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A Comparison of Soil Permeability to Water and Feedlot Effluent

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Summary Rainfall runoff from cattle feedlots is captured in holding ponds for treatment or disposal by irrigation. Compacted soil liners can be used in holding ponds to limit seepage, thereby reducing the potential for environmental degradation. The permeability of three soils, which have potential for use as holding pond liners, were compared in the laboratory using water, feedlot effluent and filtered feedlot effluent as the permeating fluids. The chemical characteristics of the soils, permeating fluids and any resulting leachate were also determined. Testing revealed that significant differences in compacted soil permeability can be expected between the different permeating fluids. These differences were attributed to variations between the chemical characteristics of water and effluent used for testing. It was concluded that for an adequate assessment of potential liner materials, permeability testing must be undertaken using fluids with chemical characteristics representative of those that are to be retained in the pond.

1. INTRODUCTION

Lot feeding of cattle has become a widely established practice to supply a product of consistent high quality. Potential environmental problems of feedlots, however, include odour nuisance, surface water and ground water pollution. These arise out of the wetting and movement of the manure from the pen surface. Water leaving the pen surfaces is laden with organic matter (from the manure) and is capable of degrading surface and ground water. Feedlots must capture and hold this effluent, pending its disposal by irrigation.

The lot feeding industry has adopted sophisticated waste management techniques to minimise the odour problems. The basis of these techniques is to minimise wetting and maximise drying of the manure on the pens. Techniques used include providing rapid drainage to holding ponds, frequent cleaning of the loose manure, sloped pen surfaces and good pen design (Lott *et al* 1994).

Feedlots yield more runoff than previously thought and as a result, holding ponds may have to be enlarged from current design practices (Lott, 1997). The holding ponds are a potential source of groundwater pollution, and soil compaction could be used during construction to reduce permeability in the liner material to an acceptable level.

The hydraulic conductivity (k) of a compacted soil (using a known quantity of energy at a pre-determined moisture content) is usually measured in the laboratory with water used as the permeating fluid. The aim of this investigation was to compare hydraulic conductivity of three distinct soil types when feedlot effluent was used for testing rather than water. The chemical characteristics of the soils and permeating fluids were also measured to determine whether any variations in k could be attributed to changes in soil chemistry.

2. MATERIALS AND METHODS

There are a variety of ways to treat and store feedlot effluent. One method commonly employed is the use of an anaerobic pond. Anaerobic ponds are generally greater than 2m deep which ensures that anaerobic conditions develop and are sustained. Ponds typically have a depth of approximately 3m, with a freeboard allowance of 0.5 to 1m. Ponds deeper than 3 to 4m are generally uneconomic to construct for most feedlot operators. Because of their common occurrence, an attempt was made to simulate anaerobic conditions which could be expected in a 3m deep pond during laboratory testing.

2.1 Soil Selection and Preparation

Soils studied were a Tertiary basalt laterite, a weathered Mesozoic mudstone and a Quaternary age black cotton soil. Feedlots are located on soils of these types in the rural areas surrounding Toowoomba, a major Queensland provincial city located about 120 km west of Brisbane. Samples were taken from road cuttings in the area surrounding the city, as at these locations there was less likelihood of contamination and a section of the soil / rock profile was clearly exposed thus ensuring correct material identification.

A 35 to 45 kg bulk disturbed sample was taken at each site. Each sample was crushed using a domestic shredder normally used to break down garden refuse. This served two purposes; it provided a relatively uniform sample of consistent particle size and simulated the behaviour of machinery used in the construction of holding ponds. Samples were then split into 12 x 2.5 kg and 2 x 1000 g sub-samples using a riffle box. The larger sub-samples were used for compaction and permeability testing. Atterberg Limits, Linear Shrinkage, Particle Size Distribution (PSD), and major ion contents were determined using the smaller sub-samples.

2.2 Fluid Selection and Preparation

Permeability tests were undertaken on each soil type using three different fluids. The first fluid used was water from the Toowoomba City supply. Effluent with a maximum suspended particle size less than 2.36 mm was then used. The final fluid used was filtered effluent that had been passed through a 0.075 mm sieve. This was undertaken to examine whether changes in permeability were principally due to pore clogging (by suspended material) or due to chemical effects. Effluent samples were obtained from the inlet channels into one of two holding ponds (pond 2 or 3) at a large integrated feedlot, abattoir, and meat processing facility located about 40 km west of Toowoomba. The effluent consisted of a combination of cattle yard pen waste, abattoir and factory spray down waste, and stormwater runoff.

Slug loadings to the holding ponds due to major runoff events can result in feedlot effluent having significantly different characteristics between loading cycles (Lott, 1997). Once in the pond, a change in the characteristics of the effluent also occurs over time, through the decomposition of the organic matter by biological and chemical processes. From a statistical viewpoint, these constantly changing conditions were not ideal for the collection of representative samples nor this short term investigation.

The effluent used was considered appropriate for the following reasons:

1. Effluent entering ponds 2 and 3 was more likely to have relatively constant characteristics due its source from a manufacturing type environment;

2. Conditions in the ponds are more stable due to regular effluent inflows;

3. The effluent from an operating feedlot, abattoir and meat processing facility is similar to the chemistry that is typically found in the feedlot industry.

2.3 Permeability Testing

A constant head permeameter was used for the investigation. In an attempt to simulate anaerobic pond conditions, the permeameter assembly was positioned in the lee of the building such that all but the surface of the reservoir was in constant shade. The investigations took place in winter when permeating fluid temperatures ranged from 4°C to 14°C.

Compaction testing was undertaken as per procedures outlined in AS 1289.5.1.1 (1993) except only three points were used to determine the moisture-density curve for each sample. Soil samples were placed into permeability moulds similar to the placement procedures outlined in AS 1289.5.1.1 (1993) except:

1. Mould volumes were generally between 910 and 962 cm^3 (allowing for spacer disc displacement);

2. The spacer disc was removed and replaced with a porous disc following compaction;

3. Three soil sub-samples were placed into separate permeability moulds at any one time;

4. The number of blows per layer using a standard compaction hammer was reduced proportionally to allow for the smaller mould volumes.

The three permeability moulds were connected to the permeameter and the manifold height fixed at a height of 3m above the compacted soil surface. A 200 mL beaker was positioned beneath the outlet of each permeability mould to collect any leachate. Fluid was then added to the permeameter manifold. Leachate volumes were recorded at irregular intervals during testing, and samples taken. After approximately 4 days, fluid in the reservoir and manifold was drained from the permeameter. Soil samples were extruded, cut in half vertically along the axis and each half cut into 3 equal sections perpendicular to the axis. The moisture contents of sections from one half were then determined in accordance with AS 1289.2.1.1 (1992). Chemical testing was undertaken on the top section (closest to the manifold inlet) of the remaining half of the soil.

A data logger recorded temperature at 10 minute intervals for a period of 6 days from commencement of permeability testing. Following testing, the information in the data logger was down loaded to a computer.

2.4 Soil and Chemical Testing

Atterberg Limits and Linear Shrinkage testing were undertaken in accordance with AS 1289.3.9 (1991), AS 1289.3.2.1 (1995), AS 1289.3.3.2 (1995), and AS 1289.3.4.1 (1995). Liquid Limit and Linear Shrinkage tests were then performed on the remaining portion of the samples using effluent passing the 0.075 mm sieve for testing purposes instead of water. Particle size distributions were determined on initial disturbed soil samples as per AS 1289.3.6.3 (1994). A specific gravity of 2.65 was assumed for all three soil types.

Major exchangeable ion contents were determined as per Method 15D3 (Raymont and Higginson, 1992) for an initial 1000 g disturbed soil sample and the top sections of extruded mould samples taken following permeability testing.

Electrical Conductivity (EC), and NO_3^-, PO_4^{3-}, and major exchangeable ion contents were determined on fluid samples taken prior to testing and leachate collected during permeability testing. Nitrate and phosphate contents were determined using Methods G1a and H2a of Raymont and Higginson (1992) respectively. Method 3500 in APHA (1995) was used to determine major exchangeable ions, while EC was assessed in accordance with Method 2510B in APHA (1995).

2.5 Calculations

Hydraulic conductivity was determined using the relationship first determined by Darcy (1856):

$$k = \frac{QL}{tAh} \tag{1}$$

where

k = coefficient of permeability (m/s);
Q = volume of permeate (m^3);
L = mould height (m);
t = time (s);
A = mould area (m^2);
h = manifold height (m).

The weighted temperatures between permeate readings as determined from the datalogger were calculated. Hydraulic conductivity was then corrected to a standard temperature of 20°C to allow for temperature related viscosity variations. Correction factors were taken from QMRD Test Method Q125 (1978).

3. RESULTS AND DISCUSSION

The two tailed Student's t-test was used to identify significant changes in material characteristics. An F-test was first applied to check whether the variances were equal or not. The t-test was then applied assuming equal variances where indicated, otherwise unequal variances were assumed. Folk (1980) noted that most statisticians do not accept an experimental result as significant unless there is a 95% probability that a change has occurred. This standard has been adopted.

3.1 Soil Classification

Cumulative plots of particle size for the three tested soil types are provided in Figure 1. There are only minor differences in grain size distribution for the three types with the noticeable differences being negligible sand sized particles in the black soil, whilst the mudstone has less clay than the other two soils.

Atterberg limits and linear shrinkage are summarised in Table 1. The soils were tested both with water and filtered effluent. These results indicate that the laterite and black cotton soils are highly plastic clays. Under the Unified Classification System (Wagner, 1957), these samples would be classified CH. The weathered mudstone would be classified as CI-CH, consistent with the lower percentage of clay present shown by the particle size analysis.

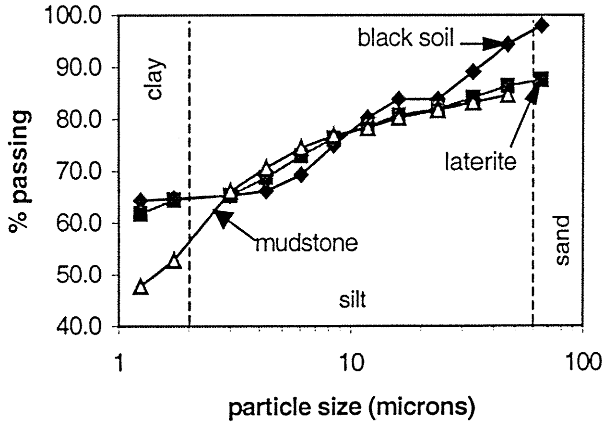

Figure 1. Particle size distribution for soils under investigation.

Compaction tests on the soils are summarised in Table 2, along with the relative densities achieved in the permeability moulds. It is of significance that poor compaction was achieved in the black soil samples tested with the effluent and filtered effluent. This highlights that these soils are difficult to work with, even under ideal laboratory conditions, hence great care will be needed in the field to achieve a satisfactory liner.

Table 1. Liquid limit (w_L), plasticity index (I_P) and linear shrinkage (LS) for soil samples tested using water and filtered effluent (in percent).

Testing fluid	Water			Filtered effl.	
Material	w_L	I_P	LS	w_L	LS
Laterite	82	43	16.5	77	14.0
Mudstone	49	30	10.0	42	8.0
Black Soil	77	44	19.5	80	21.5

Table 2. Optimum moisture content (OMC), maximum dry density (MDD) under standard compaction and relative density (R_d) achieved in the permeability moulds for all testing fluids.

	OMC	MDD	R_d (%)	
Material	(%)	(t/m^3)	min	max
Laterite	37.5	1.31	98.6	102
Mudstone	22.0	1.62	98.3	99.9
Black Soil [1]	28.5	1.37	91.9	96.8
Black Soil [2]	28.5	1.37	83.2	88.2

1. Tested with water
2. Tested with effluent or filtered effluent

3.2 Permeability

To assess if changes in permeability occurred between testing undertaken using water compared to effluent, a common point of reference was required. As a result, k after 90 hours of testing was used as most samples had apparently reached a steady state by this time. The results are summarised in Figure 2. The t-test was then used to compare the respective values.

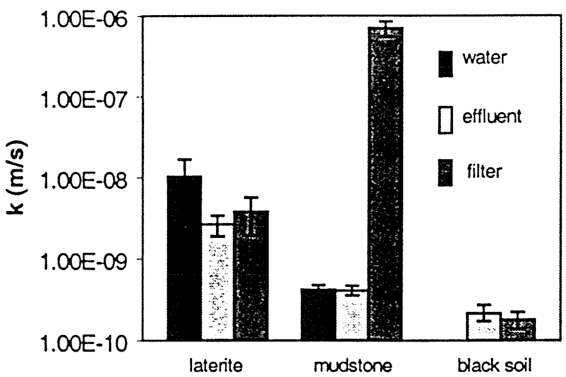

Figure 2. Mean and standard deviation of the coefficient of permeability (k) for the three soils (laterite, mudstone and black soil) and permeating fluids (water, effluent and filtered effluent).

Laterite: The results of a t-test indicated that after 90 hours of testing using filtered and unfiltered effluent as compared to water, there was approximately 85% probability that the permeability of the laterite sub-samples was lower. When the permeability results of the laterite sub-samples tested using unfiltered and filtered effluent were grouped and compared to water, there was a significant decrease in the permeability. Regulators commonly require a coefficient of permeability of less than 10^{-9} m/s for clay landfill liners so that the risk of groundwater pollution is minimal from seepage, although diffusion effects may become important once this level is reached (Hitchcock et al., 1996). Licence conditions for holding ponds similarly often require the permeability to be reduced to a specified value, contingent on site specific risk factors such as depth to the water table. Testing a marginal soil with effluent rather than water may give a sufficiently low result to make it acceptable.

Mudstone: When a t-test was used to compare the permeability of mudstone samples when effluent was used for testing against those tested using water, there was no significant difference. In contrast, when tested using the filtered effluent there was a significant increase. After about 2.5 hours, the permeability of the mudstone sub-samples tested using filtered effluent had apparently stabilised. Testing was discontinued after this time because the reservoir of the permeameter assembly had emptied. It was observed during this test that the colour in the metre of tubing above the mould cap changed from green to white, indicated that the mudstone samples dispersed completely. This resulted in soil structure breakdown, leading to a significant increase in permeability. It is not obvious why the effluent samples did not disperse although it may have been due to the presence of the coarse organic matter, which tends to alter the chemistry of the water through its cation balance and electrical conductivity. This may counteract the effects of the sodium and potassium cations or possibly the short length of the test may also be involved.

Black Soil: No permeate was observed after 100 hours of permeability testing on the black cotton soil samples using water. This prevents any statistical comparisons to be made between the effluent and water samples, although the value of k must be substantially lower in the water samples. There appeared to be clear a reason, however, for the different behaviour of the black cotton soil samples when effluent rather than water was used for testing. It was observed that when the soil samples were removed from the mould and cut open, a manure stain could be seen within selected voids. This confirms that the compaction for each sample tested with either effluent or filtered effluent was inadequate. It is highly likely that some of these voids were interconnected, and as a result, there was preferential flow through these voids rather than through the voids of the entire sample. This problem has been experienced by other researchers (Olsen and Daniel, 1981).

3.3 Fluid Chemistry

Chemical analysis of the fluids used in testing the permeability is presented in Figure 3 for the cations and Figure 4 for the anions. The abbreviations used in these figures are: water (W), effluent (E), filtered effluent (F), permeate from laterite using water (PWL), permeate from mudstone using filtered effluent (PFM), permeate from laterite using filtered effluent (PFL) and permeate from the mudstone using effluent (PEM). Three samples each of the water, effluent and filtered water were analysed but samples of the permeate varied in number from zero (where insufficient permeate was produced for testing) to five in the mudstone tested with filtered water. This limited the extent of statistical analysis of the fluids before and after seeping through the soils. In the cations, the water is significantly different to both the effluent and filtered effluent in all cases except for calcium, but the most important difference is in the levels of sodium. There is no difference between the filtered and unfiltered effluent.

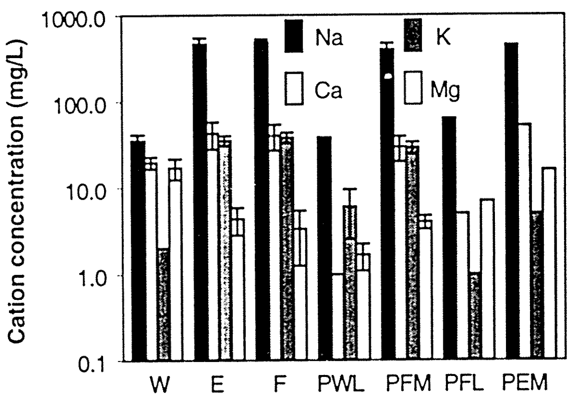

Figure 3. Mean and standard deviation of the cation concentrations in the various fluids.

There was a significant decrease in the calcium, magnesium, phosphate and nitrate (all others unchanged) in permeate samples taken during testing on the laterite using water compared to the initial water samples. It appears that the calcium and magnesium may be exchanged on the clay particles for the potassium and sodium ions (which show small but not significant increases), which should improve the stability of this soil. It also appears that the soil is acting as an effective trap for phosphorous (Figure 4), reducing the potential for groundwater pollution from this compound. Although the nitrate has decreased, this result must be treated with caution, as biological activity can readily change this into other forms of nitrogen.

Comparison of permeate from testing on mudstone using filtered effluent to initial filtered effluent samples indicated that there was a significant decrease in K^+, and a significant increase in the PO_4^{3-} and NO_3^- contents. The significant increase of PO_4^{3-} and NO_3^- in the permeate indicates that the soil contained these anions and these have been released or displaced by chloride ions upon dispersion of the soil. The K^+ decrease in the permeate could explain the dispersion, as this ion was exchanged for calcium and magnesium in the soil. There were no other significant changes.

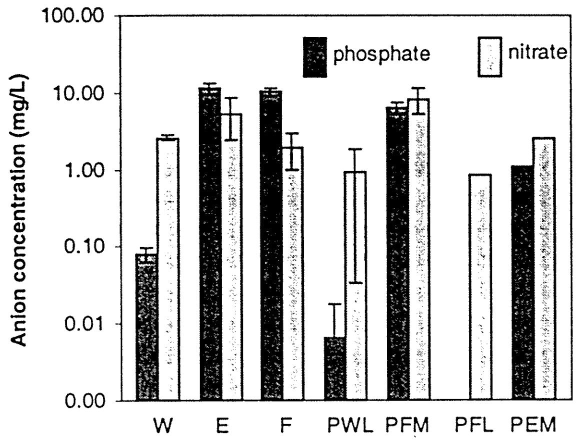

Figure 4. Mean and standard deviation of the anion concentrations in the various fluids.

3.4 Soil Chemistry

When permeability testing is conducted, the tested soil sub-sample becomes progressively saturated as fluid passes through the sample. As a consequence, apparent changes in soil chemistry following permeability testing may be due to the chemical characteristics of the water or effluent contained in the voids. To see if this effect was significant, the cation exchange capacity (CEC) determined on a dry weight basis of the 3 soils was compared (Figure 5). Differences were found only between the laterite tested with filtered effluent and mudstone tested with either effluent. Based on this result, it was assumed that differences in the cations in the soil before and after testing were mainly due to exchange processes. There is a large difference in CEC between the black soil and the other two soils and this reflects their different mineralogy.

The results of soil chemical analyses are shown in Figures 6 to 9, for each of the four main cations. For adsorbed sodium ions, there was significant exchange in both the mudstone and black soil when either of the effluents were used as the testing fluid. This indicates that sodium was likely to have been at least partly responsible for the dispersion in the mudstone when the filtered effluent was used. Given the sodicity of the mudstone (23% exchangeable sodium in the soil before testing) and lower clay content it was more prone to this failure than the other soils (although the laterite also had 20% exchangeable sodium in the soil before testing).

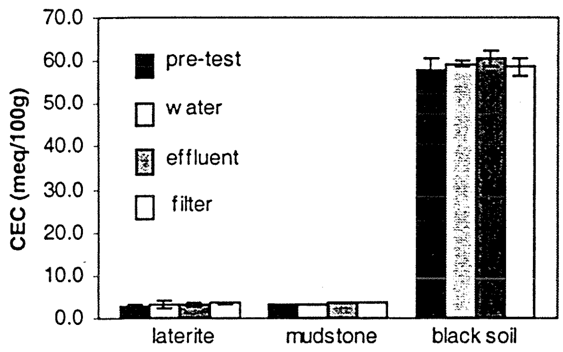

Figure 5. Cation exchange capacity (CEC) in the three soils before and after testing with water, effluent and filtered effluent.

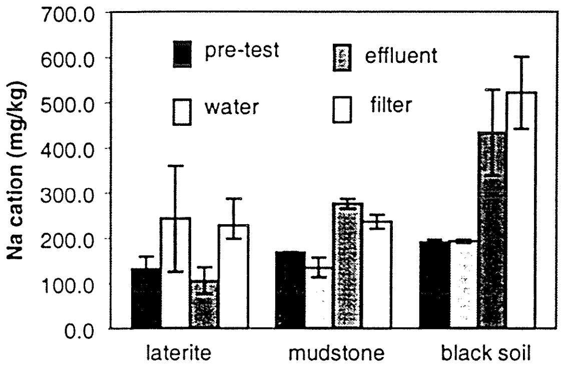

Figure 6. Mean and standard deviation of exchangeable sodium in all soils, before and after testing with water, effluent and filtered effluent.

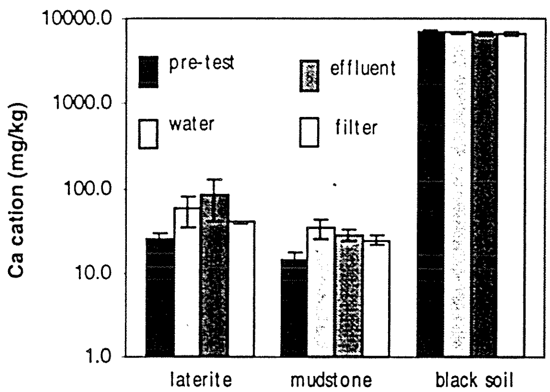

Figure 7. Mean and standard deviation of exchangeable calcium in all soils, before and after testing with water, effluent and filtered effluent.

Calcium shows a significant increase for all permeating fluids in the mudstone and the laterite with the filtered effluent. There is also a 93% and 85% probability that the calcium in the laterite increased with the water and effluent treatments. This is also consistent with the results for the permeate from the laterite when tested with water which showed a decrease in calcium. The black soil did not show any differences which is not surprising given the already very high levels of calcium present.

With the potassium, significant differences were only found with the mudstone tested with filtered effluent and the black soil tested with either effluent. Again, this is consistent with the permeate results from the mudstone with the filtered effluent, where a significant decrease in K^+ was found. This reinforces the suspected role of potassium in the dispersion of the mudstone tested with filtered effluent.

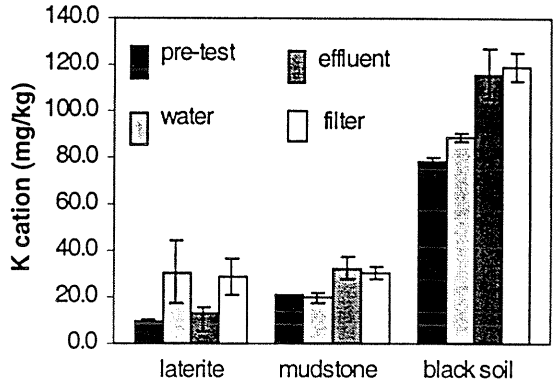

Figure 8. Mean and standard deviation of exchangeable potassium in all soils, before and after testing with water, effluent and filtered effluent

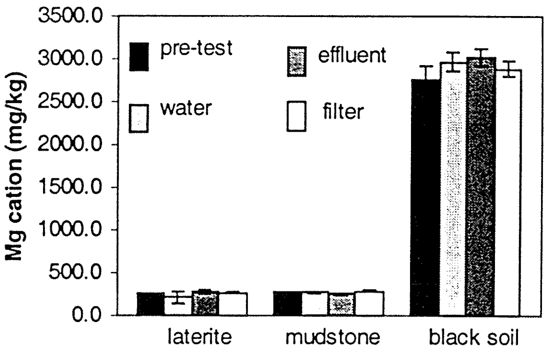

Figure 9. Mean and standard deviation of exchangeable magnesium in all soils, before and after testing with water, effluent and filtered effluent

Significant changes in the adsorbed magnesium occurred only in the laterite and mudstone soils when tested with effluent.

4. CONCLUSIONS

The results of this investigation indicate that significant physical and chemical changes occur in compacted soil when feedlot effluent is used for hydraulic conductivity testing compared to water. This can be attributed to differences between the chemical composition of the fluids used for testing. The importance of adequate compaction in obtaining satisfactory performance of a liner in the field was also highlighted. To adequately assess potential feedlot liner materials, permeability testing must be undertaken using several feedlot effluent samples, which cover the full range of potential physical and chemical compositions. Care needs to be taken that potentially dispersive soils are not used in these applications.

5. ACKNOWLEDGMENTS

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