Evaluation of clays as linings to landfill

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Abstract. The use of remoulded natural clays as low-permeability barriers or as part of multiple-layered lining systems to landfill cells is widespread. Geotechnical considerations in the evaluation of possible sources of clay and the design and construction of clay liners are addressed.

A study made of individual geological deposits within Lincolnshire is outlined and use of the term 'material suitability' to define the potential of a deposit to form a low-permeability barrier is discussed. A scheme for classifying deposits as unsuitable, marginal or suitable based primarily on plasticity data and variability is discussed and examples from the classification study are presented.

The term 'acceptability in earthworks' is also introduced and relates to the requirement to place acceptance limits on the proposed lining material to achieve the desired low-permeability barrier and to ensure the practicality of constructing the lining. The use of the moisture condition value (MCV) test in the assessment of acceptability and control of earthworks is discussed. The requirement of a maximum allowable permeability for a clay lining dictates the upper limit to the acceptable MCV range while the shear strength would usually dictate the lower limit.

Landfill comprises a mélange of waste materials, including a high percentage of decomposable wastes, which give rise to the production of various potentially troublesome gases along with a leachate containing both chemical and biological pollutants. It is common practice to construct cells (as illustrated in Fig. 1) to contain the possible pollutants. The linings to these cells generally consist of a compacted layer of low-permeability clay possibly in conjunction with a synthetic liner or liners. Guidance on containment methods can be obtained from the National Association of Waste Disposal Contractors (NAWDC) *Codes of practice for landfills* (1989), the Department of the Environment (DOE) Waste Management Paper No. 26 (1990) and the North-West Waste Disposal Officers (NWWDO) *Guidance on the use of landfill liners* (1986).

There is a recognized need to protect the environment surrounding landfill sites. To this end the proposed EU Landfill Directive, along with the Environmental Protection Act (1990), the Control of Pollution Act (1974), and water-protection legislation as detailed in the National Rivers Authority's (NRA) *Policy and practice for the protection of groundwater* (1992), emphasize the legislative and environmental obligation to prevent pollution of the ground and groundwater and obviate the dangers to future generations.

The overriding requirement in the evaluation of a clay for use as a lining material is that it should be capable of providing a low-permeability barrier following emplacement. In order to achieve this it is usual to specify the use of a clay with suitable 'material characteristics' (B. S. 5930: Anon. 1981) as defined by its plasticity, material variability and clay content. This paper outlines the use of a classification scheme to identify possible sources of suitable natural materials and is based on a study carried out in Lincolnshire.

For individual landfill sites it is also important to consider the strength, structure and other 'mass characteristics' of the clay proposed for use as a lining as it must be possible to excavate, segregate, handle and compact the deposit to an acceptable state. Thus in addition to the term 'material suitability', the term 'acceptability in earthworks' is introduced. The definition of acceptability is comparable with that adopted by the Department of Transport in the *Specification for highway works* (1991), this specification often being used as a guide to the compaction requirements for a clay lining. It is apparent that a material that is unsuitable is also unacceptable but a material that is suitable will not necessarily be acceptable.

In general highway earthworks, the use of the moisture condition value (MCV) apparatus is widespread. The MCV compaction test (Parsons & Boden 1979) was developed at the Transport and Road Research Laboratory as a control on material acceptability. The test yields reproducible results and the apparatus can be used on site to yield a rapid appraisal of material properties. On landfill sites a high degree of site control is essential and the MCV test lends itself readily to the determination of the 'acceptability' of clays forming linings. The use of the MCV test is illustrated by examination of the results for a glacial till.

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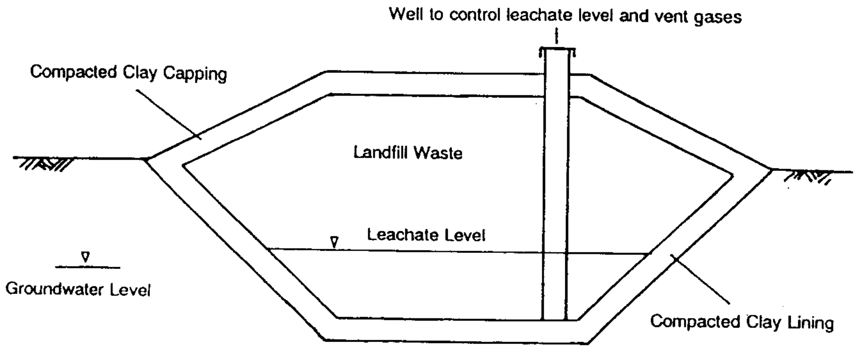

Fig. 1. Typical landfill cell.

Material suitability

Material suitability relates to the material type and whether it could potentially form a low-permeability barrier. A permeability of $10^{-9}\,m\,s^{-1}$ or less is usually specified. This degree of permeability is often defined as 'practically impervious' and taken as distinguishing clays from higher permeability silts (e.g. Somerville 1986). In terms of plasticity the division between clays and silts is known as the A-line, as shown in Fig. 2. In the study within Lincolnshire, data on individual strata were obtained from a large number of sources, but as might be expected, relatively few permeability results were obtained. It thus became necessary to identify potentially suitable deposits using the more readily available results for soil plasticity. However, permeability is related to a large number of factors and materials classed as silts based on plasticity data could achieve the required low permeability if adequately compacted within an acceptable moisture content range. Nevertheless, because of the lack of permeability test data and in accordance with NRA requirements, materials plotting below the A-line were, in general, defined as unsuitable in the study, as were materials with greater permeabilities, e.g. sands and gravels. Conversely, clays which plot above the A-line were deemed suitable or marginal.

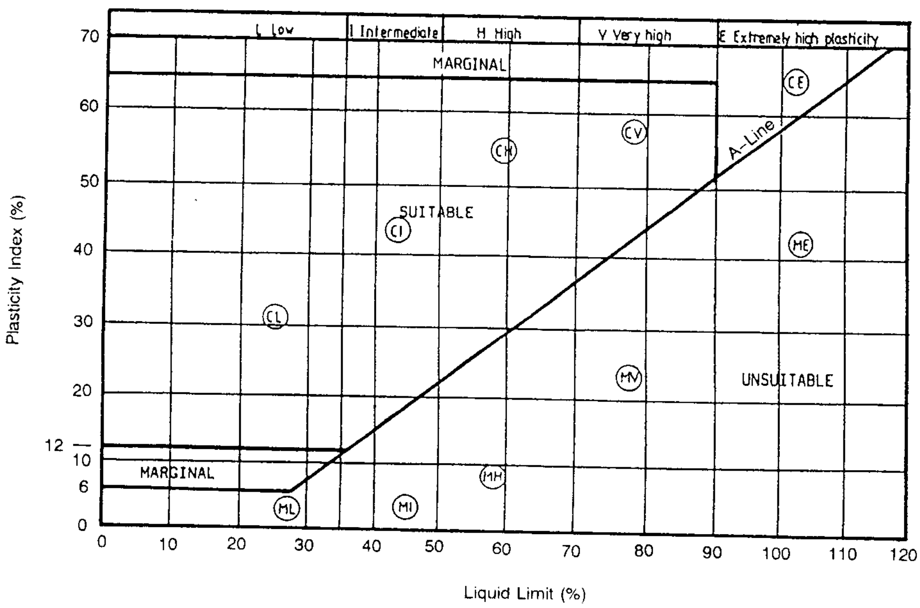

Fig. 2. Plasticity chart showing ares defined as 'suitable', 'marginal' and 'unsuitable'.

The NRA (1989) define suitable materials as those clays with a liquid limit (LL) of less than 90% and a plasticity index (PI) of less than 65%. These upper limits to LL and PI are based on criteria defined by the Department of Transport (1991) for modern earthworks plant. Materials in excess of these limits can give rise to problems with stability, deformation and compaction in earthworks. However, these limits preclude the use of extremely plastic clays. Such clay would exhibit very low permeability characteristics and if used with care may be adopted as a lining material. Sources of such materials are scarce and have not been identified within Lincolnshire. Further study of the use of such deposits would be warranted. However, for the purpose of this study, materials above these limits were defined tentatively as marginal.

The permeability of clays varies with the PI, and Murray *et al.* (1992) suggest that there appears to be a notable increase in permeability when the material has a PI of <12%. This suggests that clays with a PI of less than or equal to this value would best be defined as marginal in terms of suitability. This is considered to correspond reasonably with the NRA requirement that suitable materials should have a clay content (particle size less then 0.002 mm) of greater than 10%.

The variability of a deposit also influences its suitability; for example, glacial till whilst predominantly clay may exhibit significant variations in plasticity over short distances and contain pockets of sand, silt or other unsuitable material. Care must be taken when collating laboratory test results on a deposit to ensure that preferential sampling and testing is taken into account and the influence of material variability is fully assessed.

Based on the foregoing, deposits may be defined as 'suitable', 'marginal' or 'unsuitable' for use as linings to landfill sites and the relationship of the plasticity of clays to suitability as a lining material is illustrated in Fig. 2.

Mapping of material suitability

From published maps and geological memoirs, it is possible to identify those deposits which would obviously fall into the category of unsuitable materials, e.g. rocks, sands and gravels. The predominantly cohesive deposits require more detailed assessment. The results of the collation of plasticity data on glacial till and Lower Lias Clay from various ground investigations within Lincolnshire are presented in Figs 3 and 4. The results are interpreted as illustrating the glacial till as being marginal in terms of suitability due to the inherent variation in plasticity results, including a proportion of material with a PI of less than 12%, and the presence of unsuitable materials. The actual proportion of unsuitable materials is not readily identifiable from a cursory examination of the data in Fig. 3 and a careful examination of excavation and borehole logs is necessary to appreciate fully the influence of preferential sampling and testing.

The Lower Lias Clay results of Fig. 4 are considered to indicate the deposit as suitable (mainly CI and CH clays with a small proportion of MI and MH silts) as there is a relatively close grouping of plasticity data and little

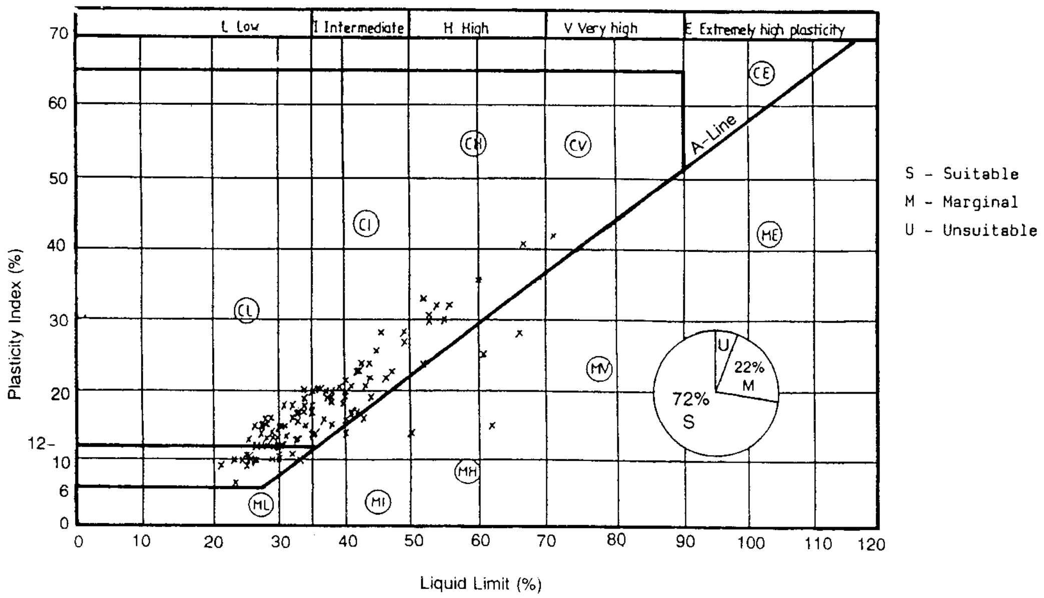

Fig. 3. Plasticity chart: glacial till.

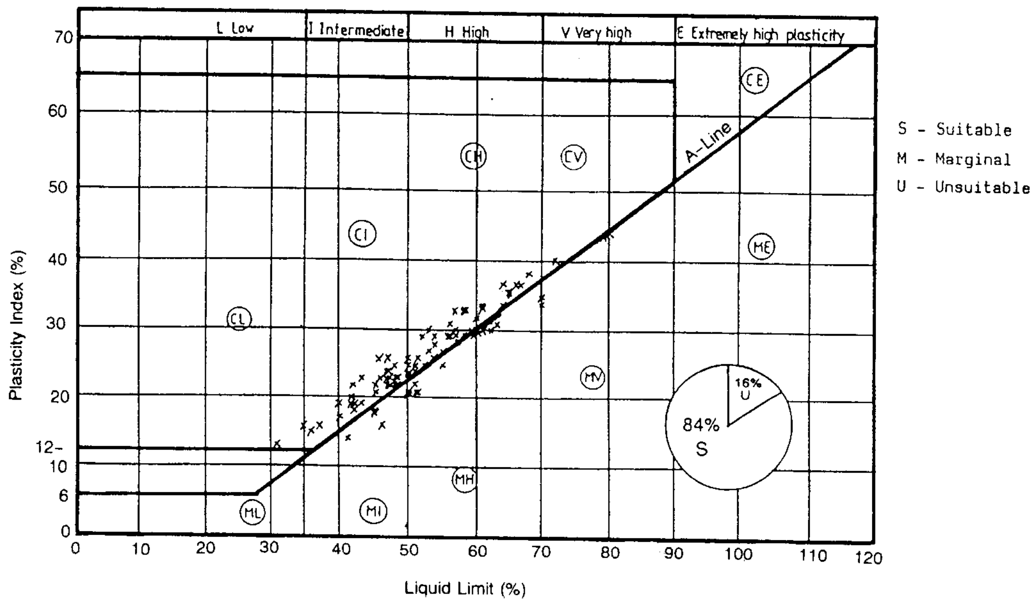

Fig. 4. Plasticity chart: Lower Lias clay.

variation in material characteristics. Those samples yielding results below the A-line were generally described visually as silty clays suggesting a significant clay content. These are thus likely to achieve the overriding requirement of a permeability of less than 10^{-9} m s^{-1} on recompaction provided they are within an acceptable moisture content range. In addition, the MI and MH soils are likely to be readily mixed with the CI and CH soils on excavation, handling and recompaction. However, this does not preclude the need to examine carefully the material from a selected source to ensure its suitability as ground conditions can vary unpredictably.

Having established a map of potential sources of suitable and marginal clays the planning of landfill sites and an appraisal of the economics of development and potential sources of clay for linings may be made. However defining a material as suitable does not mean that it is acceptable in the earthworks and this requires further analysis. Jones *et al.* (1993) present a further discussion on suitability of materials for landfill lining.

Acceptability in earthworks

A clay may have suitable material characteristics but the variation in permeability with moisture content, degree of compaction and soil structure must also be taken into account. Acceptability relates to the excavation, handling, trafficability and compaction of the materials required to achieve the desired low permeability.

Adequate compaction of materials depends on a number of factors including strength, moisture content, type of plant used, etc. If a material is too soft, stability under earthworks plant may lead to trafficability problems. If the material is too stiff it may not be possible to compact it sufficiently to achieve the low degree of permeability required. It is difficult to adequately remould very stiff clays and remove discontinuities which can lead to the establishment of seepage paths. A material defined as suitable may thus be deemed unacceptable for use in the earthworks.

Compaction and material acceptability

In determining acceptability for use as a lining material it is normal practice to carry out permeability tests on samples recompacted in the laboratory and on samples recovered during compaction trials on site as well as from the lining during construction. However such testing is time-consuming and earthworks are often controlled by moisture content and density determinations. Alternatively, the moisture condition value (MCV) test (Parsons & Boden 1979) provides a rapid means of determining the acceptability of clay soils (Murray *et al.* 1992) which, coupled with a maximum air voids requirement to monitor the degree of compaction, may be used to aid assessment of the adequacy of the completed lining.

Cobbe & Threadgold (1988) discuss the use of the MCV test in general earthworks. As shown in Fig. 5, the

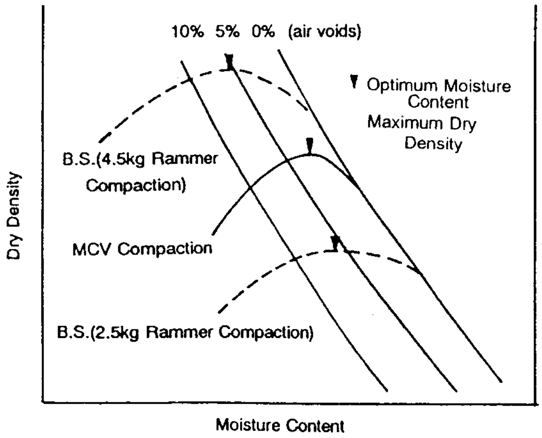

Fig. 5. Typical compaction curves.

degree of compaction achieved during the MCV test generally lies between that achieved by the 4.5 kg rammer and the 2.5 kg rammer methods of B. S. 1377 (Anon. 1990). As limiting permeability is an overriding requirement of a clay lining, there is a need to ensure a thoroughly compacted, uniform, homogeneous lining. This will necessitate detailed site monitoring and compaction probably in excess of normal earthworks levels. However, the degree of compaction achieved in a laboratory 4.5 kg rammer test is unlikely to be realized within a clay lining. Equally the low-permeability requirement would normally necessitate compaction in excess of that obtained using a 2.5 kg rammer. Densities obtained using the MCV test are thus considered more likely to represent desirable site compaction levels.

The MCV test is based on compacting a soil sample until no further change in density occurs, whereas the B. S. 2.5 kg and 4.5 kg tests are based on applying a given amount of compactive effort to a soil sample. However, the general forms of the B. S. compaction curves are similar to the MCV compaction curve but because of the different compaction criteria the optimum moisture content in the MCV compaction test tends to be closer to the zero air voids line as illustrated in Fig. 5. The differences in the compaction tests do not limit the use of the MCV test as all laboratory testing should be correlated with on-site compaction trials which may highlight the need for modifications to proposals based on laboratory testing alone. Experience suggests that more consistent results are obtained using the MCV test than the B. S. compaction tests and it is, therefore, recommended for use in the design and construction control of clay linings.

Figures 6 (a) and (b) show results for four series of tests (indicated by the different symbols) on a glacial till comprising a low-plasticity clay (PI of 15% and a clay content of 26%). These results indicate an increase in

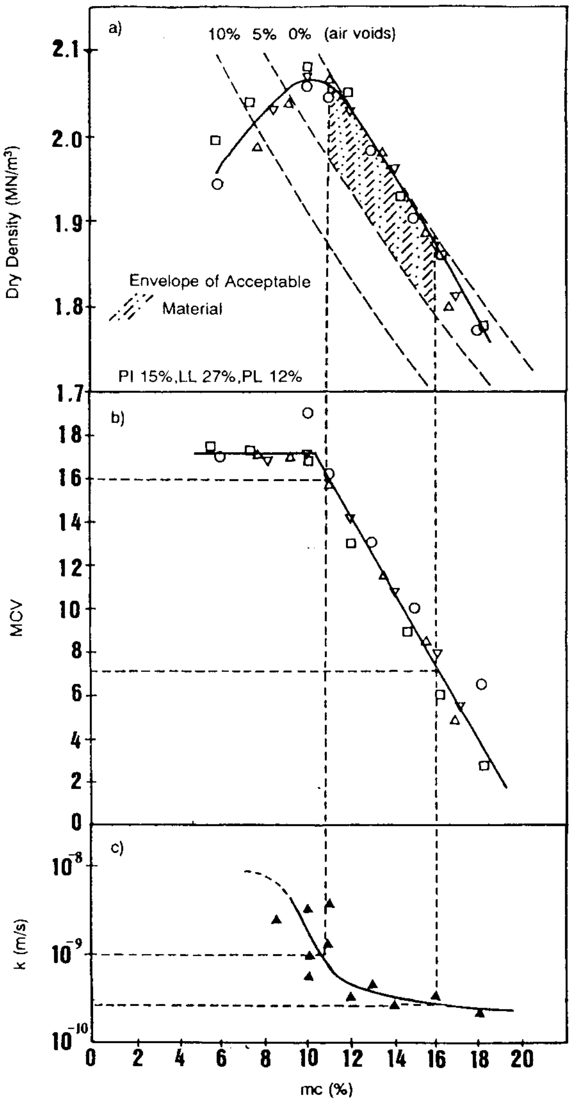

Fig. 6. MCV compaction and permeability results for low plasticity clay.

MCV with decreasing moisture content until the optimum is reached. Thereafter, for further reductions in moisture content the MCV is essentially constant. The increase in MCV is matched by an increase in remoulded shear strength as shown in Fig. 7.

Permeability requirements

In most earthworks it is the strength and degree of compaction that are the controlling parameters but in

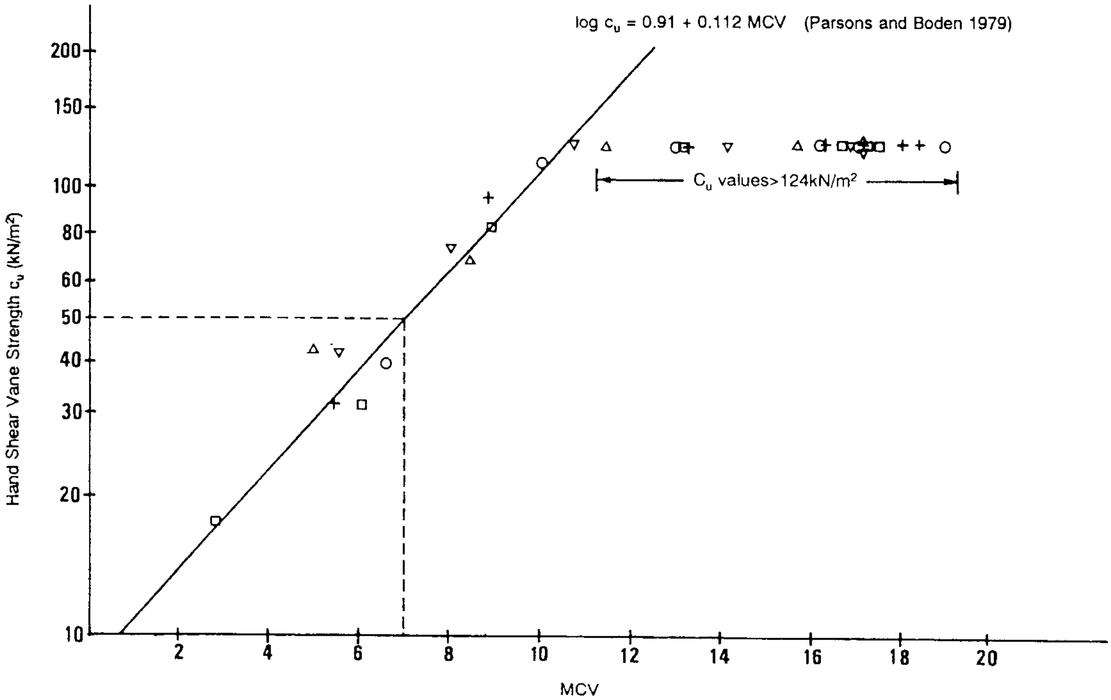

Fig. 7. Hand shear vane strength against MCV for clay of Fig. 6.

the construction of a clay lining to a landfill site a requirement for low permeability presents an additional burden on the selection and emplacement of clays.

The results of Figs 6 (a)–(c) show an increase in permeability with decreasing moisture content even though there is an increase in dry density of the clay. The results were obtained from both constant and falling pressure tests as outlined by Head (1985) and the behaviour pattern is consistent with the results reported by Needham (1991), Parkinson (1991) and Seymour (1992) amongst others. At around the optimum moisture content there is a more rapid increase in permeability, reflecting the lack of remoulding of the clay at moisture contents below the optimum value and the presence of fissures resulting in preferential seepage paths. Obviously, greater compactive effort at these relatively low moisture contents would produce a greater degree of compaction and a reduction in permeability, but as discussed previously this may not be readily achievable on site. Observations during laboratory compaction operations on the drier samples suggest the presence of discontinuities which are also likely to exist during *in situ* emplacement of the fill. The acceptable lower limit to moisture content should therefore be greater than the optimum moisture content as determined from the MCV compaction series.

Control of construction

It is necessary to establish relationships between the permeability and other soil parameters such as MCV (or moisture content) and density and use these to control acceptability and compaction. However, this should not be taken as precluding the need for further permeability testing on the compacted lining material as an assurance that the control criteria are adequate.

For a clay of suitable plasticity, test results suggest that the lower limit for the moisture content should be dictated by the permeability requirement. However, the upper limit to the moisture content is likely to be dictated by the shear strength of the clay because although the permeability requirement may be met, handling, compaction and trafficking become more difficult. This, in conjunction with stability considerations, makes a minimum shear strength requirement essential. Typically an undrained shear strength (c_u) of no less than 40–50 $kN\,m^{-2}$ is required in earthworks.

Figure 7 presents results of hand shear vane strength tests carried out during the four series of tests reported in Figs 6(a) and (b) and indicated by the different symbols. It can be seen that for a strength of 50 $kN\,m^{-2}$ an MCV of 7 would be required. Thus in order to achieve a permeability of less than $10^{-9}\,m\,s^{-1}$

and to satisfy the emplacement requirements, the laboratory test results suggest it appropriate to ensure the clay of Fig. 6 has an MCV of between 7 and 16. Compaction trials should be undertaken to ensure the required densities (and permeability) are achievable using a practical layer thickness and number of passes of the selected roller. Should the requirements not be met, the results of the trials may be used to restrict further the acceptable MCV range. A controlled compaction trial prior to the main earthworks is considered essential to alleviate potential problems in the construction stage.

Parkinson (1991), amongst others, has noted that permeabilities from field tests are perhaps 10–100 times greater than those from laboratory tests. It may be possible to reduce the discrepancy by careful site control but if necessary this may be allowed for by reducing the acceptable upper limit of MCV.

It is also worth noting that the lower limit to moisture content of 11% (MCV of 16) is close to the plastic limit of 12% for the glacial till. The plastic limit is the moisture content at which a cohesive soil stops behaving as a plastic material and starts behaving as a brittle material. At the plastic limit cracking starts to appear in thin threads (3 mm) of cohesive soil rolled by hand. These discontinuities, which can also be expected to be present in clay linings, would tend to increase permeability. This appears to be reflected in Fig. 6 where there is a more rapid increase in permeability for a given change in moisture content below a moisture content of 11–12%. There also appears to be a greater scatter of permeability results below the plastic limit and this may be a function of the frequency, orientation and continuance of fissures which will vary from sample to sample. On this basis, an MCV of 14 corresponding to a moisture content of 12% (the plastic limit of the glacial till) may be considered a more appropriate limit to ensure the permeability requirement is met.

Based on the laboratory results it is possible to set upper and lower bounds on material acceptability. If this is added to a compaction requirement of no more than 5% air voids, the envelope of acceptable material and compaction as detailed in Fig. 6(a) is obtained. It would be necessary in practice to ensure that with 5% air voids the permeability requirement is still met. However, the uptake of free water by the clay forming the lining would mean a reduction in air voids, due to suction and percolation effects, and the clay complying closer with the fully compacted state and an acceptable permeability. This would result in a corresponding softening of the lining, the consequences of which may have to be taken into account.

Consideration should also be given to the type of compaction plant to be employed on site. It is recognized that a discontinuity often exists between clay layers compacted using a smooth roller. Such discontinuities may well present seepage paths. For this reason it would be considered preferable to adopt tamping rollers in the construction of clay linings. These rollers knead and remould the soil, providing a more homogeneous material and reducing the risk of major discontinuities (and thus potential seepage paths) remaining. A smooth wheeled roller may then be used to provide an acceptable surface finish to the lining.

Conclusions

A study carried out in Lincolnshire to identify possible sources of 'suitable material' to form landfill liners has shown that materials may be classed as unsuitable, marginal or suitable based on the collation of plasticity data and an appraisal of variability.

For a material to be designated as suitable does not mean that it is acceptable for use in earthworks. In order to achieve the desired low permeability and to facilitate excavation, handling and compaction, the material must have acceptable mass characteristics such as moisture content, structure and strength.

The acceptability of a material for use in a clay lining is dictated by a maximum allowable permeability. Although this will require permeability determinations during construction of the lining, earthworks operations are generally controlled by moisture content, density and strength determinations. The alternative use of the moisture condition value and air voids determinations is recommended as a control on material acceptability and as an indicator of the degree of compaction achievable on site.

In control of the earthworks by the MCV test the lower limit to moisture content should be greater than the optimum moisture content (as defined by MCV compaction series) and is controlled by the maximum permeability requirement of 10^{-9} m s^{-1}. This dictates the upper limit to the acceptable MCV range.

The upper limit to moisture content is likely to be controlled by the strength of the clay and its handling, trafficability and compaction requirements. This would dictate the lower limit to the acceptable MCV range.

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