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John F. McBride
Iowa State University

Robert Horton
Iowa State University, rhorton@iastate.edu

Michael L. Thompson
Iowa State University

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Evaluation of Three Iowa Soil Materials as Liners for Hazardous-Waste Landfills[1]

JOHN F. MCBRIDE, ROBERT HORTON and MICHAEL L. THOMPSON

Department of Agronomy, Iowa State University, Ames, IA 50011

A hazardous-waste landfill site usually requires a liner constructed of compacted soil material to help prevent the migration of hazardous wastes from the landfill. The performance of a compacted soil liner is partly a function of the physical properties of the soil materials used. The physical properties of three Iowa soil materials were examined to obtain information concerning their effectiveness as liner materials. Particle size distribution, Atterberg limits, particle density, undisturbed bulk density, and moisture-density relations were determined for till, loess, and paleosol materials. In addition, permeability and solute breakthrough measurements were made on compacted samples of the three materials. All compacted soil materials had permeabilities of less than 10^{-9} meters per second. On the basis of the physical properties of each soil material and current methods used to evaluate the potential effectiveness of a liner, the till soil material seemed to be the best suited.

INDEX DESCRIPTORS: hazardous-waste landfill, compacted liner, permeability, solute breakthrough curves.

Our technological society produces a variety of hazardous chemicals that must be disposed of. For the foreseeable future, landfills will be used for the disposal of these hazardous wastes. Ideally, the disposal of hazardous wastes should be done with minimal effects on the environment. According to the Iowa Department of Natural Resources, the State of Iowa currently does not run or manage a hazardous-waste landfill (personal communication). A few private landfills exist, but the majority of wastes destined for hazardous-waste facilities is transported out of state. The growing reluctance of states with hazardous-waste landfills to accept hazardous wastes generated by other states and the cost and problems of shipping hazardous wastes across the country have created the need to examine the potential for Iowa to construct and run a hazardous-waste landfill.

Tuthill et al. (1972) present hydrogeologic criteria for the development of landfills in Iowa. Also, they examine the geology in Iowa groundwater districts for landfill site selection. The prime objective in siting a landfill is the prevention of hazardous waste migration from the landfill. For example, Tuthill et al. (1972) state that the karst area of northeastern Iowa is a poor location for siting a landfill because of the network of channels in the dissolved limestone. Some potential landfill sites may need corrective measures to prevent waste migration. A common corrective measure is to construct a liner with compacted soil material. The performance of a compacted soil liner is partly a function of the physical properties of the soil material used.

In the event that the State of Iowa constructs a hazardous-waste landfill, information on the effectiveness of Iowa soil materials as liner material may be needed. Miller et al. (1978) have presented a report of engineering data for soils representing 264 soil series in Iowa. In the present paper, we add to this data bank by reporting the pore size distributions, permeabilities, and solute breakthrough curves of three soils developed in major Iowa geologic materials (till, loess, and paleosol) that may be used as liner materials.

MATERIALS AND METHODS

B horizon material was collected at depths of 60-120 cm from three soils developed in till, loess, and paleosol parent materials, respectively. The till-derived soil was sampled in a Nicollet mapping unit (Boone Co., Iowa: NW¼NW¼, S9, T83N, R25W). Nicollet soils are fine-loamy, mixed, mesic Aquic Hapludolls. The loess-derived soil was Fayette, a fine-silty, mixed, mesic Typic Hapludalf (Tama Co., Iowa: 98 m S and 396 m W of the center of S2, T83N, R16W). The exhumed paleosol was Clarinda, a fine, montmorillonitic, mesic, sloping Typic Argiaquoll (Clarke Co., Iowa: 274 m N and 610 m W of the SE corner of S18, T72N, R26W).

Bulk samples of each material were collected by excavation. The bulk samples were air-dried and ground to pass a 2-mm sieve. The particle density of each material was determined with a pycnometer, according to Blake (1965a). Sand, silt, and clay contents were determined either by total fractionation (sedimentation and weighing) or by a pipette technique similar to that of Day (1965) (Walter et al., 1978). Atterberg limits (plastic limit, liquid limit, plasticity index) were obtained for each material according to the ASTM Test D-4318-84.

The particle size distribution data and the Atterberg limits were classified by using the United States Department of Agriculture (USDA) textural triangle (Soil Survey Staff, 1951), the American Association of State Highway and Transportation Officials (AASHTO) classification (Highway Research Board, 1945), and the Unified classification (Corps of Engineers, 1953).

Undisturbed cores were collected with a hydraulically driven tube, 0.065 m in diameter. The cores were cut into segments about 0.076 m long, placed in plastic bags, and stored at 4°C. Bulk density was determined on fragments of 70 to 100 cm^3, selected from the cores, by using the paraffin coating technique of Blake (1965b).

The air-dried, ground materials were used to determine the standard Proctor moisture-density relations. Several subsamples of each material were rewetted to a range of moisture contents and then compacted in a 0.1-m-diameter mold by using a 2.5-kg rammer with a 0.3-m drop, according to the ASTM Test D-698-78, Method A (1982).

The pore size distribution of undisturbed and compacted samples of each material was determined by mercury porosimetry. Compacted samples were prepared at moisture contents 1 to 2% higher than optimum, a value was obtained from the moisture-density relations. First, the undisturbed and compacted samples were broken into fragments of $\sim$2 cm^3. Second, the fragments were plunged into liquid nitrogen and then dried in a freeze dryer for 4 to 5 days (Zimmie and Almaleh, 1976).

Porosites of triplicate freeze-dried fragments ($\sim$1 cm^3) of each material were measured by using a Quantachrome SP-200 mercury porosimeter in four intrusion steps: 0 to 0.1 MPa, 0.1 to 8.3 MPa, 8.3 to 41.4 MPa, and 41.4 to 414 MPa (60,000 PSI). Because the volume of mercury intruded was recorded continuously as a function of pressure, cumulative pore size could be calculated with the capillary rise equation:

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Table 1. Particle size distribution, liquid limit, plastic limit, and plasticity index of soil materials.

Soil	Particle size distribution Clay (<2μm)	Silt (2-50μm)	Sand (50-2000μm)	Liquid limit	Plastic limit	Plasticity index
	--------- %	-----------				
Nicollet	21	25	54	28	15	13
Fayette	35	57	8	35	21	14
Clarinda	44	35	21	56	28	28

$$r = -(1/P)(2\gamma \cos \beta)$$

where r is the equivalent pore radius (m), P is the pressure (Pa), γ is the surface tension of mercury (N/m), and β is the wetting angle of mercury (assumed to be 140°). Cumulative porosity was plotted as cumulative intruded volume versus equivalent pore radius.

Soil permeability is the most common measurement used to estimate the potential effectiveness of a liner material (United States Environmental Protection Agency, USEPA 1978). The permeability (saturated hydraulic conductivity) of each compacted material was measured by using a 0.1-m-diameter, 0.1-m-long permeameter. Three replicates of each subsoil material were compacted at moisture contents ~1 to 2% above optimum, determined from the moisture-density relation. De-aired, saturated $CaSO_4$ solution (adjusted to 0.06% formaldehyde to control microbial growth) was introduced at 6.9 kPa pressure at the bottom of the permeameter to slowly saturate the compacted sample. The source of the pressure was compressed air. The air was separated from the saturated $CaSO_4$ solution by a rubber membrane within the solution container to help prevent the desaturation of the soil material. After the material was saturated, the $CaSO_4$ solution was introduced at the top of the permeameter at hydraulic gradients of ~170 to 270 m/m, and the rate of solution movement through the sample was measured over time.

In addition, solute breakthrough curves were obtained for each compacted subsoil material. A de-aired, 0.05*N* $CaCl_2$ solution with 0.016% Acid Fuchsin (a red dye) and 0.06% formaldehyde was used as the tracer solution. The dye gave a visual test for any permeameter wall effects. The tracer solution was exchanged for the saturated $CaSO_4$ solution and allowed to leach through the compacted soil sample under the same hydraulic gradient used in the permeability test. Leachate was collected in equal-volume increments with a fraction collector and was analyzed for chloride concentration with an automatic titrator.

RESULTS AND DISCUSSION

Table 1 presents the particle size distribution, liquid limit, plastic limit, and plasticity index determined for the Nicollet, Fayette, and Clarinda soil materials. Particle size distributions, Atterberg limits, and moisture-density relations of the soils in this study are similar to those presented for comparable soils by Miller et al. (1978). Nicollet material had the least clay and the most sand, whereas Clarinda material had the most clay and an intermediate sand content. Fayette material, derived from loess, was highest in silt. The Nicollet sample had somewhat more sand than is currently defined for Nicollet B horizons (~4% more). The percentage clay in each material is reflected by the values of the Atterberg limits. As percentage clay increases, the Atterberg limits increase.

Table 2 presents the classification of each material according to the USDA, AASHTO, and Unified classifications. According to the AASHTO classification, which classifies soil material according to its suitability for highway subgrade (A-1 is the highest suitability class), Clarinda material is the least suited (A-7 is the next to lowest suitability class). In addition, according to the AASHTO and Unified classifications, Clarinda materials are subject to extremely high volume change.

Table 3 presents the particle density, undisturbed bulk density, and the compacted (Proctor) bulk density and moisture content from the moisture-density relations determination. Nicollet material compacts to the highest bulk density. Compacted Clarinda material has a maximum bulk density lower than undisturbed Clarinda material. Thus, the *in situ* consolidation stress for the undisturbed Clarinda material was greater than the compactive force during the moisture-density relations test.

Figure 1 presents the moisture-density relations for Nicollet, Fayette, and Clarinda soil materials. Compaction of these materials at higher-than-optimum moisture contents provides bulk densities slightly lower than the maximum values. The materials were compacted at higher-than-optimum moisture content to obtain higher percentage water saturation.

Figure 2 presents the cumulative pore size distribution of each soil material (undisturbed and compacted) determined by mercury porosimetry. The semilog plot is cumulative intruded volume versus equivalent pore radius. Compaction of Fayette material yielded a decrease in pore size in the 0.5- to 2.0-μm range compared with undisburbed samples. Both the compacted Clarinda and compacted

Table 2. Classification of soil materials according to USDA, AASHTO, and Unified classifications.

Soil	USDA	AASHTO	Unified
Nicollet	sandy clay loam	A-6 (3)	CL
Fayette	silty clay loam	A-6 (10)	CL
Clarinda	clay	A-7-6 (18)	CH

Table 3. Particle density, undisturbed bulk density, compacted bulk density and optimum moisture content of soil materials.

Soil	Particle density	Undisturbed bulk density	Compacted bulk density	Optimum moisture
	(Mg/m^3)	(Mg/m^3)	(Mg/m^3)	(%)
Nicollet	2.59	1.66	1.84	14
Fayette	2.71	1.41	1.67	18
Clarinda	2.69	1.59	1.45	27

Table 4. Permeability of three compacted replicates of each soil material.

Soil	Permeability (m/s) I	II	III	Mean
Nicollet	5.47×10^{-11}	6.58×10^{-11}	1.22×10^{-10}	8.08×10^{-11}
Fayette	2.84×10^{-10}	2.67×10^{-10}	2.61×10^{-10}	2.71×10^{-10}
Clarinda	4.18×10^{-11}	2.97×10^{-11}	5.05×10^{-11}	4.07×10^{-11}

Fayette soil materials have most of their pores in the 0.1- to 2.0-μm range, whereas compacted Nicollet has most of its pores in the 0.1- to 10.0μm range.

Table 4 presents the permeabilities of three replicates of each compacted soil material. The mean permeablity of each material is less than 10^{-9} m/s, the value currently used by the USEPA as the criterion for a material's suitability as a landfill liner. Fayette has the highest permeability of the three materials, although Clarinda had more porosity. Fayette material must have larger openings or better connections in its pore space than does Clarinda material.

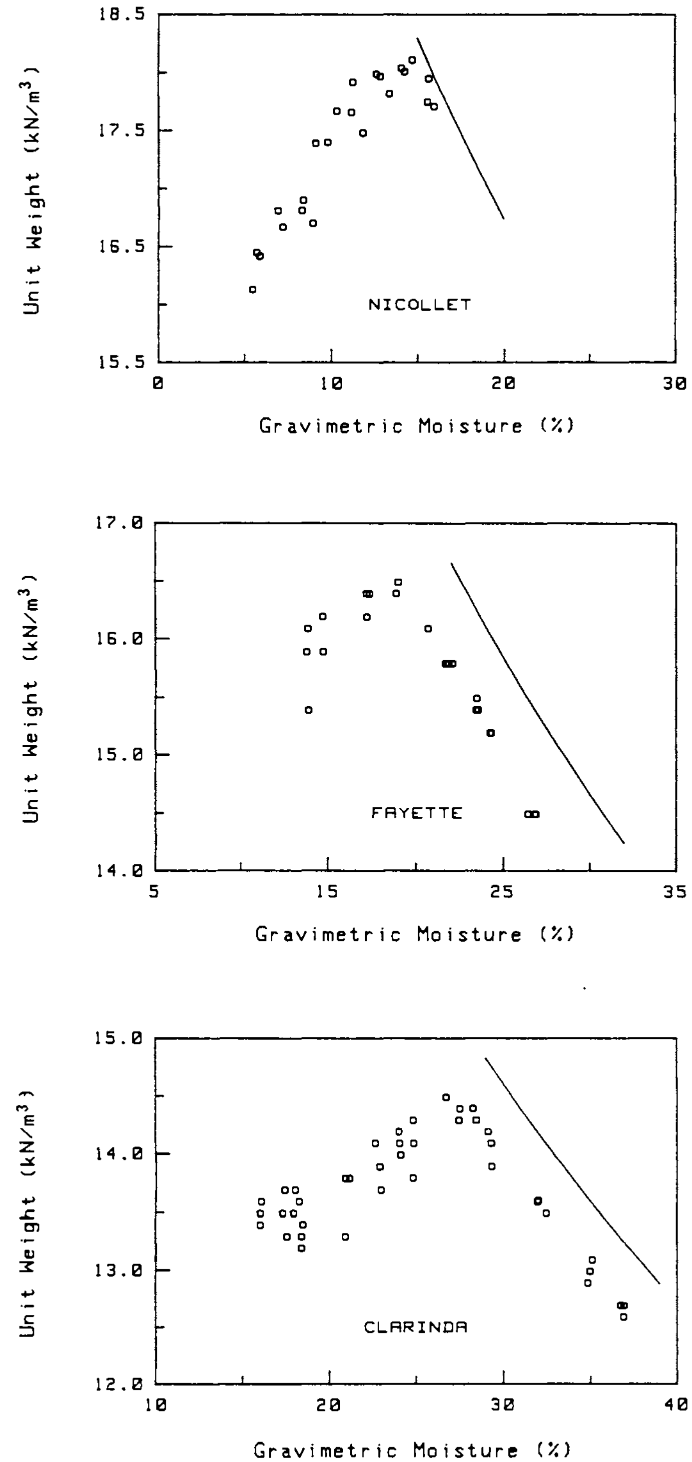

Fig. 1. Moisture-unit weight relations for Nicollet, Fayette, and Clarinda subsoil materials.

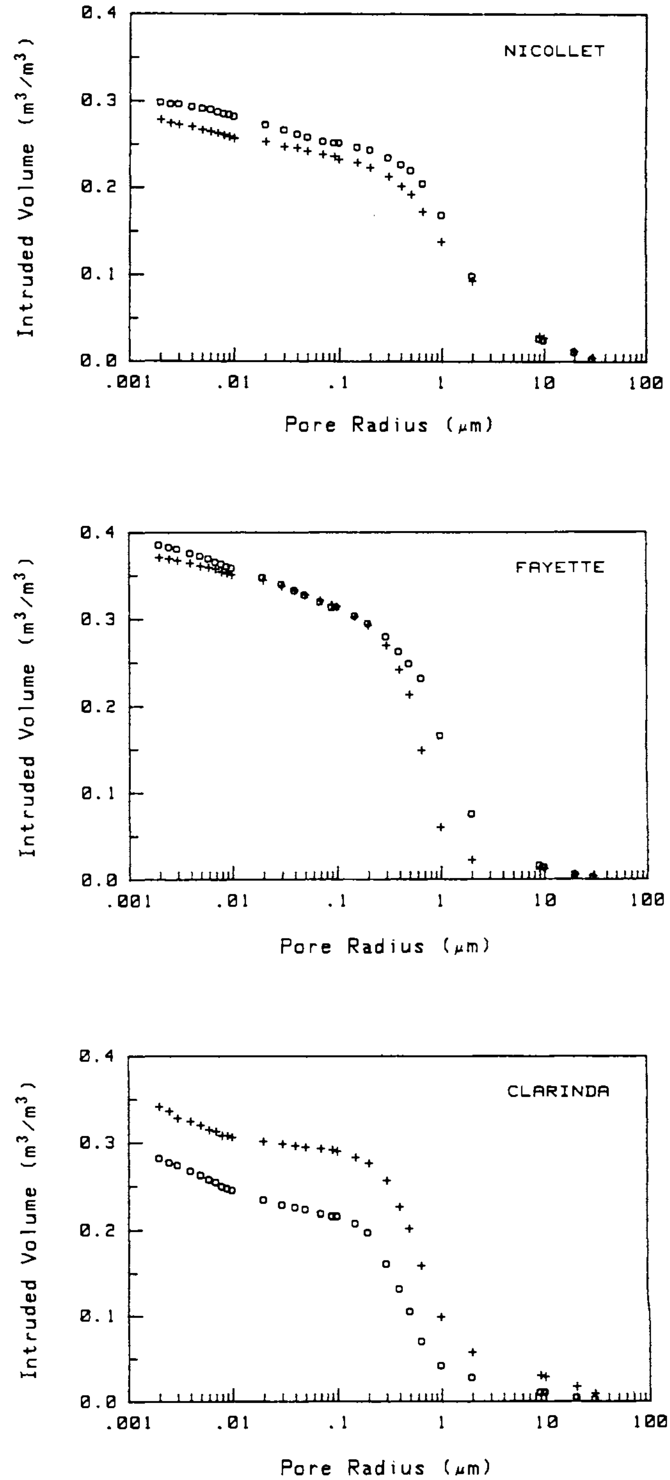

Fig. 2. Cumulative pore size distribution for compacted (+) and undisturbed (o) Nicollet, Fayette, and Clarinda subsoil materials.

Figure 3 presents the solute breakthrough curves from the three replicates of each compacted soil material. The plots are relative concentration of chloride versus relative pore volume. One pore volume is equal to the total porosity of the bulk soil volume. In all cases, chloride appeared in the effluents when about 0.2-0.25 of one pore volume of solution had leached through the sample. Assuming the same hydraulic gradient, the first appearance of chloride under liners of equal thickness of these compacted materials would occur first with Fayette, then Nicollet, and, lastly, Clarinda materials.

Because USEPA regulations stipulate that a liner should prevent migration of pollutants during the active life of a unit, the pore volume required for the first appearance of chloride should be considered in the determination of the active life of a liner composed of materials considered in this paper. What liner thickness would prevent any appearance of a non-interacting solute for 100 years? This thickness can be estimated by

$$L = KIT/B$$

where L = liner thickness (m), K = permeability (m/s), I = hydraulic gradient (m/m), T = time (s), and B = effective breakthrough porosity (m^3/m^3). B is calculated by multiplying the relative breakthrough porosity (in this study, 0.20-0.25) by the total porosity. Total porosity can be determined by Hg porosimetry or calculated from the compacted bulk density and the particle density. By using the mean permeabilities given in Table 4 and assuming hydraulic gradients of 1.33 m/m, we calculate that liners of compacted Nicollet, Fayette, and Clarinda materials would have to be 4.7 m, 14.2 m, and 1.9 m thick, respectively, to prevent breakthrough within 100 years. It is important to note that these calculations do not take into account the possibility that shrinking and swelling may alter the compacted liner's permeability.

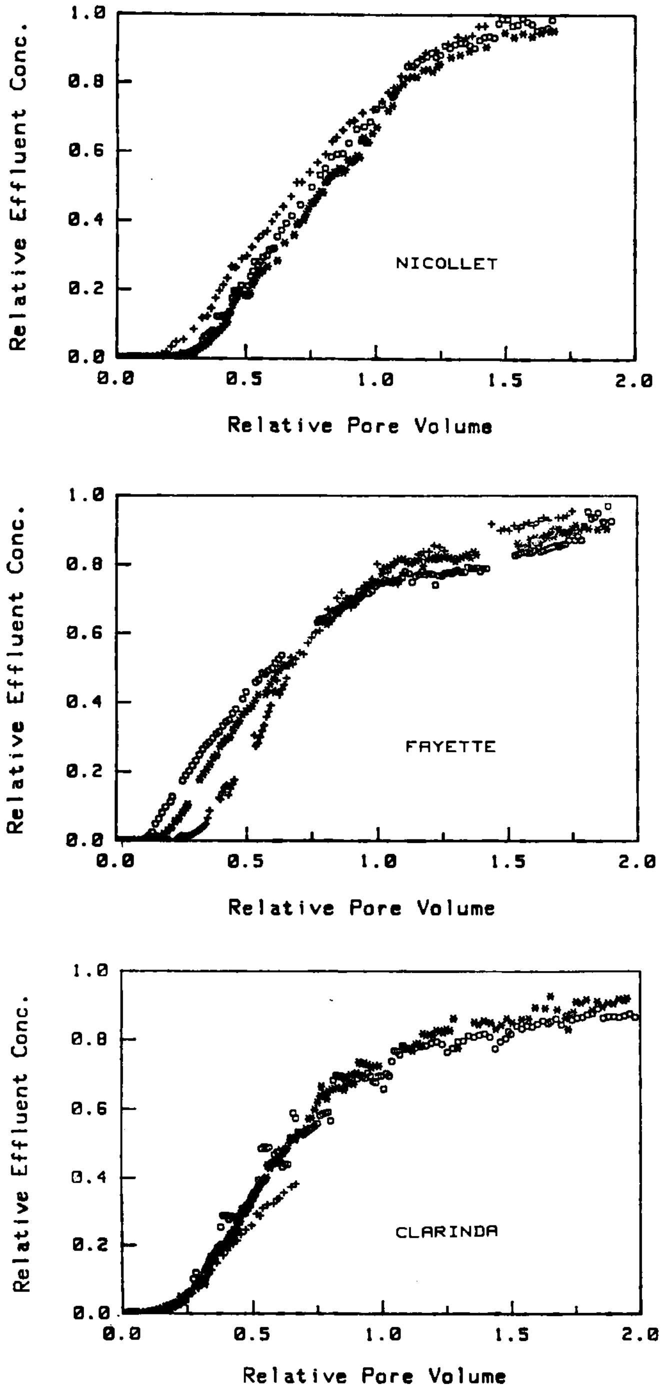

Fig. 3. Solute breakthrough curves from three replicates of compacted Nicollet, Fayette, and Clarinda subsoil materials.

CONCLUSIONS

According to the measurements of permeability made on compacted samples, all three soil materials investigated in this study are suited for the construction of a liner of a hazardous-waste landfill. Compacted samples of the three materials have permeabilities of less than 10^{-9} m/s, the current permeability criterion. On the basis of the time of first appearance of chloride in the solute breakthrough experiments, the paleosol material is best suited. But, of the three materials, the paleosol material (Clarinda) has the least desirable engineering property: a high shrink-swell potential. On the basis of the properties of each material and the current methods used to evaluate the potential effectiveness of a liner, the till material seems to be the best suited of the three soil materials considered.

The three soil materials evaluated in this study were chosen to be broadly representative of major soil materials in Iowa. Although the data may be useful to indicate expected properties of soils similar to those investigated, the data should not be extrapolated and used in actual design situations.

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