraulic conductivity, K_{eff}, reduced to about twice the measured manure hydraulic conductivity, K_{manure}, for a manure seal, D_1 equal to 3 mm (Table 5). A seal thickness of 8 mm reduced the effective hydraulic conductivity, K_{eff}, to slightly lower than measured manure hydraulic conductivity. Note that the overall K_{eff} also increases with an increase the thickness of the soil layer thickness. The seal layer still exerts primary control on the effective hydraulic conductivity behavior even when the thickness of soil layer is 1 m (compare Row 5 data with Row 1data). However, the seal begins to lose its effectiveness with increasing penetration of the seepage front.

The hydraulic conductivity values measured in soil columns after scraping off the manure seal suggest that reductions in hydraulic conductivity are primarily due to the manure seal formation. These results also suggest that presence of any clogging or coatings in soil pores had little effect on hydraulic conductivity values. However, the formation of a 3 mm seal due to ponded manure in soil columns does not fully account for the reduction in hydraulic conductivity values. Similar observations can be arrived at by comparing interval hydraulic conductivity values (Table 4).

Several possibilities and scenarios listed below may have to be considered for rigorous analysis;

- unsaturated conditions caused by the manure seal on top of the soil surface;
- unsaturated conditions caused by gas production within the soil column;
- temporary clogging of pore spaces by manure particles; or
- preferential flow or flow conditions to low hydraulic head.

CONCLUSIONS

The results of this research program suggest that the formation of the manure seal is the primary factor for the reduction of hydraulic conductivity of all the soils tested in a controlled low-temperature environment. The following answers are provided to the questions in the introduction based on the research studies presented and discussed in the paper :

1. The rate of flow reduced by two to three orders of magnitude;
2. Soil texture had little apparent effect upon flow reduction;
3. The amount of time of manure ponding seems to have little effect upon flow reduction;

4. Flow reduction is primarily due to the formation of a manure seal. Organic particles and coatings within the soils had little effect upon hydraulic conductivity;
5. The seal is sensitive to temperature. Two unplanned heating events resulted in increased flow rates;
6. Seal removal followed by ponding with a chemical solution resulted in the hydraulic conductivities recovering back to original values measured with water.

The above findings were based on studies undertaken in a controlled environment. Several other questions can be raised; some of which are listed below;

1. Is there a possibility of unsaturated conditions to occur beneath the seal?
2. Is there a contribution to seal growth by micro-organisms within the soil?
3. What is the effect of the high ionic strength of the manure upon clay and its soil pore structure?
4. Would any of these observed effects be similar if study temperatures were higher e.g., 12°C or 20°C?
5. What would be the effect of field conditions (i.e., wet-dry and/or freeze-thaw cycles) upon the seal and that of the soil permeability?

The research program discussed in this paper is a fundamental baseline study. Further research studies are necessary to answer all the questions listed above. There are several other questions that can be raised related to the construction, design and location of manure structures to provide better guidelines. However, those issues are beyond the scope of this paper, due to space limitations and are not discussed.

ACKNOWLEDGEMENTS
The authors acknowledge the Saskatchewan Agricultural Development Fund and SPI (Sask Pork) for funding

REFERENCES
Allison, L.E. 1947. Effect of microorganisms on permeability of soil under prolonged Submergence. *Soil Science* 63:439 – 450.

Avnimelech, Y. and Z. Nevo. 1963. Biological clogging of sands. *Soil Science* 98:222-226.

Barrington, S.F. and P.J. Jutras. 1985. Selecting sites for earthen manure storages.

Barrington, S.F., P.J. Jutras, and R.S. Broughton. 1987a. The sealing of soils by manure. Part I. Preliminary investigations. *Canadian Agricultural Engineering* 29(2):99-105.

Barrington, S.F., P.J. Jutras, and R.S. Broughton. 1987b. The sealing of soils by manure. Part II Sealing mechanisms. *Canadian Agricultural Engineering* 29(2):105-109.

Barrington, S.F. and R.S. Broughton. 1988. Designing earthen storage facilities for manure storage. *Canadian Agricultural Engineering* 30:289-292.

Barrington, S.F. and C.A. Madramootoo. 1989. Investigating seal formation from manure infiltration into Soils. *Transactions of American Society of Agricultural Engineering* 32(2):851-856.

Chang, A.C., W.R. Olmstead, J.B. Johanson, and G. Yamashita. 1974. The sealing mechanism of wastewater pond. *Journal Water Pollution Control Federation* 46(7):1715-1721.

Culley, J.L.B. and P.A. Phillips. 1982. Sealing of soils by liquid cattle manure. *Canadian Agricultural Engineering* 24:87-89.

Davis, S., W. Fairbank and H. Weisheit. 1973. Dairy waste ponds effectively self-sealing. *Transactions of American Society of Agricultural* 16:69-71.

deTar, W.R. 1979. Infiltration of liquid dairy manure into soil. *Transactions of American Society of Agricultural Engineering* 22:520-558.

Fonstad, T.A. 1996. Effects of manure ponding on soil hydraulic properties. M.Sc. Thesis. Department of Agriculture and Bioresource, University of Saskatchewan.

Gangbazo, G., D. Cluis and M. Vallidres. 1989. Nitrogen seepage from earthen-built manure storage tanks. ASAE/CSAE Paper No. 892002. ASAE/CSAE International Summer Meeting.

Majumder, G. 1997. Evaluation of sealing and seepage beneath ponded hog manure storages. M.Sc. Thesis. Department of Agriculture and Bioresource, University of Saskatchewan.

Manitoba Agriculture. 1994. *Farm Pracitices Guidelines for Hog Producers in Manitoba* (DRAFT).

McCalla, T.M. 1950. Studies on the effect of microorganisms on rate of percolation of water through soils. *Soil Science Society of America Proceedings*. 15:182-186.

McConkey, B.G., C.D. Reimer and W. Nicholaichuk. 1990. Sealing earthen hydraulic structures with enhanced gleization and sodium carbonate I. Laboratory study of the effect of a freeze-thaw cycle and a drying interval. *Canadian Agricultural Engineering* 32:163-170

Miller, D.C., J.B. Robinson and R.W. Gillham. 1985. Self-sealing of earthen liquid manure storage ponds. I. A case study. *Journal of Environmental Quality* 14(4):533-538.

Mitchell, R. and Z. Nevo. 1963. Effect of bacterial polysaccharide accumulation on infiltration of water through sand. *Applied Microbiology* 12(3) 219-223.

Nicholachuk, W. 1978. Seepage control in excavated earthen reservoirs. *Canadian Agricultural Engineering* 20:97-101

Ontario Ministry of Agriculture, Food and Rural Affairs, 1991, 1994. Agricultural Pollution Control Manual.

Rowsell, J.G., M.H. Miller, and P.H. Groenbelt. 1985. Self-sealing of earthen liquid manure ponds. II. Rate and mechanisms of sealing. *Journal of Environmental Quality* 14(4):539-543.

Saskatchewan Agriculture and Food. 1992. *Site Evaluation for an Earthen Manure Storage.*

Soil Conservation Service, U.S. Dept. of Agriculture. 1993. Design and construction guidelines for considering seepage from agricultural waste storage ponds and treatment lagoons. Technical Note 716, Revision 1. South Texas Technical Center, Fort Worth, Texas.