Science and Technology, 6(2001) 21-34

Selection of Liner Materials and Design of Hazardous Water Facilities in Saudi Arabia

***Sahel N. Abduljauwad and #Ali M. Dakkak**

**Department of Civil Engineering, King Fahd University of Petroleum and Minerals Dhahran 31261,Saudi Arabia, #Department of Economics, King Abdulaziz University, Jeddah 21422, Saudi Arabia.*

اختيار وتصميم مواد تبطين مكائن التخاص من الفضلات الخطرة في المملكة العربية السعودية

ساهيل عبدالجواد وعلي دكاك

خلاصـة: ان التَطّوّر السريع في المملكة العربية السعودية قْدْ انتج طيفا واسعا من الفضلات. وقد تم انشاء عدة مصافى ومصانع بتروكـيماويات خـلال العقديـن الماضـيين، وهذه الصّناعاتِ قْدْ انتجتْ فضلات سامّة كثيرة تحتاجُ لتصميم صحيح لمُعَالَجَتها والتخاص منها. وتتناول هذه الورقةِ تصميم وإختيار مواد تبطين لاثنين من مواقع التخاص من الفضلات الخطرة. ويقع أحد هذين الموقعيـن فـى الولايات الشرقية من المملكة العربية السعودية، بينما يوجد الثاني في الجزءِ الغربي. وسَتُقّدّمُ هذه الورقة وصفا كاملا مفصلا عن مباطن التربة الطبيعية والصناعية ونظام جمع وازالة عصارة الفضلات.

ABSTRACT: Rapid development in Saudi Arabia has produced a broad spectrum of wastes. In the last two decades, several refineries and petrochemical industries have been established. These industries have produced sludges and other toxic wastes which need proper planning for their handling and disposal. This paper covers design and selection of liner materials for two hazardous waste disposal sites. One of them is located in the Eastern Province of Saudi Arabia, while the second one is located in the Western part. The paper will present complete design details of the natural compacted and geosynthetic soil liners and the leachate collection and removal system for primary liners and leak detection/leachate collection and removal system for secondary liners.

1. Introduction

Landfill will remain a significant component of hazardous waste management practice. Landfill is often used for residues from other treatment or disposal technologies/processes. As a result of serious environment and health problems with old and abandoned dump sites and the very high costs associated with cleanup measures at contaminated sites, the concepts of a specially engineered landfill have been introduced where wastes are segregated in a site which is selected for its natural containment properties and then engineered so as to isolate the wastes as far as possible from the environment. A landfill for hazardous waste is considered a technology of last resort to be used after every effort has been made to reduce, mitigate or eliminate the hazards posed by such wastes.

The disposal of hazardous wastes is a global problem. Rapid development in Saudi Arabia has produced a broad spectrum of wastes. In the last two decades several refineries and petro-chemical industries have been established. These industries have produced sludges and other toxic wastes which need proper planning for their handling and disposal. The Kingdom is fortunate in that environment concerns were recognized at an early stage of industrial development. This resulted in the establishment of agencies such as Meteorology and Environmental Protection Administration (MEPA) and the Royal Commission for Jubail and Yanbu to regulate industries so that environmental damages are minimized.

Compacted soil liners have been used for many years as engineered hydraulic barriers for waste-containment facilities (U.S. Environmental Protection Agency, 1985). Compacted soil liners are frequently used in conjunction with geomembrane to form a composite liner, which usually consists of geomembrane placed directly on the surface of a compacted soil liner. The thickness of soil liners is usually between 600 and 900 mm, but occasionally the thickness may reach 1.2-3.0 m.

Compacted soil liners are composed of clayey materials that are placed and compacted in layers called lifts. The materials used to construct soil liners include natural soils, bentonite, soil blends and other materials. The most common type of compacted soil liners is one that is constructed from naturally occurring soils that contain a significant quantity of clay soils that are classified as CL, CH, or SC in the Unified Soil Classification System (USCS) outlined in ASTM D-2487. Soil liner materials are excavated from borrow pits, which may be located either on or off-site. The soil in the borrow pit may be used directly without processing or may be processed to alter the water content, break down large pieces of materials, or remove oversized particles (Abduljauwad, 1994).

A survey was conducted to find suitable materials that can be used as soil liners. In the Eastern Province, it has been found that suitable materials are unavailable locally. However, local soils can be blended together to achieve the requirement. Two types of marl were mixed together with percentages of 30% and 70%. The geotechnical properties of the mixture, compaction curves and the variation in hydraulic conductivity with moisture content indicate that the mixture satisfies all specifications for a soil liner with a hydraulic conductivity of 1×10^{-8} cm/sec and a reasonable plasticity, which will not be difficult to work with in the field (Abduljauwad, 1993). For the Western Province facility, seven types of clay samples were collected and subjected to complete laboratory geotechnical investigation. The laboratory tests include grain size analysis, Atterberg limits, compaction, hydraulic conductivity, shear strength, X-ray diffraction analysis, organic matter, and soil pH (Abduljauwad, 1998). Results indicate that soil No. 1 collected from Nwabah is quite suitable material that can be used as a soil liner. However, since this soil contains large clods, it should be processed prior to its use in the construction of the low permeability layer by pulverizing such clods. This paper covers site selection, design and selection of liner material for disposal sites.

2. Material Selection and Specifications

Soil liner materials are selected so that a low hydraulic conductivity will be produced after the soil is remolded and compacted. Although the performance specification is usually hydraulic conductivity, construction quality assurance considerations dictate that restrictions should be placed on certain properties of the soil used to build a liner. For example, limitations may be placed on the liquid limit, plastic limit, plasticity index, percent fines, and percent gravel allowed in the soil liner material. Also, compatibility of the waste in contact with the liner should be investigated.

The process of selecting construction materials and verifying the suitability of the materials varies from one project to another. In general, the process is as follows (U.S. Environmental Protection Agency, 1985):

1. A potential borrow source is located and explored to determine the vertical and lateral extent of the source and to obtain representative samples, which are tested for properties such as liquid limit, plastic limit, plastic fines, etc. The borrow source should also be checked for the presence of deleterious materials such as roots, organic matter, and debris.
2. Once construction begins, additional observations and tests may be performed in the borrow pit to confirm the suitability of materials being removed.
3. After a lift of soil has been placed, additional construction quality assurance tests should be performed for final verification of the suitability of the soil liner materials.

A variety of tests is performed at various stages of the construction process to ensure that the soil liner material conforms with specifications. However, tests alone will not necessarily ensure an adequate material; observations by qualified construction quality assurance personnel are essential to confirm that deleterious materials (such as roots, wood, organic matter, rocks, stones, bricks, construction or demolition debris, or other unacceptable materials that are not allowed in the specifications) are not present in the soil liner material.

Some soil liner materials must be processed prior to use. The principal preprocessing steps that may be required include the following: drying of soil that is too wet, wetting of soil that is too dry, removal of oversized particles, pulverization of soil clods, homogenization of a nonuniform soil, and addition of bentonite. Tests are performed by construction quality assurance personnel to confirm proper preprocessing, but visual observations are needed to confirm that proper procedures have been followed and that the soil liner material has been properly preprocessed.

The criteria for choosing a clay is primarily based on the recompacted hydraulic conductivity achievable under field conditions (Daniel, 1990). A clay that can be compacted to obtain a low hydraulic conductivity (1×10^{-7} cm/sec or less) sample when compacted to 90-95% of the maximum Proctor's dry density at wet of optimum moisture content is chosen for a landfill liner construction. Note that clay with a high liquid limit (LL) tends to develop more desiccation cracks, clay with a very low plasticity index (PI) or plastic limit (PL) is less workable, and a well-graded soil is expected to develop low hydraulic conductivity when compacted properly. Therefore, the PI, LL, and some minimum requirements regarding grain size distribution should be specified. Inorganic clays of medium plasticity are best suited for liner construction. Usually a soil with the following specifications would prove suitable for liner construction (Daniel, 1993): LL greater than or equal to 30%, PI greater than or equal to 15%, 0.074 mm and less fraction (P200) greater than or equal to 50%, and clay fraction greater than or equal to 25%. The minimum percentage compaction (usually 90-95% of the maximum modified Proctor's density) should be specified. To obtain better kneading action and lower hydraulic conductivity, all compaction must be done at wet of optimum moisture. Note that the shape of the grain size distribution curves should be studied to confirm that they are close to an "inverted S" shape. The specifications regarding Atterberg limits and grain size percentages are also helpful in quality control during construction.

In reality, it may be difficult to obtain clay that will satisfy all the specifications described above. Field experience indicates that clayey soil with the following values can also be compacted to obtain a low hydraulic conductivity liner: PI between 10 and 15%, LL between 25 and 30%, 0.074 mm or less fraction between 40 and 50%, and clay content between 18 and 25%. However, it is prudent to perform field trials for such marginal clayey soils.

3. Compacted Soil Liners

A survey was conducted in both Eastern and Western Provinces of Saudi Arabia (in the vicinity of the construction sites) to find suitable natural materials that can be used as soil liners. In the Eastern Province of Saudi Arabia, it has been found that suitable materials are unavailable locally, so local soils will be blended together to achieve the required low hydraulic conductivity. A plastic marl was found that could be used for the compacted soil liner. One should be cautious about using highly plastic soils (soil with plasticity indices > 30%) because these materials form hard clods when the soil is dry and are very sticky when the soil is wet. Highly plastic soils, for these reasons, are difficult to work with in the field. However, special techniques such as addition of lime or other type of soil, can alleviate some of the problems with construction utilizing highly plastic soils so that even these soils may be usable. Figure 1 shows the grain size distribution for different types of marl collected from the Eastern Province of Saudi Arabia. Marl # 1 has a plastic limit, liquid limit and plasticity index of 75%, 135% and 60%, respectively, while all other marls are nonplastic. A 30% of Marl # 1 was mixed with 70% of Marl # 2 to overcome the problem of high plasticity of Marl # 1. The mixture has a plasticity index of 11%. The compaction curves and the variation in hydraulic conductivity with moisture content for Marl # 1 and Marl # 2 and their mixtures are shown in Figures 2 and 3, respectively. Marl # 1 satisfies all the requirements for soil liner, but have very high plasticity and low strength. It is very clear that the mixture satisfies all specifications for a soil liner with a reasonable plasticity, which will not be difficult to work with in the field.

In the Western Province of Saudi Arabia, a survey was conducted (in the vicinity of the construction site) to find a suitable natural material that can be used as a soil liner. Bulk samples were collected from seven different areas. Table 1 shows the locations from which the samples were collected and summarizes the visual description of samples. The collected samples were air dried and pulverized until all soil aggregations were reduced to minus 40 sieve size. Samples were subjected to the following testing program: grain size analysis (sieve analysis & hydrometer tests, ASTM D-421 & ASTM D-422), Atterberg limits (ASTM D-4318), moisture-density relationship (standard & modified proctor compaction tests, ASTM D-698 & ASTM D-1557), hydraulic conductivity tests (constant head, ASTM D-2434 and flexible wall permeameter, ASTM D-5084), unconfined compression test (ASTM D-2166), X-ray diffraction analysis (XRD), organic matter and soil pH.

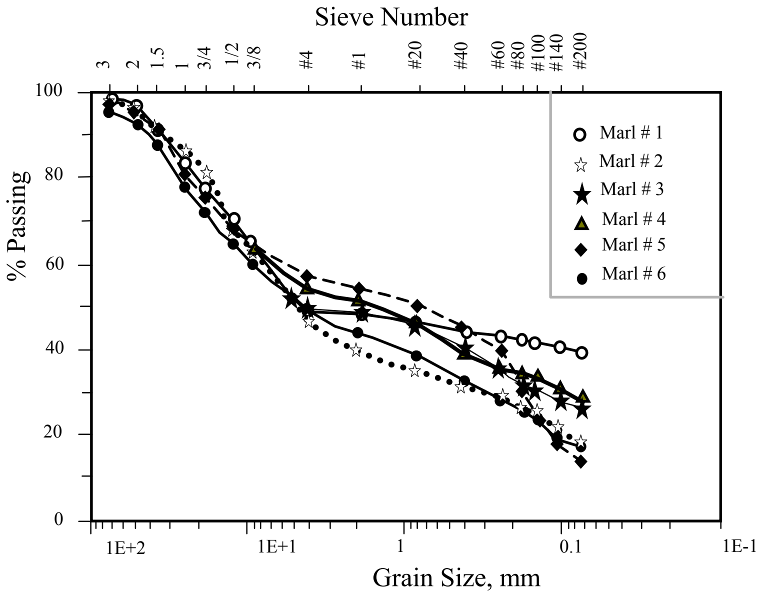

Figure 1. Grain size analyses of different types of marls for the Eastern Province of Saudi Arabia.

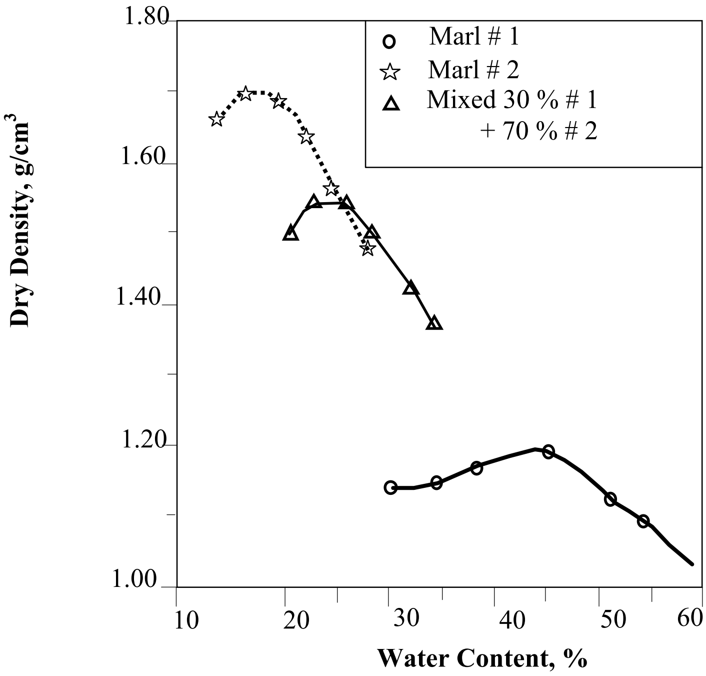

Figure 2. Compaction curves of Marl # 1 and Marl # 2 and their mixture.

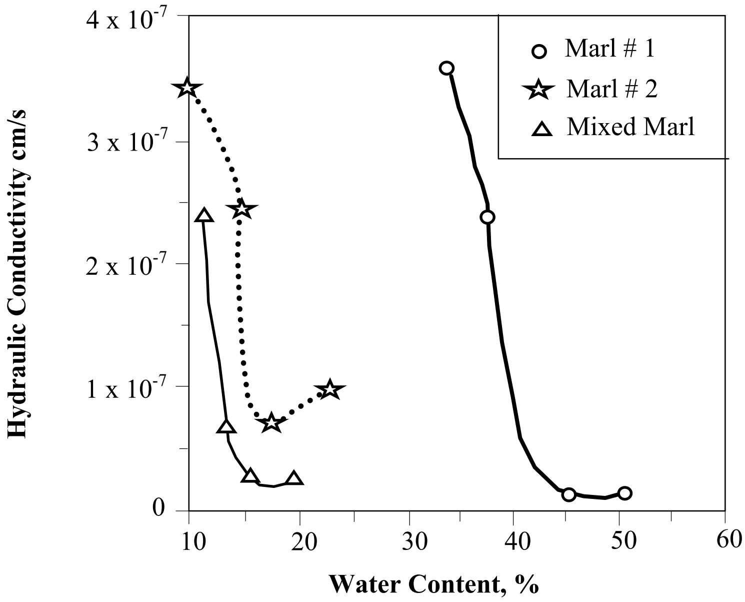

Figure 3. Comparison of hydraulic conductivity curves for Marl 1, 2 and the mixture.

The sieve and hydrometer analyses were conducted to determine the grain size distribution as depicted in Figure 4. The percentage of fines (the fraction of soil on a dry-weight basis that passes through the opening of the No. 200 sieve, opening size = 0.075 mm) for all samples exceeded 80%. Many regulatory agencies require at least 50% fines. Also, the maximum particle size for all samples does not exceed 2 mm and construction specifications usually restrict the maximum allowable particle size between 25 mm and 50mm for compaction consideration, but which may be much less for protection against penetration of an adjacent geomembrane. The clay content (the percentage of soil that has an equivalent particle diameter smaller than 0.002 mm) is a very important parameter that influences the hydraulic conductivity of soil. The clay contents for samples 1 to 7 are 70%, 56%, 20%, 16%, 20%, 48% and 48%, respectively. Soils must have at least 10−20% clay in order to be capable of being compacted to a hydraulic conductivity of $\leq 1 \times 10^{-7}$ cm/sec. Sample No. 1 has the maximum percentage of clay size particles.

Table 1: Locations and summary of visual description.

Sample No.	Location	Color	Description
1	Nwabah	Greenish grey	Homogeneous, stiff bulk samples
2	Rabegh-1	Dark brown	Non-homogeneous, stiff blocks with major silt intrusion
3	Rabegh-2	Light brown	Non-homogeneous, block samples with major silt intrusion
4	Al-Yatma	Light brown to yellowish	Silty clay, intrusion of roots and plant leafs
5	Al-Mashenea	Light brown to yellowish	Silty clay, intrusion of roots and plant leafs
6	Al-Madinah	Dark brown	Homogeneous medium clay lumps
7	Al-Madinah-Alaqool	Light brown	Homogeneous desiccated clay

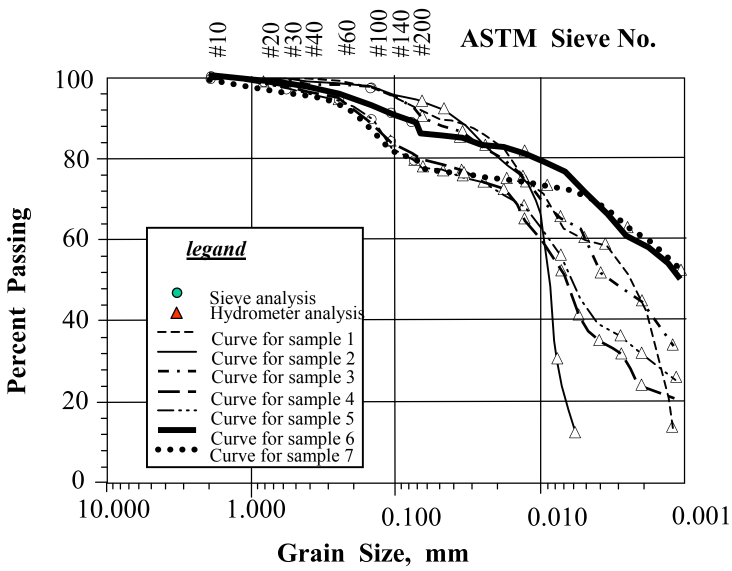

Figure 4. Grain size distribution curves for the samples.

The plasticity characteristics of a soil are quantified by Atterberg limits (liquid & plastic limits) and plasticity index. Table 2 summarizes liquid limit, plastic limit and plasticity index for the investigated soil samples. The liquid limit and plasticity index of samples Nos. 1, 2, 3 and 6 satisfy the required specification of soil liner materials (LL ≥ 30% & PI ≥ 15%) that can be compacted to obtain the low hydraulic conductivity of 1×10^{-7} cm/sec.

Table 2: Summary of liquid limit, plastic limit and plasticity index for investigated soils.

Sample ID	# 1	# 2	# 3	# 4	# 5	# 6	# 7
Liquid limit %	53.50	44.00	63.50	27.20	26.80	41.60	35.70
Plastic limit	26.89	25.71	33.05	25.27	23.74	26.31	24.96
Plasticity index	26.61	18.29	30.45	1.93	3.06	15.29	10.74

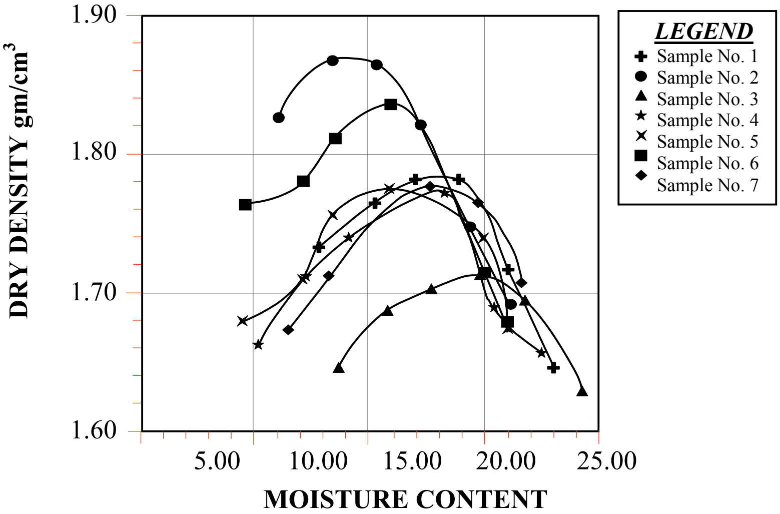

Figure 5. Compaction curves for investigated soils.

The largest maximum dry density of 1.87 g/cm^3 at an optimum moisture content of 13.85% was observed for sample No. 2, while the smallest maximum dry density of 1.71 g/cm^3 at an optimum moisture content of 19.8% was observed for sample No. 3 (Figure 5). It should be stated that sample No. 3 has the largest plasticity index of all investigated samples. Sample No. 1 has the maximum dry density of 1.78 g/cm^3 at an optimum moisture content of 17.75%.

Hydraulic conductivity of soils is measured in the laboratory with either rigid or flexible wall permeameters. In this study, both the constant head test and flexible wall permeameter, with a back pressure, were used to estimate the hydraulic conductivity of investigated soils. Both methods gave almost consistent identical results. Figures 6 and 7 compare the hydraulic conductivity for the investigated samples. The lowest value of 1.8×10^{-9} cm/sec was obtained for sample No. 2 and the largest value of 4.77×10^{-7} cm/sec was obtained for sample No. 5. Sample No. 1 has a minimum hydraulic conductivity of 4×10^{-9} cm/sec at a water content of 21%.

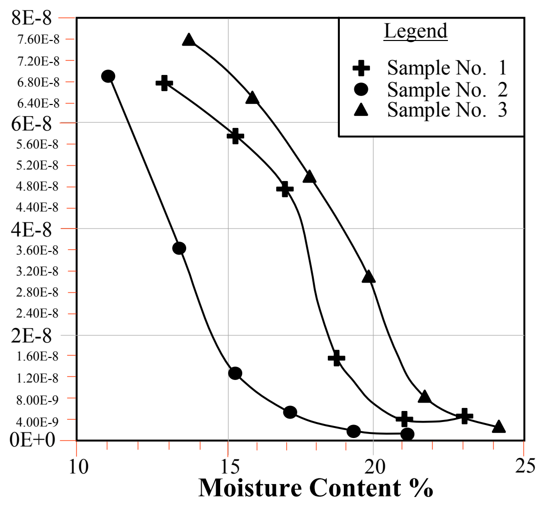

Figure 6. Comparison of hydraulic conductivity curves for Sample No.1,2&3

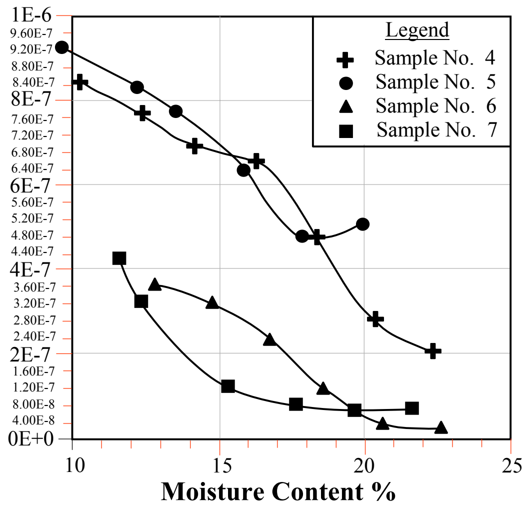

Figure 7. Comparison of hydraulic conductivity curves for Sample No.4,5,6&7

A critical step in design of a compacted soil liner is the determination of the range of acceptable water content and dry unit weight values of the soil. Table 3 summarizes the unconfined compressive strength for the seven soil samples at their optimum moisture contents. The maximum strength of 1500 kPa was obtained for sample No. 6, while the minimum value of 680 kPa was obtained for sample No. 4. The unconfined compressive strength for sample No. 1 at the optimum moisture content is 1460 kPa. Figure 8 shows the effect of molding water content on the unconfined compressive strength of sample No. 1. It can be observed that samples compacted dry of optimum have higher strengths than those compacted wet of optimum. Therefore, it is very important that these results should be analyzed with compaction curve and hydraulic conductivity curves to decide on an acceptable range of water contents that should be used for the compaction of a soil liner in the field.

Based on the results of all geotechnical tests, it can be seen that samples No. 1 and 2 satisfy all requirements for a good soil liner material. However, as indicated earlier, the borrow area of sample No. 2 contained a large amount of blocks of silty soil and, therefore, the soil is not homogeneous. Thus, sample No. 2 was excluded and sample No. 1 is the best candidate for the soil liner material. This sample satisfies grain size, plasticity, compaction, hydraulic conductivity and strength requirements.

It is very important to specify the range of water contents that should be used in the construction of a soil liner in the field. It was explained earlier that it is usually preferable to compact the soil wet of optimum to minimize hydraulic conductivity. However, the soil must not be placed at too high a water content. Otherwise, the shear strength will be too low. There may also be a great risk of desiccation cracks forming if the soil dries, which is very much possible due to the very high temperature at the construction site, and ruts may form when construction vehicles pass over the liner. Figure 8 shows the acceptable zone, which represents the zone of acceptable water content/dry unit weight combination:

The maximum dry density = 1.78 g/cm^3
The minimum acceptable dry density = 1.69 g/cm^3
The acceptable range of water content $18\% \le w \le 21\%$

Table 3: Unconfined compressive strength.

Sample No.	1	2	3	4	5	6	7
Moisture content %	17.75	13.85	19.80	18.20	16.00	18.50	17.50
Unconfined compressive Strength kPa	1460	960	1000	680	860	1500	1320

With these specifications, the maximum laboratory hydraulic conductivity and the minimum unconfined compressive strength will be 2.8×10^{-8} cm/sec and 800 kPa, respectively. Furthermore, soil No. 1 was subjected to two more tests including organic matter and X-ray diffraction analysis to confirm its complete suitability as a liner material. The organic matter was estimated using potassium dichromate acid digestion method (Handbook of Agronomy). A very low value of 0.00236% was obtained. The X-ray analysis indicated that the mineralogical composition of the sample was as follows: 50% quartz (SiO_2), 25% chlinochlore [$(Mg,Fe)_6(Si,Cr)_4O_{10}(OH)_8$], 18% albite [$(Na,Ca)Al(Si,Al)_3O_8$], 5% palygorskite ($MgAlSiO_4O_{10}(OH).4H_2O$), and 2% halite (NaCl). All minerals present in the sample are quite stable ones. The soil pH is 6.83.

It should be emphasized that since soil No.1 consists of large bulk (clods), it should be processed at the construction site by pulverizing the soil, utilizing special clay crushing equipment. After adjusting the water content of soil, it should be compacted by heavy footed compactors with large feet that fully penetrate a loose lift of soil.

4. Design of Landfill

The landfill in the Eastern Province of Saudi Arabia will be designed using 80 mil high density polyethylene (HDPE) geomembrane/clay composite liner. A double liner system will be used with a leachate collection layer located above the primary liner and a leak detection layer located between the two liners. A 1 m compacted soil liner (a mixture of 30% of Marl # 1 and 70% of Marl # 2) will be used between the natural soil and the secondary liner. The landfill will be constructed 3 m above the compacted soil liner (Area Method). Above-ground landfills have the advantage that leachate can be drained by gravity, the facility is conspicuous and therefore is not easily forgotten and ignored, and construction of liner and drainage system components occurs on more or less level ground, which simplifies the construction.

The mixture of Marl # 1 and Marl # 2 will be placed in a loose lift 200–300 mm thick. The water content will be adjusted to achieve the required dry density to satisfy the hydraulic conductivity requirements. Heavy compactors will be used. The weight of compactors should not be so heavy that it becomes bogged down in the soil. The dry density, moisture content and hydraulic conductivity tests of the compacted soil liner were conducted for quality control purposes. A large number of density and moisture content tests were conducted during construction to ensure uniformity. Furthermore, three in-situ hydraulic conductivity tests were conducted following the procedure discussed earlier. All tests gave an average hydraulic conductivity of 1.36×10^{-7} cm/sec which is 6.8 times greater than the laboratory hydraulic conductivity (2×10^{-8} cm/sec). This result was expected and is quite satisfactory.

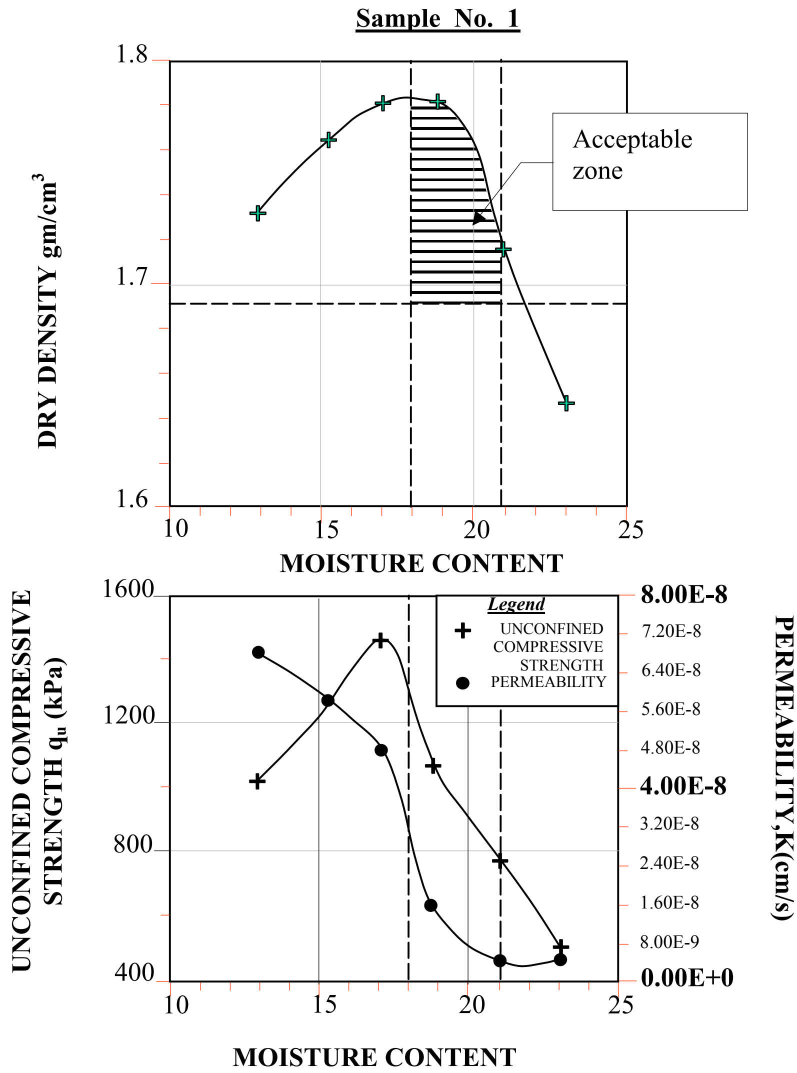

Figure 8. Acceptable zone for field compaction chlinochlore [$(Mg,Fe)_6(Si,Cr)_4O_{10}(OH)_8$], 18% albite [$(Na,Ca)Al(Si,Al)_3O_8$], 5% palygorskite ($MgAlSiO_4O_{10}(OH).4H_2O$), and 2% halite (NaCl). All minerals present in the sample are quite stable ones. The soil pH is 6.83.

To achieve a good composite action, the geomembrane was placed against the soil with good intimate contact. If stones of a size and shape that could puncture the geomembrane exist in the soil liner, the stones will be removed. To achieve an intimate contact, the surface of the compacted marl on which the geomembrane is placed should be smooth rolled with a steel-drum roller. This will be followed by the construction of the leak detection and removal system, the primary liners, and the primary leachate collection and removal system. To avoid the accumulation of leachate at the bottom of the landfill, the primary leachate collection area is graded into a series of sloped terraces. The terraces are shaped so that the leachate that accumulates on the surface of the terraces will drain to leachate collection channels. Perforated pipe will be placed in each leachate collection channel to convey the collected leachate to a sump, from where it is removed for re-application to the surface of the landfill after mixing with sand (Abduljauwad, 1993).

The facility will be above the ground disposal site, a side slope of 3 to 1 (horizontal to vertical) will be used. A trench will be dug on the berm and the geomembrane liners will be inserted in the trench for anchoring. The dimensions of the trench need to be calculated so that pullout does not occur. The possibility of potential instability that could occur in the foundation soil, the refuse, or the cover was evaluated prior to the construction of the facility. Figures 9 to 11 show complete design details for the proposed landfill.

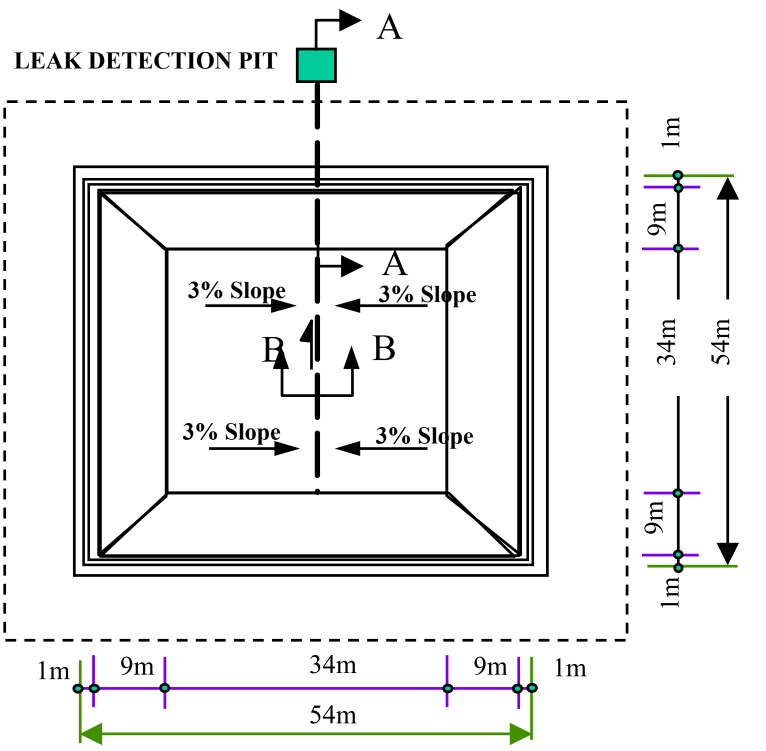

Figure 9. Plan view of the landfill constructed in the Eastern Province.

The Class I landfill at Yanbu of the Western Province of Saudi Arabia was designed in accordance with the Resource Conservation and Recovery Act (RCRA), Subpart 264 (1995). The landfill consists of a double lined waste containment cell, waste space and landfill cap. A soil fill material has been previously placed on the site at Yanbu. The soil fill was placed to an elevation of 1.5 m (above sea level) and compacted. This should ensure that the site is above the flood plain and above the high groundwater table. The landfill will be constructed above the elevation of 1.5 m to ensure that hydrostatic pressure is not exerted against the geomembrane liners in the waste cell. Therefore, the landfills will be constructed upward and cannot be constructed below grade.

The double lined waste containment cell consists of the following from top to bottom: soil protection layer, geotextile, sand drainage layer, 60 mil HDPE liner, composite drainage net, 60 mil HDPE liner, geosynthetic clay liner (GCL), low permeability layer (compacted clay), and soil fill material (previously placed). Soil No. 1 collected from Nwabah will be used for the low permeability layer. Following construction of the compacted soil layer, a GCL shall be utilized to help ensure waste cell containment integrity The GCL has a very low permeability (1×10^{-9} cm/sec) and will act as a supplement to the compacted soil layer. The GCL shall be prehydrated and covered immediately to minimize the loss of moisture. The GCL should also be needle punched to eliminate the danger of free swell. Primary and secondary geomembrane liners will be utilized within the waste cell for dual containment. HDPE liner material was chosen to line the waste cell due to the material's excellent chemical resistance properties. Smooth liner material will be placed along the landfill bottom and textured liner material will be placed along the sideslopes and ramps. A thickness of 60 mils will be required for both containment layers.

A composite drainage net will be used along the landfill bottom as part of the secondary leachate collection system and along the sideslopes as the primary and secondary leachate collection systems. Along the bottom of the landfill, the composite drainage net will be sandwiched between two layers of HDPE liners. Along the sideslopes of the waste containment cell, the secondary composite drainage net will also be between the two geomembranes.

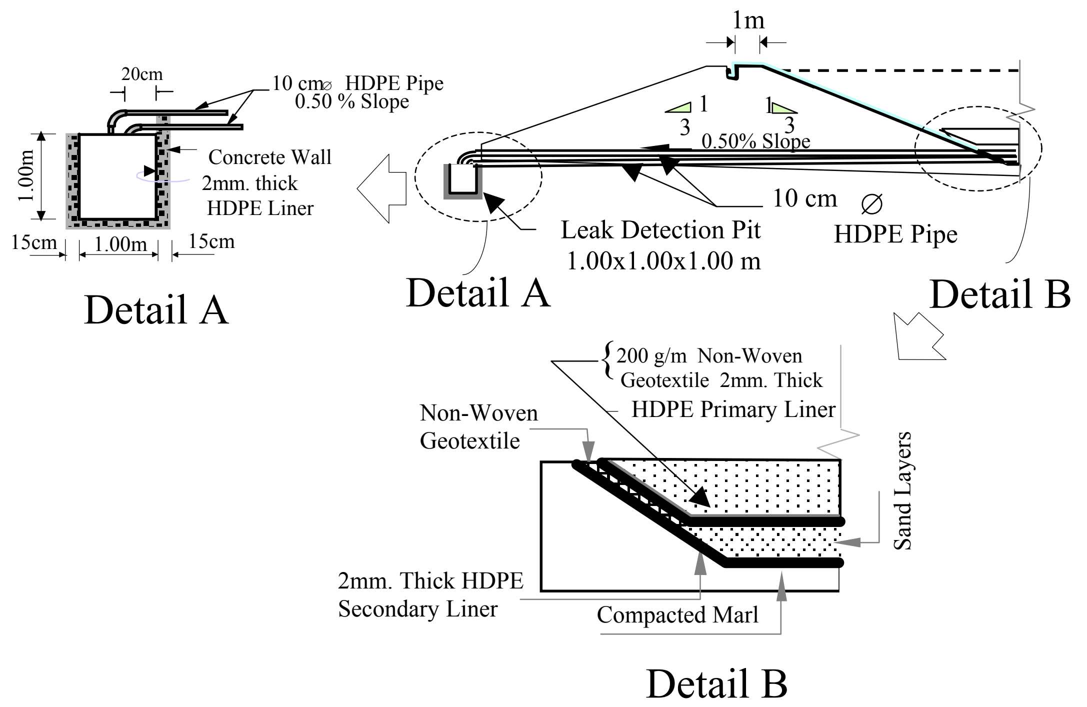

Figure 10. Section A-A through the berm, the composite liners and leachate collection system.

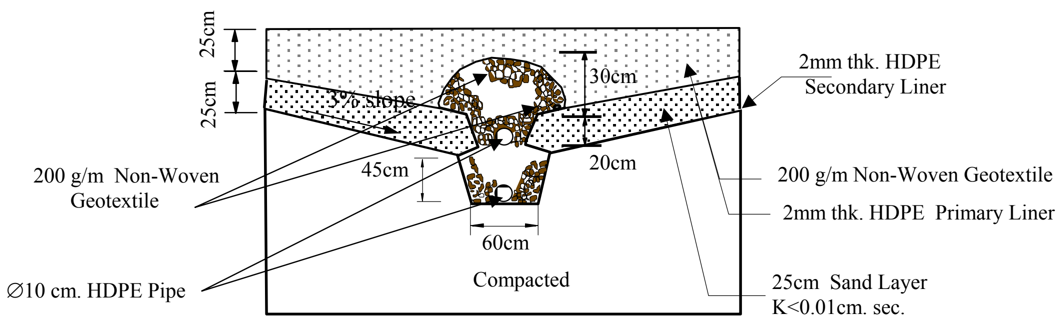

Figure 11. Details of the primary and secondary leachate collection system (Section B-B).

The primary drainage net will lay on the surface of the primary geomembrane. The primary composite drainage net will be covered immediately by a sacrificial geotextile layer to minimize UV degradation of the geotextile on the composite drainage net. The sacrificial geotextile will remain in-place until the waste is placed vertically along the sides of the waste cell. At that time, it may be removed or left in-place (Figure 12).

A sand drainage layer shall be placed on top of the primary geomembrane liner. Sand material was chosen in lieu of a composite drainage net due to its ability to provide additional protection to underlying geosynthetic layers. The sand drainage layer shall be sloped to promote drainage toward the leachate collection and detection systems. Preliminary hydraulic conductivity testing shall be performed on the sand material prior to mobilization of material to the site. The sand material shall have a hydraulic conductivity greater than or equal to 1×10^{-2} cm/sec and less than 5 percent fines.

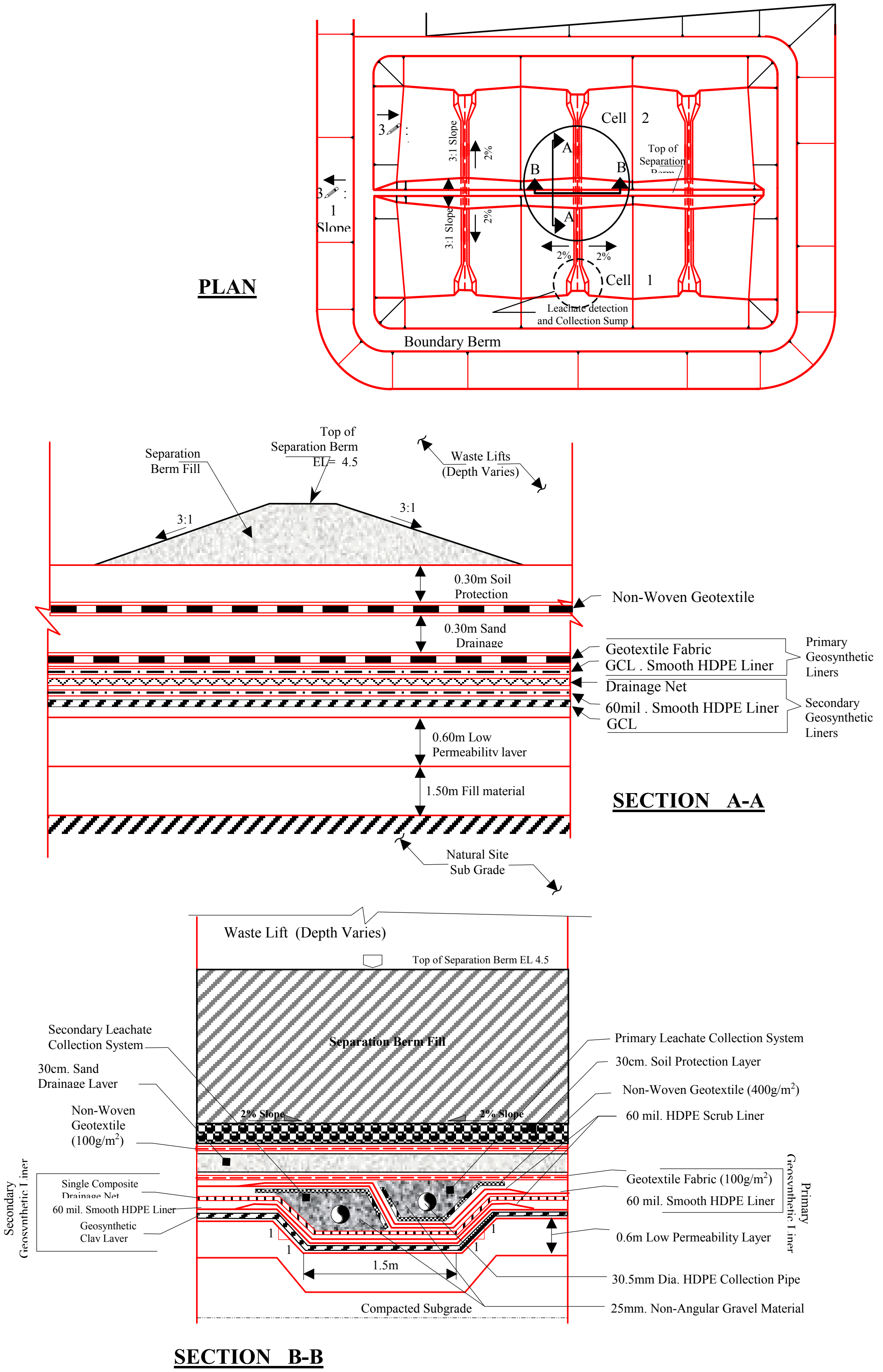

Figure 12. Design details for hazardous waste landfill in the Yanbu area.

A soil protection layer will be required to be placed above the sand drainage layer. The soil protection layer will provide additional protection to the geosynthetic layers and prevent clogging of the sand drainage layer. The soil protection layer will be 0.3 m in depth. A thin geotextile will be placed between the soil protection layer and the sand to prevent mixing of the two materials.

The initial waste layer shall be placed above the soil protection layer in a 0.6 m lift. Following placement of the initial waste lift, subsequent waste lifts shall be placed at a depth of 30 cm. They shall be consolidated with compaction equipment. A minimum number of passes by the compaction equipment will be required to consolidate each waste layer. Due to the unknown nature of waste entering the landfill, specific compaction requirements are not being specified. The final layer of waste will be required to be screened to less than 1.25 cm. This will be required to prevent punctures of the geosynthetic layers in the Cap.

Waste will be placed within each of the landfill cells in a systematic manner. Two cells were used for each landfill and a soil separation berm separates the cells (i.e., cells "a" and "b"). The HDPE liner runs beneath the separation berm and completely lines both cells to prevent leachate from escaping the landfill.

The leachate collection systems for the landfills consist of sand, composite drainage net, gravel filled sumps, and leachate collection piping. Sand bedding will lay on the top of the landfill bottom. The landfill bottom will be sloped toward leachate collection sumps at a minimum grade of 2 percent. A composite drainage net will be placed along each landfill sideslope to promote drainage to the leachate collection sumps. There are a total of six sumps within each landfill. HDPE pipe will be placed along the landfill sidewalls and enter the sumps. The HDPE pipe will then run continuously from one cell to an adjacent cell. This will allow for a contingency access point should it be needed.

The HDPE pipe will be perforated on the bottom so that leachate may be pumped from each sump. A suction hose will be located within each HDPE sump pipe for pumping leachate from the sumps. Figure 12 shows the complete design details for Yanbu landfill.

5. Conclusions

Due to rapid industrialization in the Kingdom of Saudi Arabia, it has become necessary to develop waste disposal methods applicable to the local climatic conditions. Also, there is a need to develop environmental awareness program in the region. Suitable materials for soil liners are obtained by either blending two different types of marls or using an average plasticity homogeneous clay to achieve the required low hydraulic conductivity and good strength.

6. Acknowledgements

The authors acknowledge the financial support of Environmental Service Company and Al-Murjan Environmental Management & Technology Co. Ltd. for conducting this work. The support of King Fahd University of Petroleum & Minerals for the presentation of this paper is really appreciated.

References

ABDULJAUWAD, S.N. 1993. Environmental impact assessment study of a proposed hazardous waste management facility in Dammam, Saudi Arabia, Report submitted to Meteorology and Environmental Protection Administration (MEPA), Jeddah, Saudi Arabia.

ABDULJAUWAD, S.N. 1994. Design, construction and monitoring of hazardous waste landfill, Report submitted to Meteorology and Environmental Protection Administration (MEPA), Jeddah, Saudi Arabia.

ABDULJAUWAD, S.N. 1998. Selection of soil liner material for Al-Murjan landfills, Report submitted to Al-Murjan Environmental Management & Technology Co. Ltd., Dammam, June.

DANIEL, D.E. 1990. Summary review of construction quality control for compacted soil liners, *Proceedings of Symposium on Regulation, Performance, Construction, Operations of Waste Contaminant System*, San Francisco, Nov. 6-7, ASCE, New York.

DANIEL, D.E. 1993. *Geotechnical Practice for Waste Disposal*, Chapman & Hall Co., New York.

U.S. CODE OF FEDERAL REGULATIONS , 1995. 40 CFR 264, USUPA, Office of Research and Development, Washington, D.C., U.S.A.

U.S. ENVIRONMENTAL PROTECTION AGENCY ,1985. Draft minimum technology guidance on double liner systems for landfills and surface impoundments – Design, construction and operation, EPA/530-SW-014, Office of Solid Waste and Emergency Response, Washington, D.C., 70.

Received 4 March 2000
Accepted 1 June 2000