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Reclamation of solid waste landfills by capping with dredged material

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Abstract

A cost-effective method for reclaiming solid waste landfills by capping with clayey dredged material is illustrated in this paper using a closure design developed for bauxite residue landfills in Texas. The design consisted of capping the landfills with dredged material obtained from maintenance dredging at a nearby bay and establishing a vegetative layer on the cap using salt-tolerant plant species. A research methodology comprised of laboratory cylinder tests, field revegetation tests and computer-based transport modeling was used to evaluate the effectiveness of the various capping alternatives and to select the final design parameters for the landfill. Results from this study indicated that a cap consisting of a 0.31 m (1.0 ft) sandy dredged material layer (topsoil layer for establishing vegetation) underlain by a 0.61 m (2.0 ft) clayey dredged material layer (low permeability layer) can be used as an effective barrier for closure of solid waste landfills yielding effective isolation of the waste from the environment. The design developed in this study can be applied to other similar solid waste sites with minor modifications depending upon the waste properties, site characteristics, and closure requirements of the facility. © 1997 Elsevier Science B.V.

Keywords: Solid waste; Bauxite residue; Dredged material; Landfills, reclamation; Capping; Revegetation; Chemical transport; Modeling

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1. Introduction

Efficient and environmentally sound disposal of solid waste material calls for a multi-disciplinary effort [1]. Typically, information about the physical, chemical and biological processes that need to be considered in particular solid waste disposal

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situations are linked together by means of predictive techniques or computer models (Fig. 1). The principal aim in the decision-making process is to protect the environment and enhance public health, while optimizing the cost. Although the scientific, technological, political and economic information required to make an optimal choice among land and sea disposal sites is now generally available or attainable, there are many constraints on policy implementation including: (a) the statutory framework; (b) public administration processes; (c) economic factors; (d) environmental concerns; and (e) information limits and public attitudes.

A sound knowledge of the factors governing waste migration processes (Fig. 2) is essential in order to develop a successful closure design for solid waste landfills. Increased pressures from regulatory agencies in recent years require the closure of existing solid waste landfills by capping with clean (uncontaminated) material. Most regulators require that landfills be capped using compacted clays which aid in minimizing surface water infiltration and upward contaminant migration, while maximizing the

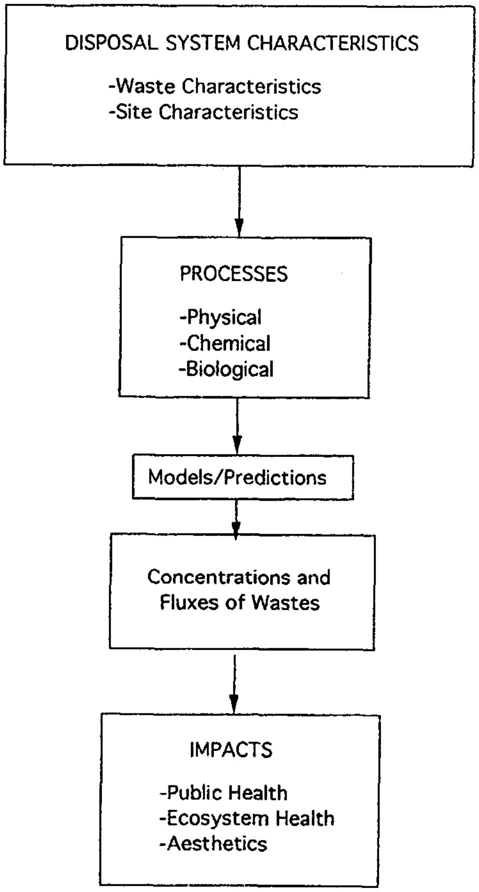

Fig. 1. Disposal system design for impact assessment.

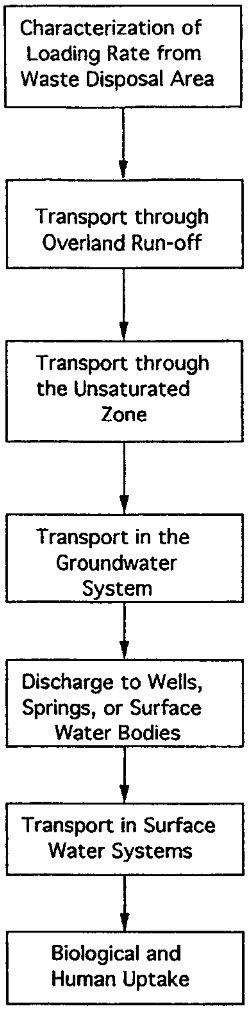

Fig. 2. Waste migration pathways.

runoff. Closure of the landfill by capping restricts the upward migration of chemicals from the waste material and provides a zone of cleaner material at the surface. A topsoil layer placed over the capping material is often used to establish a vegetative cover.

Clays have been recognized historically as "ideal" capping materials due to their low permeability (typically less than $1.0 \times 10^{-7}\,\mathrm{cm\,s^{-1}}$). However, industrial by-products may be suited for consideration as capping materials for solid waste landfills provided they are "clean" and satisfy the low permeability requirement (less than $1.0 \times 10^{-7}\,\mathrm{cm\,s^{-1}}$). Use of such materials typically results in considerable cost savings for the landfill operator, since such material is often very inexpensive. Recently, there have been many studies to investigate the use of alternate materials (such as paper sludges and waste water treatment sludges) as capping materials for solid waste landfills

[2–4]. This paper presents a closure design for solid waste landfills by capping with clayey dredged material (available from maintenance dredging of rivers and harbors) using a closure design developed for bauxite residue landfills in Texas. The use of clean material dredged from rivers and harbors as a capping material is attractive for several reasons: (a) economic—dredged material is readily available from maintenance dredging projects; (b) environmental—the silty and clayey dredged material provides a low-permeabilty barrier and may be subsituted for a clay cover in order to restrict the upward migration of chemicals; and (c) beneficial—provides a beneficial use for dredged material in coastal areas [5,6].

The Bayer process of extracting alumina from bauxite ore [7] results in alkaline tailings because of the sodium hydroxide treatment. In the past, these tailings were disposed by direct pump-out into the marine environment. This was practised in Europe [8], Japan [9], and the United States [8]. However, marine disposal is no longer permitted by the signatories of the London Dumping Convention. This led to an alternative technique which involved disposal of the tailings in a diked area on land insulated at the base and sides by impermeable clay layers or bitumen liners [10–12]. These disposal sites were eventually reclaimed by revegetation of alkaline tolerant plant species. The primary environmental concerns associated with such disposal include contamination of groundwater, soil pollution, dust control, erosion by surface runoff, infiltration, and stability under various environments [13–15]. In order to address these issues, an innovative approach of closure of bauxite residue landfills by capping with clayey material dredged from a nearby bay was recently proposed by the Aluminum Company of America (ALCOA) plant in Point Comfort, Texas. However, the capping process involved several unknowns including: (a) will the pore fluid from the bauxite residue travel upward into the dredged material layer or will the pore fluid from the dredged material travel into the bauxite residue layer?; (b) what is the effect of time on the chemical transport process between the bauxite residue and dredged material layers?; and (c) what is the effect of dredged material thickness, type of interface between the dredged material and bauxite residue layers (sand layer, geotextile filter, no filter) on plant growth and soil chemical properties? In order to answer these unknowns, a unique research approach was undertaken at Texas A & M University (TAMU) in College Station, Texas. The effect of several variables (including thickness of dredged material cover, separation interface between the bauxite and dredged material layers, surface water depth, and water table location) on chemical transport (and final cap design parameters) was evaluated using laboratory cylinder tests, field revegetation tests, and computer-based numerical modeling of chemical transport at the closed landfill. Details of the geo-environmental monitoring techniques used in this study are discussed below.

2. Materials and methods

The physical and chemical properties of the bauxite residue are well documented [16–18]. However, there would be minor variations in the properties of the residue due to site and operation specific parameters. In order to better define the geotechnical and geochemical properties of the bauxite and dredged materials, laboratory characterization tests were conducted at TAMU. Dredged material at the site was classified into two groups: (a) fine (clayey) dredged material which was considered for use as the low permeability layer in the cap design; and (b) coarse (sandy) dredged material, which was considered for use as the topsoil layer in the cap design. Since the chemical migration rate is primarily dependent on the fine (clayey) dredged material cap (low permeability barrier) properties, all "dredged material" testing in this paper refers to the fine dredged material. Geotechnical tests were conducted at the Geotechnical Laboratory, TAMU, and included: (a) water content; (b) solids content; (c) Atterberg limits; (d) grain size; (e) specific gravity; (f) vane shear strength; and (g) consolidation and permeability. Details of the test procedures are described in [19]. In general, the bauxite residue was wet (average water content of 66%), clayey with some silts (about 96% finer than no. 200 sieve), was moderate reddish brown in color, and of moderate compressibility (cumulative sample strain of 17%). The dredged material was very wet (average water content of 100%), clayey (100% finer than no. 200 sieve), olive gray in color, and moderately to highly compressible [cumulative sample strain of 46%, see Table 1(a)]. The coefficient of permeability for the bauxite residue was 10^{-8} cm s^{-1} (10^{-10} ft s^{-1}), whereas that for the dredged material was 10^{-9} cm s^{-1} (10^{-11} ft s^{-1}). Further details of the geotechnical characteristics of the bauxite and dredged materials may be obtained from [20].

Geochemical tests were conducted at the Soil and Crop Sciences Laboratory, TAMU,

Table 1
Summary of (a) geotechnical and (b) geochemical properties of dredged material and bauxite residue

Parameter	Dredged material	Bauxite residue
(a)		
Water content (%)	84–115	56–75
Solids content (%)	46–55	57–64
Liquid limit (%)	93–106	50–65
Plastic limit (%)	31–35	38–45
Clay (% particles < 0.002 mm)	80	25
Silt (% between 0.002 and 0.074 mm)	20	65
Sand (% particles > 0.074 mm)	0	10
Specific gravity	2.79–2.86	3.45–3.65
Undrained vane shear strength (kPa)	6.1–7.5	7.6–20.3
Coefficient of consolidation (cm^2 s^{-1})	1.0×10^{-4}	2.7×10^{-3}
Coefficient of compressibility	1.10	0.65
Cumulative sample strain (%)	46	17
Coefficient of permeability (cm s^{-1})	6.0×10^{-9}	5.8×10^{-8}
(b)		
pH	7.5	13.07
Electrical conductivity (ds m^{-1})	6.0	18.36
Total Alkalinity (meq l^{-1})	0.002	0.754
Calcium (mg l^{-1})	292	Not detectable
Magnesium (mg l^{-1})	1715	9.7
Sodium (mg l^{-1})	10432	23924
Potasium (mg l^{-1})	430	582

and included the following: (a) pH, (b) electrical conductivity, (c) total alkalinity, (d) calcium, (e) magnesium, (f) sodium, and (g) potasium. In general, the dredged material had a pH of 7.5, an electrical conductivity of 6 ds m^{-1}, and very low total alkalinity (0.002 meq l^{-1}). The bauxite residue was highly alkaline (total alkalinity of 0.75 meq l^{-1}, and sodium content of 24000 mg l^{-1}) with a pH of 13 and an electrical conductivity of 18 ds m^{-1} [see Table 1(b)]. These data were considered as initial values of the bauxite and dredged materials (representative of the undisturbed initial states) for the chemical transport analyses described later in this paper. Quality control of the laboratory data was maintained using analysis of randomly selected duplicate samples for geochemical and geotechnical properties.

2.1. Laboratory experiments

The following laboratory tests were conducted to study the geotechnical and geochemical behavior of bauxite and dredged materials: (a) cylinder tests, (b) mini-cylinder tests, (c) bulking factor tests, (d) dredged material mini-tray tests, and (e) dredged material tray tests. Details of these are given below.

2.1.1. Cylinder tests

Seven sets of laboratory cylinder tests comprised of a total of 21 cylinders were installed at the Hydromechanics Laboratories, TAMU, for studying the nature and rate of exchange of chemicals between the bauxite and dredged material layers. The number of experimental sets was chosen based on variables that include: (a) the presence of a separation layer (interface) between the bauxite and dredged materials [none, sand layer, geotextile]; (b) thickness of sand layer [8 cm (3 in), 15 cm (6 in)]; (c) type of geotextile [woven, non-woven]; (d) depth of surface water [3 cm (1 in), 8 cm (3 in), 31 cm (12 in)]; (e) water table position [at the surface, at the interface and in between]; and (f) depth of dredged material [0.61 m (2 ft), 0.91 m (3 ft), 1.22 m (4 ft)].

Typically, the experimental cylinders were 2.44 m (8 ft) high, 20.3 cm (8 in) in diameter, and made of Plexiglass (Fig. 3). There were six sampling ports in each cylinder: two in the bauxite residue layer and four in the dredged material layer. Liquid samples were withdrawn through the sampling ports at regular intervals of time for geochemical analysis. The geochemical tests were conducted at the Soil and Crop Sciences Laboratory, TAMU, and included the following: (a) sodium, (b) calcium, (c) potassium, (d) pH, (e) total alkalinity, and (f) electrical conductivity.

2.1.2. Mini-cylinder tests

Eight mini-cylinder tests were used to select the most suitable geotextile for field tests. The test cylinders were 0.46 m (18 in) tall, 0.1 m (4 in) in diameter, and made of Plexiglass with a 0.15 m (6 in) catchment basin at the base (see Fig. 4). Different commercially-available geotextiles were placed in each of the cylinders. Dredged material with an average water content of 100% and a bulk density of 1282 kg m^{-3} (80 lb ft^{-3}) was placed on top of the geotextile layer. A 0.05 m (2 in) layer of water was placed on top of the dredged material and the cylinder was then covered to minimize

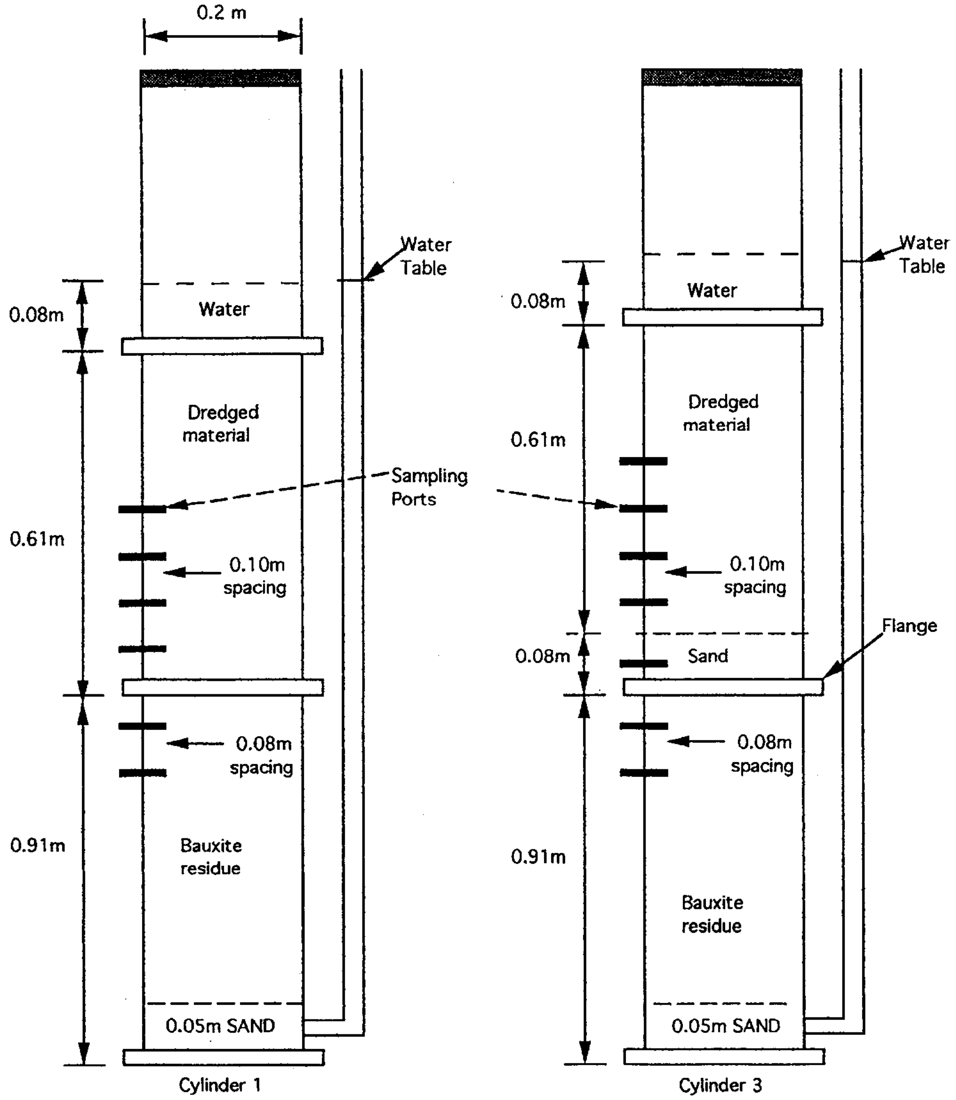

Fig. 3. Typical cylinder setup (note that cylinder no. 2 is similar to cylinder no. 1 with a geotextile interface between the dredged material and bauxite residue layers).

evaporation. The amount of water trapped in the catch basin was then observed as a function of time.

2.1.3. Bulking factor tests

The bulking factor (B.F.) is defined as the ratio of the volume of the sediments in the containment area to the *in situ* (undisturbed) sediment volume. It is often used as a critical parameter in the design of confined disposal facilities to estimate the required area of containment and to predict the available future storage volumes. Bulking factor

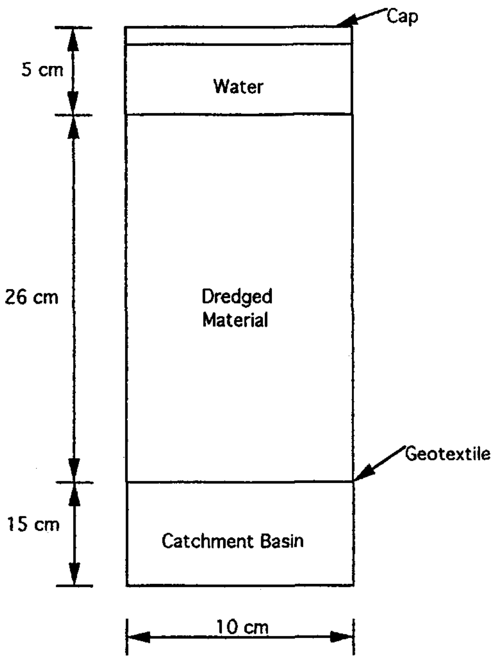

Fig. 4. Schematic of mini-cylinder test setup.

tests were conducted on the bauxite residue, fine (clayey) dredged material, and the coarse (sandy) dredged material to determine their bulking and settling properties. In order to study the effects of saline (30 parts per thousand sea-salts) water (S.W.) and fresh water (F.W.) on particle settling, each material was tested using two cylinders, one of which was filled with saline water, while the other was filled with fresh water. A known volume of the material was mixed in a mechanical mixer and poured into a 1 l graduated Plexiglass cylinder. The settling rate of the material was then observed visually over regular intervals of time. After the rate of settling attained near equilibrium conditions, the bulking factor was estimated by evaluating the ratio of the final observed volume to the initial sediment volume.

2.1.4. Dredged material mini-tray tests

Four mini-tray tests were conducted at the Geotechnical Laboratories, TAMU to develop a relationship between solids content and coefficient of permeability (k) of the dredged material. Dredged material was placed in 12 in long, 6 in deep oval trays at an initial solids content of 30%. The trays were then oven-dried to final solids contents of 40, 50, 60 and 85%. Samples were then taken for laboratory (falling head) permeability tests in order to generate a relationship between the solids content and coefficient of permeability.

2.1.5. Dredged material tray tests

Seven dredged material tray tests were conducted at the McNew Laboratory, TAMU, to evaluate the rate and nature of surface crack formation. A knowledge of the nature of surface desiccation crack formation and healing in the dredged material layer is important since cracks increase the effective permeability thereby increasing the chemical migration rates at the site. Dredged material was placed in 0.91 m (3 ft) long, 0.91 m (3 ft) wide trays at an initial slurry concentration of 30% solids under varying conditions of temperature and humidity. The nature and rate of surface crack generation was monitored using direct measurements and photographs for the first four trays (trays 1–4) over a six-month period.

For the last three trays (trays 5–7), dredged material was pumped in three layers at different times in order to observe the effects of placing the dredged material cap in several lifts. Dredged material was placed in the trays as follows: (a) tray no. 5—three 0.15 m (6 in) deep layers; (b) tray no. 6—three 0.31 m (12 in) deep layers; and (c) tray no. 7—three 0.46 m (18 in) deep layers, respectively. Each successive layer was pumped in after the previous layer developed sufficient cracks. The nature and rate of surface crack generation was monitored using direct measurements and photographs for these tests as well. After the final layer generated surface cracks, samples were taken for falling head permeability tests in order to determine the cumulative permeability of the layered dredged materials.

2.2. *Field tests*

The main purpose of the field program was to establish and monitor the survival rates of different vegetative species planted on a small section of the landfill simulating the various final cap design configurations. The field plot consisted of three subplots 46 m (150 ft) wide and 31 m (100 ft) long, each with (a) no physical interface, (b) a geotextile interface, and (c) a sand interface between the bauxite residue and dredged material, respectively (Fig. 5). The thickness of the dredged material was varied from 0.31 m (1 ft) to 1.53 m (5 ft) across the width of the test plot. This layer was then topped by a 0.15 m (6 in) sandy dredged mateial layer as topsoil for vegetation. The plot was surrounded by a dewatering ditch filled with sand near the retaining levee in order to facilitate lateral drainage of the leachate.

The dredged material overlying the bauxite residue was characterized by taking core samples for geochemical and geotechnical analyses. Samples were taken by hand with a sampling probe all the way to the underlying layer of geotextile, sand or bauxite residue. Following sampling, eight species of saline and alkaline tolerant plants were planted in April, 1992 to form a vegetative cover. The success of the vegetative growth was monitored by plant counts conducted at regular intervals of time.

2.3. *Computer-based boundary element model*

The validity of the field and laboratory test results was cross-checked using a computer-based numerical simulation of the capped landfill. A two-dimensional boundary element model with varying vertical permeabilities was developed to predict the nature and rate of chemical transport through porous media [21]. Chemical transport at the capped landfill could occur due to four effects: (a) advection, (b) diffusion, (c)

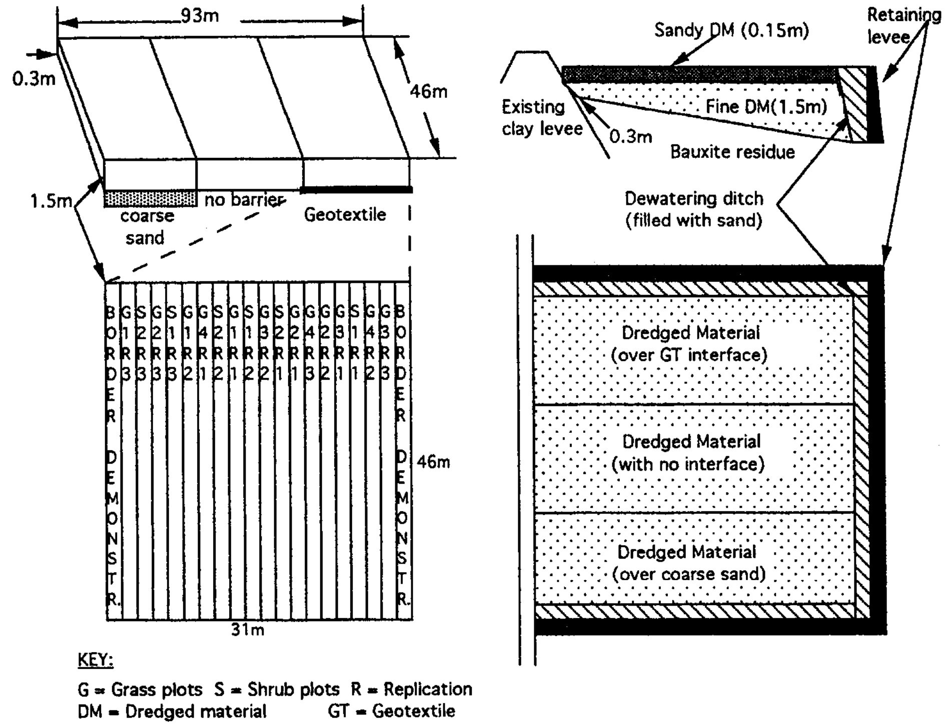

Fig. 5. Schematic if the test plot.

dispersion, and (d) seepage flow. For simplicity, the first three processes were considered to be minor since the forces that caused them were very low at the site. Therefore, transport via seepage flow was considered as the major pathway for chemical exchange at the capped disposal site. Linear boundary elements were employed to account for the variability of potentials and fluxes within an element. The primary aim was to model the system in order to obtain the advective flow potential (u). Consolidation of the materials was taken into account by using a transient layer permeability formulation in the model based on the principles outlined in [22,23]. The chemical transport at the disposal site was then given by:

$$Q_H = -k(\mathrm{d}u/\mathrm{d}x)A \tag{1}$$

$$Q_V = -k(\mathrm{d}u/\mathrm{d}y)A \tag{2}$$

where Q_H and Q_V are time-dependent horizontal and vertical alkaline salt-transport rates in the x and y directions, respectively, k is the transient layer permeability (media is assumed to be isotropic for simplicity, $k_\mathrm{H} = k_\mathrm{V}$), and A is the cross-sectional area perpendicular to the flow direction.

The boundary element method was chosen as the modeling technique because of its

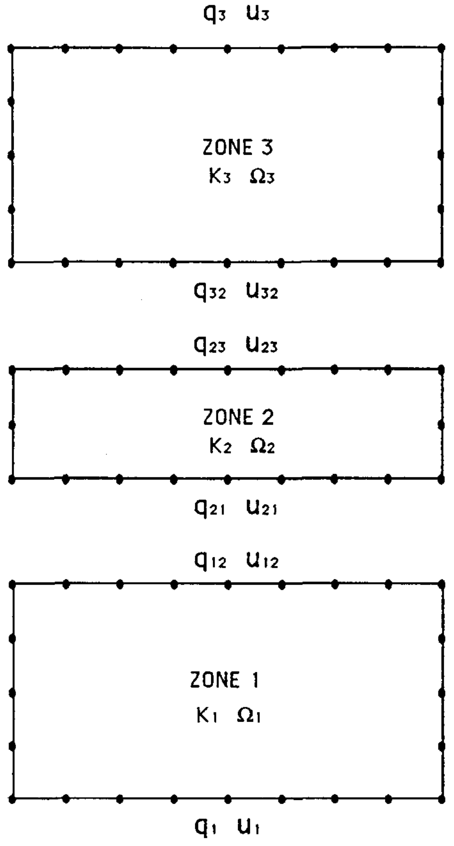

Fig. 6. Boundary element model for the three-zoned case (note: k_i = zonal permeability, u_i = zonal potential, q_i = zonal flux and Ω_i = subdomains).

unique capability to compute the transport parameters within the domain from the specified boundary values of certain parameters (inflows, potentials, etc.). Each layer with a unique geotechnical/environmental property was defined as a separate zone. The following logical sequences were used by the model to solve this problem: (a) generation of input data defining the geometry of surface elements; (b) integration of the kernal-shaped function products to generate system matrices; (c) assembly of equations for each subdivision; (d) solution of the system of equations to generate the unknown boundary data; and (e) substitution of boundary data into domain integrals to obtain values at interior points.

The boundary element model formulation for the three-zoned condition is given in Fig. 6. In this figure, zone 1 corresponds to bauxite residue, zone 2 corresponds to sand or geotextile (as the case may be), and zone 3 corresponds to the dredged material. Note that for the no interface case the properties of zone 2 are assigned a value of zero.

The model was then solved for the flow potentials in the various zones ($k = k_i$ in Ω_i, where $i = 1$, 2 and 3 for the three zones) using the Laplacian porous flow Eq. (3a), equilibrium Eqs. (4a) and (4b), and compatibility Eqs. (5a) and (5b) given below:

$$\nabla 2(k\mathbf{u}) = 0 \tag{3a}$$

where ∇ is the differential operator given by;

$$\nabla(\ ) = \{\mathrm{d}(\ )/\mathrm{d}x\} + \{\mathrm{d}(\ )/\mathrm{d}y\} \tag{3b}$$

and

$$u_{12} = u_{21} \tag{4a}$$

$$u_{23} = u_{32} \tag{4b}$$

$$k_1 q_{12} = -k_2 q_{21} \tag{5a}$$

$$k_2 q_{23} = -k_3 q_{32} \tag{5b}$$

Treating the three zones in Fig. 6 as three distinct boundary element problems, and using a series of mathematical manipulations (using equilibrium and compatibility equations) to integrate the individual formulations, an $N \times N$ banded matrix formulation (where N is the number of nodal points) as given below is obtained:

$$[H][u] = [G][q] \tag{6}$$

where

H = boundary integral of $(p\ q*)$ where $q* = \mathrm{d}u*/\mathrm{dn}$;
$u*$ = fundamental solution to the Laplace equation = $(1/2\pi)\ \ln\ (1/r)$;
$\mathbf{n}$ = normal vector;
r = the distance between the source point and the field point;
$\mathbf{u}$ = nodal potential matrix;
G = boundary integral of $(p\ u*)$; and
$\mathbf{q}$ = nodal flux matrix.

Eq. (6) was solved by a special column interchange procedure in which all the specified boundary information is transposed to the left-hand side. Further details of the mathematical model were presented in [21,24].

3. Results

The results of the above mentioned investigations were used to evaluate the effectiveness of dredged material as a barrier against chemical migration from the bauxite residue (solid waste) layer. The quality assurance/quality control (QA/QC) of the laboratory and field measurements were established by withdrawing random duplicate samples for analysis. The data obtained from duplicate sample analysis matched well with the twin sample, thereby confirming the validity of the sampling and analytical methodologies [21,24]. Details of the experimental/analytical results are presented below.

3.1. Laboratory experiments

3.1.1. Cylinder tests

The average total alkalinity of the bauxite residue was 0.75 meq ml^{-1}; it was very low in the dredged material (0.002 meq ml^{-1}) and virtually undetectable [Table 1(b)]. After closely studying the geochemical properties of both the bauxite and dredged materials, it was decided to choose total alkalinity as a leading indicator of the chemical transport process, since it was the parameter with the largest variation between the two materials. Transport parameters were computed from laboratory experiments by observing the rate of chemicals transported over specified intervals of time [25]. Initially, geochemical analysis was conducted on liquid samples withdrawn from the laboratory cylinders at regular intervals of time. Fig. 7(a) and (b) illustrates typical geochemical (alkalinity) trends observed in the laboratory cylinder tests using liquid samples of the pore fluids in bauxite and dredged material layers withdrawn at regular intervals of time.

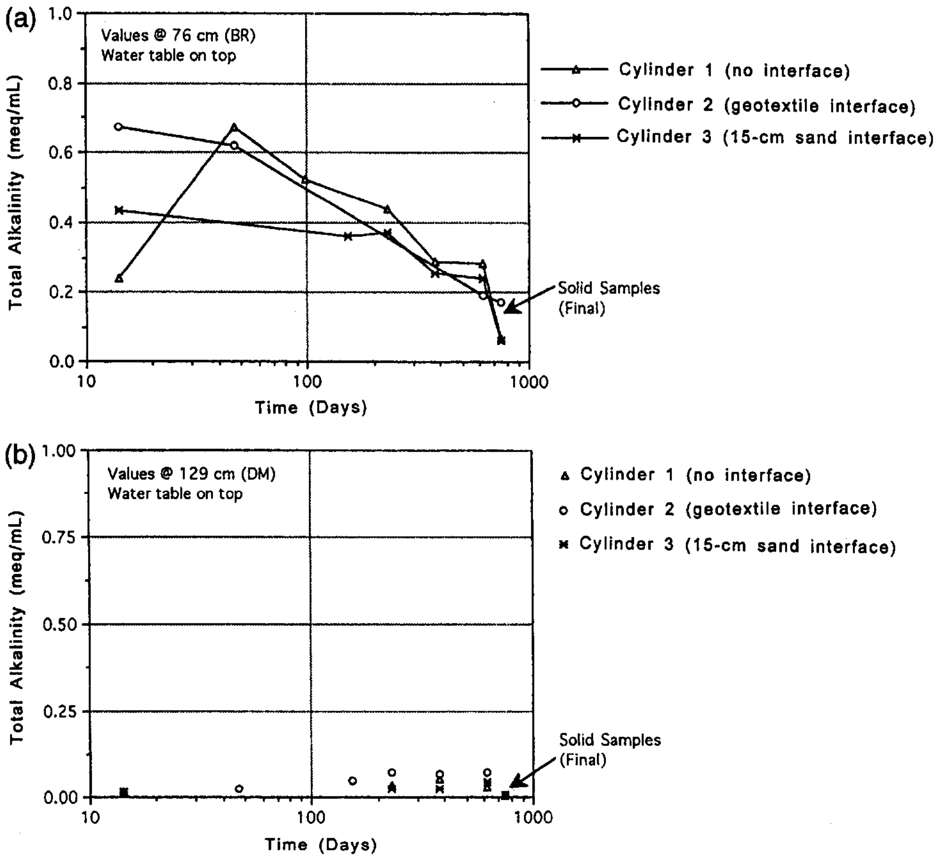

Fig. 7. Alkalinity vs. time plot for cylinders 1, 2 and 3 (note that all the samples are liquid samples except for the solid samples taken at the completion of tests).

Note that Fig. 7(a) displays alkalinity variation with time in the bauxite residue layer at a depth of 0.76 m (2.5 ft) from the base of the cylinder, whereas Fig. 7(b) is based on data from the dredged material layer at a depth of 1.3 m (4.25 ft) from the base. In general, there was a trend of decreasing alkalinity with time in the bauxite residue layer for all cylinders (irrespective of the interface type). This could be explained by the movement of less-alkaline fluid from the dredged material layer into the residue layer over a period of time [26]. The alkalinity values in the dredged material layer were negligibly affected in this process.

After longer intervals of time (greater than 2.5 years), it was difficult to withdraw liquid samples from the laboratory cylinders due to some sampling ports getting clogged with the material particles. Therefore, upon completion of the tests, sets of solid samples were taken at regular intervals of time for geochemical analysis in order to test the validity of the first sampling scheme. Fig. 8(a)–(c) illustrates the typical alkalinity trends observed in the laboratory cylinder tests using solid samples withdrawn from the cylinders. A comparison of the sampling techniques (solid samples vs liquid samples) indicated that the two techniques yielded similar pH and total alkalinity values, but differed significantly in electrical conductivity and cation concentrations. Overall, the observed solid samples were much more consistent than some of the liquid samples. A close study of Fig. 8(a)–(c) indicates that, irrespective of the nature of the interface, the pore fluid in the dredged material had a tendency to neutralize or dilute the alkalinity of the bauxite residue. In some cases (with no interface between the bauxite and dredged material), there was a noticeable zone of mixing near the interface. This may have been the result of lack of control during placement of the dredged material layer in the test cylinder.

3.1.2. Mini-cylinder tests

The vertical permeability values for the various geotextiles tested using the mini-cylinders are summarized in Table 2. In order to be an effective interface against vertical migration of chemicals from the waste (bauxite) layer, the selected geotextile should have the least vertical permeability. Based on the above criteria, the non-woven geotextile (type 4561) with a vertical permeability of $1.01 \times 10^{-12}\,\mathrm{cm\,s^{-1}}$ was recommended for use in field studies.

3.1.3. Bulking factor tests

The long-term (8000 h) bulking factors obtained from the bulking factor tests were as follows: (a) bauxite residue—B.F. (F.W.) = 2.6; B.F. (S.W.) = 1.55; (b) fine dredged material—B.F. (F.W.) = 1.87; B.F. (S.W.) = 1.32; (c) coarse dredged material—B.F. (F.W.) = 1.18; B.F. (S.W.) = 1.04. This indicates that in a fresh water environment, for every cubic meter (or cubic yard) of material excavated, about 2.6, 1.87 and 1.18 cubic meters (or cubic yards) of disposal volumes will be required for the bauxite residue, fine dredged material, and coarse dredged material, respectively. Similarly, in a salt water environment, for every cubic meter (or cubic yard) of material excavated, about 1.55, 1.32 and 1.04 cubic meters (or cubic yards) of disposal volumes will be required for the bauxite residue, fine dredged material, and coarse dredged material, respectively. The required disposal volume in the salt water environment is considerably lower than the

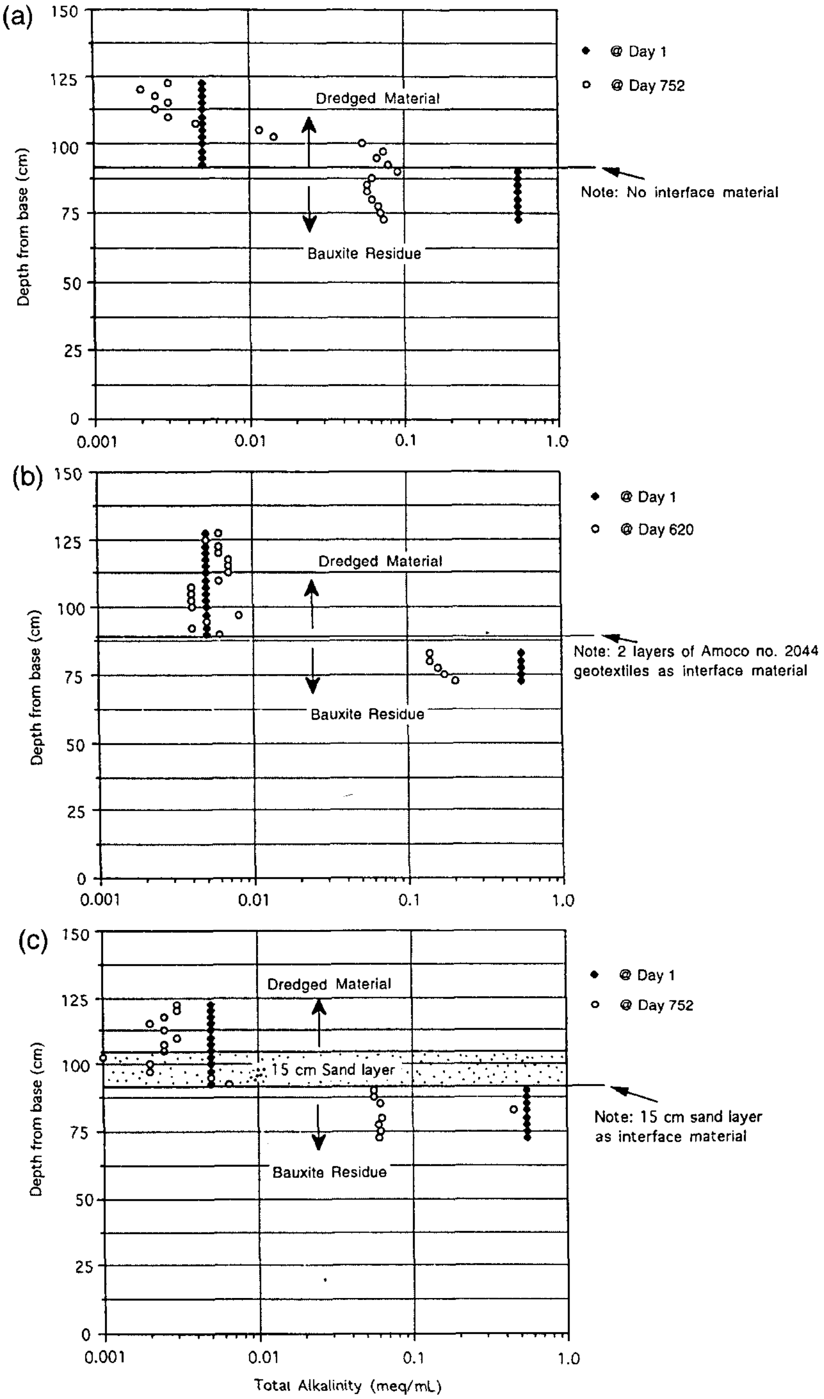

Fig. 8. (a) Total alkalinity vs. depth for (a) cylinder 1, (b) cylinder 2 and (c) cylinder 3.

Table 2
Summary of mini-cylinder test results

Cylinder number	Geotextile type [a]	Vertical permeability (cm s^{-1}) [b]
1	EPRN 172	1.48×10^{-7}
2	CEF 2006	2.59×10^{-7}
3	CEF 2044	1.67×10^{-7}
4	CEF 1198	3.06×10^{-7}
5	CEF 1199	2.96×10^{-7}
6	4553	2.78×10^{-9}
7	4545	9.26×10^{-10}
8	4561	1.01×10^{-12}

[a] Geotextile type numbers refer to fabric characteristics (strength, elongation, roll width, etc.) and is listed in [27].

[b] Vertical permeability was computed based on the amount of water trapped in the catchment basin due to a 10 cm (4 in) water layer on top of the mini-cylinders for 125 days.

fresh water environment due to enhanced flocculation of the individual particles. These results will be used to estimate the *in situ* volume of the cap material required to satisfy given layer thickness criteria during final design.

3.1.4. Dredged material mini-tray tests

Falling head permeability tests were conducted on the samples taken from the dredged material mini-tray tests in order to establish a relationship between varying solids content and the coefficient of permeability. The results, presented in Fig. 9, indicate a linear relationship between the coefficient of permeability and solids content, as expected from theory. These results will be used to determine the optimum solids content of the cap layer during final design.

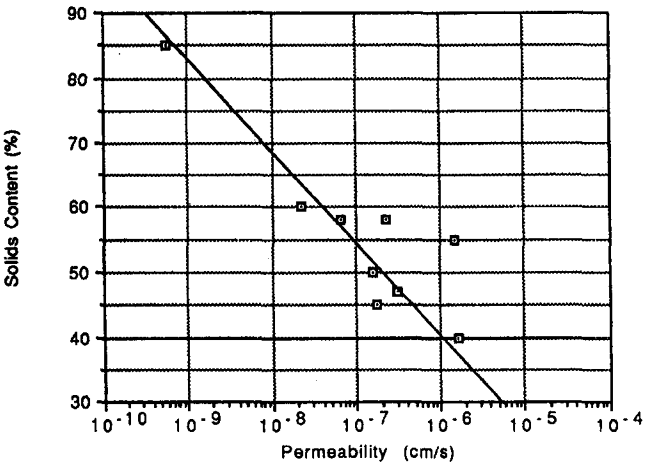

Fig. 9. Solids content as a function of permeability for dredged material.

Table 3
Summary of dredged material permeability from tray tests

Tray no.	Sample no. (depth, m) [a]	Solids content (percent)	Vertical permeability (cm s^{-1})	Effective permeability (cm s^{-1}) [b]
5	5A (0.10)	74	3.0×10^{-9}	3.2×10^{-8}
5	5B (0.20)	65	1.5×10^{-8}	
5	5C (0.30)	60	4.0×10^{-8}	
6	6A (0.18)	68	1.0×10^{-8}	1.7×10^{-8}
6	6B (0.36)	66	2.0×10^{-8}	
6	6C (0.54)	61	4.0×10^{-8}	
7	7A (0.30)	63	2.0×10^{-8}	8.0×10^{-7}
7	7B (0.60)	46	5.0×10^{-7}	
7	7C (0.90)	42	8.0×10^{-7}	

[a] Samples were collected at mid-depths of each layer after initiation of crack formation.
[b] Effective permeability was computed for the trays using stratified flow equations [28].

3.1.5. Dredged material tray tests

Vertical and effective permeabilities of the samples taken from the dredged material tray tests are presented in Table 3. As expected from theory, tray no. 5 with the least

Table 4
Summary of plant survival observed during the field revegetation tests

Plant species [a]	Survival counts [b] (May 1992)	Survival counts [b] (July 1992)	Survival counts [b] (October 1992)
Geotextile interface plot			
Alkali sacaton	94	82	79
Common Bermuda grass	88	67	70
Alecia Bermuda grass [c]	70	24	36
Panic grass	43	26	23
Wheat grass	29	11	5
Salt-bush [d]	99	5	0
No interface plot			
Alkali sacaton	86	75	59
Common Bermuda grass	52	36	44
Alecia Bermuda grass [c]	67	54	58
Panic grass	20	16	15
Wheat grass	14	10	8
Salt-bush [d]	99	8	0
Sand interface plot			
Alkali sacaton	78	62	70
Common Bermuda grass	63	47	35
Panic grass	32	18	15
Wheat grass	32	15	5

[a] All plant species were planted in April 1992 (except salt-bush).
[b] Survival rated per 99 plantings made for each species.
[c] Represents only one replication within each main plot.
[d] Salt-bush was planted only in May 1992.

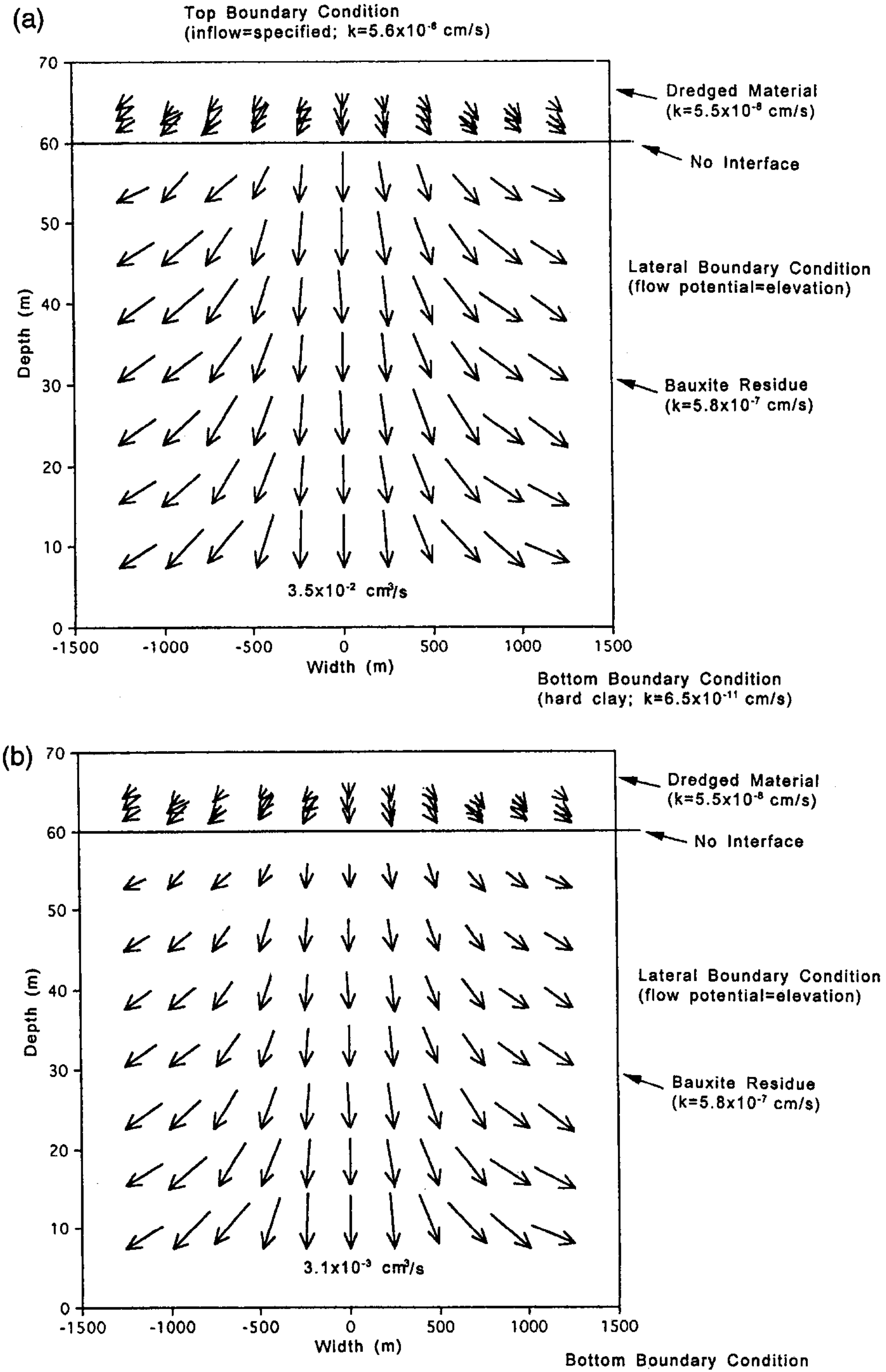

Fig. 10. Chemical transport patterns at the disposal site for (a) no interface, time = 0.01 year, (b) no interface time = 1 year and (c) no interface, time = 10 years.

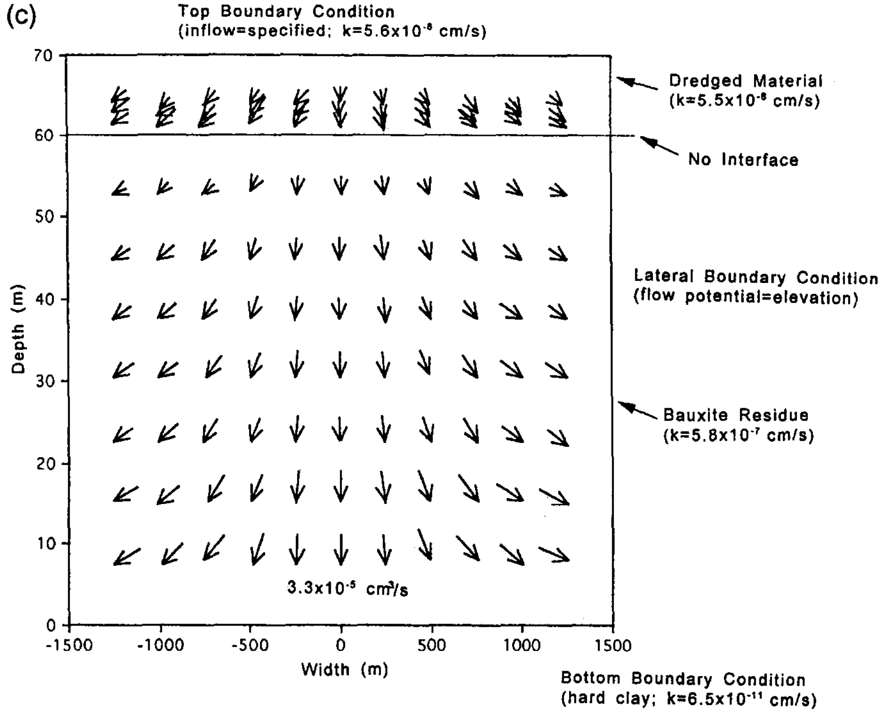

Fig. 10 (continued).

layer thickness (and hence the maximum solids content) had the smallest coefficient of permeability. Therefore, in order to improve the ability of the dredged material layer to act as an effective barrier against upward migration of chemicals from the bauxite layer, a lift thickness of 0.3 m was recommended for cap construction.

3.2. Field tests

Samples of the dredged material taken to characterize the field cap had water contents ranging from 35 to 55% and a pH of 6.8–8.1. Electrical conductivity values were lower for the dredged material above the sand interface and soluble cations were dominated by sodium. The results of monitoring to assess plant survival rates is presented in Table 4. Based on these results, plants yielding the best vegetative results at the test site such as coastal Bermuda grass, alecia Bermuda grass, alkali sacaton, and salt-bush were recommended for use following closure. Note that these studies were conducted under natural environmental conditions at Point Comfort, Texas. In order to further increase vegetative success at the site, surface amendment and fertilization were recommended for full scale application. Further details of the field revegetation tests can be obtained from [21,24].

3.3. Computer-based boundary element model

The chemical transport patterns in the disposal site as a function of time predicted by the computer model are shown in Fig. 10(a)–(c). A close observation of Fig. 10(a)–(c) indicates there is only marginal chemical transport occurring at larger time intervals. Therefore, the dredged material cap would act as an effective barrier with minimal surface water infiltration, while preventing the upward migration of chemicals from the bauxite residue layer. The model results also agreed well with transport values derived from laboratory experimental results and theory [21]. Further details of the model runs and analytical results can be obtained from [21,24].

4. Discussion

The results of these investigations could be applied to evaluate the use of dredged material (from new work or maintenance dredging projects) as a final cap for a wide range of solid waste landfills. Results of this study indicate that the dredged material can be used as a substitute material for the low permeability layer in hazardous waste caps and would meet the $1.0 \times 10^{-7}\,\mathrm{cm\,s^{-1}}$ permeability requirement for such a layer required by many state and federal regulatory agencies in the United States. Essentially, the same techniques described in this paper can be used for characterizing the waste, and evaluating the effectiveness of dredged material cap as a barrier against various types of solid and hazardous wastes.

Successful capping of solid waste disposal sites requires careful and well-planned geo-environmental design and subsequent monitoring. In general, solid wastes can be classified into four categories [29]: (a) hazardous wastes—as defined by Code of Federal Regulations, paragraph 40; (b) Class I wastes—solid wastes which, after defined testing, contain specific constituents which equal or exceed listed levels or are ignitable or corrosive; (c) Class II wastes—any non-hazardous solid waste which cannot be classified as Class I or III; and (d) Class III wastes—inert and essentially insoluble wastes that are not readily decomposable.

The bauxite residue generated at Alcoa's Point Comfort plant meets the criteria of a Class II solid waste, and hence requires closure and confinement. A conceputal design for closure of solid waste disposal sites using dredged material as a capping layer is illustrated in Fig. 11. The disposal site should ideally be confined by impermeable boundaries as shown. At the perimeter, drainage ditches filled with sand should be provided to trap the lateral transport of salts, if any. Notice that there are three options available for use as the interface between the solid waste and dredged material. These depend on the type of solid waste and the potential for upward chemical transport and include: (a) no interface between dredged material and solid waste; (b) use of sand as an interface in between [thickness: 8 cm (3 in), 15 cm (6 inches), etc.]; and (c) use of geotextile as an interface in between (type of geotextile: woven, non-woven; number of layers of geotextile: one, two, etc.). Note that there are several other parameters that can be varied, such as water table position, depth of dredged material cap, and slope.

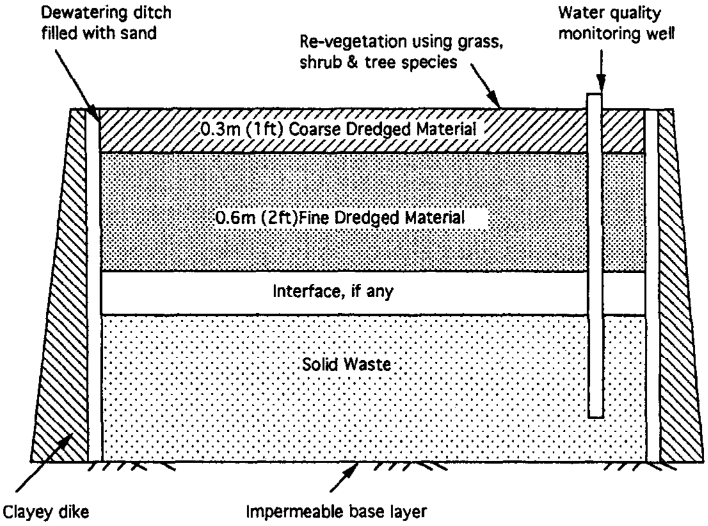

Fig. 11. Suggested closure design for dredged material capping of solid waste landfills.

Ideally, the solid waste should be capped by a layer of fine dredged material [a 0.61 m (2 ft) layer of clayey material was recommended]. The fine layer should be covered by a layer of coarser dredged material [a 0.31 m (1 ft) layer of silty and sandy material is recommended] to ensure a better medium for vegetation. Vegetation can subsequently be developed on the surface through planting grasses, shrubs, and tree species. The ideal dredged material cap should have a loam texture, a pH in the range of 5.5–8.0, a minimum organic content of 1.5% by weight and a maximum soluble salt content of $500\,\mathrm{mg\,l^{-1}}$.

Essentially the same cap design can be used for a variety of solid and hazardous waste sites with minor variations depending on waste type, local dredged material type, and state/federal regulations. The success of this operation depends on such factors as economics, environmental regulations and a good knowledge of the geochemical and geotechnical properties of both the solid waste and the dredged material.

5. Conclusions

This paper describes an environmentally beneficial and cost-effective use of dredged material for closure of solid waste landfills. Experimental and model results indicated that the dredged material cap would provide adequate physical and chemical isolation to the bauxite residue layer by minimizing surface water infiltration and restricting the upward migration of chemicals. Results from this research indicated that, if carefully placed, all three types of interfaces studied (no interface, geotextile and sand) can be successfully used in capping disposal sites. The recommended cap consists of a 0.61 m (2 ft) layer of fine clayey dredged material (low permeability layer) covered by a 0.31 m (1 ft) layer of coarser (silty and sandy) dredged material (vegetative layer). Recommended species for revegetation of the dredged material cap include coastal Bermuda grass, alecia Bermuda grass, alkali sacaton, and salt-bush. The dredged material cap should ideally have a loam texture, a pH in the range of 5.5–8.0, a minimum organic content of 1.5% by weight and a maximum soluble salt content of $500\,\mathrm{mg\,l^{-1}}$. In order to further increase vegetative success, surface amendment and fertilization could also be used.

Essentially the same cap design presented in this paper can be used for a variety of solid and hazardous waste sites with minor variations depending on state/federal environmental regulations, waste type, and local dredged material type. The same techniques described in this paper can be used for characterizing the waste, and evaluating the effectiveness of dredged material cap as a barrier against various types of solid and hazardous wastes. It is hoped that the knowledge gained from this study will assist the civil/environmental/ocean engineer in considering the environmental advantages of employing dredged material as a cap for other types of waste containment areas as well.

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Appendix A. Nomenclature

A	cross-sectional area perpendicular to the flow direction
G	boundary integral of $(p\ u*)$
H	boundary integral of $(p\ q*)$
i	arbitrary variable ($i = 1,2,\ldots,n$)
k	transient layer permeability
k_H	transient horizontal layer permeability
k_V	transient vertical layer permeability
N	number of nodal points
$\mathbf{n}$	normal vector
Q_H	time-dependent horizontal alkaline salt-transport rate
Q_V	time-dependent vertical alkaline salt-transport rate
$\mathbf{q}$	nodal flux matrix
$q*$	normal derivative of $u*$
r	distance between the source point and the field point
$\mathbf{u}$	nodal advective potential
$u*$	fundamental solution to the Laplace equation
x	lateral (width) dimension
y	material thickness

∇	standard differential operator
T	boundary
Ω	domain

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