Difficulties associated with the specification of protection geotextiles using only unit weight

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Keywords: Geotextiles, Landfills, Laboratory research, Mechanical properties, Design method

ABSTRACT: In the majority of developed countries, landfills have full containment barrier systems. These often include a geomembrane overlain by a geotextile protection layer that in turn is overlain by a granular drainage layer. The designer is required to specify a geotextile that will both prevent damage and excessive straining in the geomembrane. At present there are two divergent approaches to the design of geotextile protection layers. In a number of European countries (following the lead of Germany) long-term environmental stress cracking resulting from local concentrations of strain in HDPE geomembrane is considered critical, while in the USA mechanical damage to the geomembrane is the key concern. In addition to this difference of approach, the methods used for assessing geotextile protection differ. In Europe, the performance based ‘Quo Vadis’ tests developed in Germany is increasingly being employed, and in the USA it is common to specify using the unit weight of the geotextile. This paper presents the results of an investigation of the applicability of specifying the protection performance of a geotextile by unit weight. Results are presented of both index and performance testing of three needle punched non-woven geotextiles with the same unit weight. The results show a large degree of variation in protection performance related to manufacturing process of geotextile, and hence demonstrate clearly that unit weight should not be used as the criteria for the design of geotextile protection layers.

1 INTRODUCTION

It is now common practice in most developed countries for new landfills to have full containment barrier systems, together with drainage systems that allow collection and removal of leachate from the site. Increasingly, the drainage blanket comprises coarse gravel, which is separated from the geomembrane liner by a protection geotextile. Different countries have their own methodology for the design and specification of this protection geotextile; in particular the difference between some European countries and the US could not be greater.

In Germany, the local strain within High Density Polyethylene (HDPE) geomembrane is limited to 0.25% as measured in the “Quo Vadis” static load test (Dixon & Von Maubeuge, 1992). The concern is that any significant local strain will act as a point of stress concentration and thus there is potential for environmental stress cracking to occur. In the US however, the role of a protection geotextile is seen simply as preventing the puncture of a geomembrane and there is no upper limit given for the local strain. Given these two extremes, the landfill designer is faced with difficulties in the design and specification of protection geotextiles.

In many countries the practice is to design and therefore specify protection geotextiles by their mass per unit area (unit weight). However, it has been postulated, e.g. Shercliff (1996), that the protection performance of a needle punched geotextile is controlled by the type of fibres and needling process, in addition to quantity of fibres present.

This paper presents the results of an investigation of the applicability of specifying the protection performance of a geotextile by unit weight. Results are presented of both index and performance testing of three needle punched geotextiles with very similar unit weights but different manufactured quality. Reasons for the large variation in protection performance are discussed, and a theory describing geotextile performance postulated. Implications for designers are highlighted.

2 GEOTEXTILE PROTECTORS

Concerns over long-term efficiency of sand leachate drainage layers have lead to the adoption of gravel to replace the sand. This has resulted in the need to introduce a protection layer between the gravel and geomembrane in order to ensure the long-term integrity of the leachate and gas barrier. In the UK, it is common practice to use a source of gravel local to the site, and this results in a wide range of possible gradings and particle shapes being used. In conjunction with variations in the depth of waste at different sites, these variables mean that site specific designs are required for geotextile protection layers. The key requirement is that the geotextile should prevent damage to the geomembrane, and in the case of many European countries, restrict the long-term strains in the geomembrane.

The mechanism by which geotextiles cushion point loads from individual stones is complex. It must also be remembered that the geotextile is only the top layer of a composite system that includes the geomembrane and mineral liner underlying the geomembrane. In addition, the influence of temperature and time (creep) must be considered. Given these controlling factors, it is unrealistic to expect simple index tests, or methods of characterising the geotextile, to provide an assessment of the field performance of a protection layer. A more rigorous approach than those presently being used by many designers is required.

3 CURRENT DESIGN METHODS

3.1 *Design based on puncture resistance*

The design of geotextile protectors is widely carried out using the method proposed by Narejo *et al.* (1996). This method is based on a factor of safety applied to the puncture resistance of the combined geotextile/geomembrane system. These authors developed an empirical formulation to determine the required unit weight of the protection geotextile for a site specific application. First, the short-term failure of the geotextile/geomembrane system is determined based on hydrostatic truncated cone test data, and modification factors are then applied to correlate this data to actual field conditions. These modification factors consider the stone shape, stone arrangement and arching. Partial factors are then applied to account for creep, chemical and biological degradation.

The basic design equation takes the form:

$$p'_{allow} = (p_{allow}) \left(\frac{1}{MF_S x MF_{PD} x MF_A} \right) \left(\frac{1}{FS_{CR} x FS_{CBD}} \right) \tag{1}$$

where p_{allow} is the maximum allowable pressure from the hydrostatic truncated cone test with an implied factor of safety of 1, p'_{allow} is the allowable pressure for site specific conditions, MF_S is the modification factor for shape of stone, MF_{PD} is the modification factor for packing density, MF_A is the modification for soil arching, FS_{CR} is the partial factor for long-term creep and FS_{CBD} is the partial factor for chemical/biological degradation.

The global factor of safety, FS, is defined as:

$$FS = \frac{p'_{allow}}{p_{reqd}} \tag{2}$$

where p_{reqd} is the maximum pressure expected on the geotextile/geomembrane system.

The maximum allowable pressure p_{allow}, is related to the unit weight of the protection geotextile and the stone size, and for a 1.5 mm thick HDPE geomembrane and a virgin polymer needle punched non-woven geotextile, this is given as:

$$p_{allow} = 450\frac{M}{H^2} \tag{3}$$

where M is the mass per unit area (unit weight) of the geotextile, and H is the effective protrusion height (one half of the stone diameter). This method makes a number of assumptions that may not always be correct.

One of the main assumptions made in the development of this theoretical model is that there is frictionless contact between the protrusion and the geotextile, see Wilson-Fahmy *et al.* (1996). This assumption, together with the assumed uniform protrusion shape, idealises the model to such an extent that the mechanism for transferring the applied force through the geotextile is not considered. As described in Section 7, the authors believe that consideration of the transfer of force through the geotextile is a fundamental part of understanding the protection performance of a needle punched non-woven geotextile.

3.2 *Design based on limiting geomembrane strain*

This design approach considers that the long-term performance of a geomembrane liner is governed by the local strain induced in the geomembrane, due to concerns about environmental stress cracking. The concept of limiting geomembrane strains is based on internal pressure creep tests carried out in Germany on pipes manufactured from the same High Density Polyethylene (HDPE) resins as geomembranes. Based on this work, the ‘Quo Vadis’ working group (Dixon & Von Maubeuge, 1992) decided that a value of 6% total elongation of a geomembrane is the maximum allowable for it’s satisfactory life-time performance. A safety factor of 2.0 was applied, thus setting a permissible total elongation of 3%. Allowing for strains induced by installation and long-term settlement of the sub-strata, the group set 0.25% local strain from the cylinder test as the limit. Clearly more research is required to establish a more rigorous scientific basis for defining this threshold.

The strains in geomembranes underlying geotextile protectors are now routinely assessed in Germany and the UK using the cylinder test first established by the “Quo Vadis” group, and subsequently formalised by the UK Environment Agency (1998). It is a design tool for the selection of an appropriate geotextile protector for site specific applications. The Environment Agency (EA) methodology was developed to provide consistency in the undertaking and reporting of the cylinder test, and has been adopted by testing houses and designers in the UK. The criteria employed to evaluate the performance of the geotextile are in terms of both damage and deformation of the geomembrane. The geotextile protection is adequate if there is: no damage to the surface of the geomembrane in terms of cracks, no sharp indentations, and local strains are less than 0.25%. Definition and measurement of local strain is critical to interpretation of the test results. The EA methodology defines local strain as ‘The difference between the deformed length of a straight line between two points on either side of a deformation and the undeformed length between the same two points, divided by the undeformed length’. Measurements are made for orthogonal axes through the three greatest indentations. The average strain for each axis is calculated, and these are the ‘local strains’. A full discussion of the EA methodology, including issues of local strain measurement and pass/fail criteria, is provided by Gallagher *et al.* (1999).

A good example of a site specific approach to protection geotextile design is given by Smolkin & Chevrier (1997). The authors present a case study of the design approach used for the selection of a needle punched non-woven protection geotextile in a Canadian landfill. A cylinder test was carried out on the proposed materials. Due to site specific conditions, post construction settlement was considered to be very small and therefore the 0.25% strain criterion was considered overly conservative. Smolkin & Chevrier (1997) report on an approach based on allowable long-term tensile stress based on the work of Berg & Bonaparte (1993) and an assessment of the long-term strains from Duval (1993). This approach resulted in allowable strains from the cylinder test of 1% to 2% being deemed acceptable.

4 MANUFACTURE OF NEEDLE PUNCHED NON-WOVEN GEOTEXTILE PROTECTORS

4.1 *The manufacturing process*

A manufacturer of needle punched non-woven geotextiles is essentially converting a raw material of short (staple) length fibres into a wide sheet and rolling these ready for use on site. The fibres are first opened out by a coarse combing method, then spread out on a bed and carded, or fine combed, to produce a thin sheet (or web) of fibres on a conveyor belt. This thin web is then laid in a concertina fashion using a computer controlled cross lapper across the required width of the geotextile, in order to form a thick cushion of fibre (a bat). The bat is then guided towards the first (tacker) loom and needled to form a sheet. The sheet passes through a second, up bunch, loom and a third, down punch, loom and is then rolled and bagged ready for dispatch.

4.2 *Designing a manufacturing plant*

As with all relatively new applications it is often the case that a product designed for one purpose is transferred for use in another. This is good from a commercial viewpoint as the potential market will increase and provide the company with greater diversity and less risk. However, this may not be best for the end user. The ideal situation would be to design a plant to meet the precise needs of the application.

It is worth considering the factors that control the design of a new plant specifically intended to produce needle punched non-woven geotextiles to meet the current market demands in landfill liner protection. To ensure market competitiveness the aim would be to produce a geotextile that meets the minimum performance criteria, and at minimum cost. The factors that have both performance and cost implication are:

- Fibre type – polymer, diameter, cross sectional shape, length, tenacity, crimp;
- Fibre blend – mixture of different types of fibre usually different diameters but could have more variations;
- Fibre lubrication – to reduce heating effect when needles pass through;
- Needle shape – length, cross sectional shape, cross sectional area, number of barbs, position of barbs;
- Needle density on board and needle pattern;
- Needling rate – often relating to three separate needle looms, two down punch and one up punch.

The two design criteria outlined in Section 3 could result in significantly different protection geotextiles being manufactured in order to meet the criteria (i.e. minimum unit weight or limiting geomembrane strains). An extreme example of a possible approach would be if plant was designed to produce geotextile with a given unit weight, at minimum cost. The following factors would be considered:

- Fibre type – cheapest polymer that could be needled, random mix of diameter, length, area, tenacity and crimp;
- Fibre blend – use either single diameter fibre or random waste fibre;
- Needle shape – cheapest to achieve minimum knotting of fibres;
- Needle density – as widely spaced as possible;
- Needle rate – as little as possible to achieve minimum knotting.

The end product would be an inconsistent geotextile that has low performance characteristics, but meets unit weight requirements. There would then be virtually no quality assurance needed. Although this type of approach is implicitly encouraged through design by unit weight, it is clearly unsatisfactory. Geotextile protection material must be designed based on performance criteria.

5 DESCRIPTION OF THIS INVESTIGATION

In order to assess the effect of unit weight on the protection performance of a needle punched non-woven geotextile, three materials of similar unit weights were subjected to both index and performance laboratory tests. The geotextiles used were:

- Geotextile A - high performance geotextile with a unit weight of 1000g/m^2;
- Geotextile B - medium performance geotextile with a unit weight of 1000g g/m^2;
- Geotextile C - Special production low performance geotextile with a unit weight of 1000 g/m^2 produced by light needling.

GEOfabrics Ltd, UK using the same machinery produced all three geotextiles. Geotextiles A and B are standard materials, however Geotextile C was produced specifically for this investigation. Samples were selected to have the same unit weight.

5.1 *Index testing*

A series of index tests was carried out on each of the three geotextiles as follows: Mass per unit area (BS EN 965); CBR puncture resistance (EN ISO 12236); tensile strength (EN ISO 10319); drop cone (EN 918) and thickness (EN 964-1:1965). These tests were carried out in order to categorise the three materials and it should be noted that the tests do not necessarily give an indication of the performance of the three materials on site. However, there is now good statistical evidence to suggest that the CBR puncture resistance represents the closest indication of the protection performance of a needle punched non-woven geotextile Shercliff (1998). This is likely to be related to the fact that in the CBR test the application of the force is in the same plane as drainage stone loading a geotextile protector in the field, and also because it takes into account the bending stiffness of the geotextile. These arguments will be expanded in Section 7.

5.2 *Performance testing*

To simulate site conditions more closely the static load test or “cylinder” test was used in accordance with the guidelines published by the UK Environment Agency (1998). The cylinder test consists of a 330 mm diameter segmental cylinder which has a lower plate supported by three load cells. On this plate a dense rubber pad is placed simulating a clay base. A lead tell-tale sheet is placed on the rubber to make a permanent record of geomembrane deformation. The site materials are then placed in order in the cylinder and a load is applied and maintained for 100 hours. The cylinder is then dismantled and the lead plate recovered. The three greatest indentations are measured and recorded as outlined in Section 3.

A specific UK landfill site was chosen as being typical of many in the UK. Materials used on this site included: 2 mm HDPE geomembrane liner, the geotextile protector, and a sub rounded split 10 to 20 mm flint drainage gravel. The grading curve for the drainage stone is given in Figure 1. Since the test was carried out at a temperature of at 20°C and was for a duration of 100 hours, a load simulating the depth of landfill (21 m) was multiplied by a combined factor of 2.5.

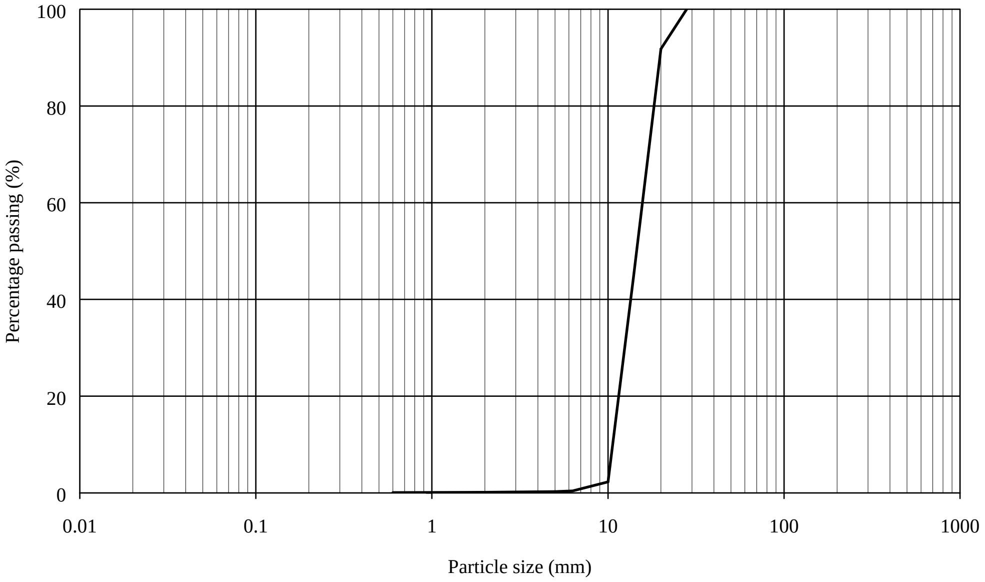

Figure 1. Particle size distribution results for the drainage stone.

6 RESULTS OF THIS INVESTIGATION

6.1 *Index testing*

The results of the index testing carried out are summarised in Table 1. The numbers presented are the mean of five individual tests carried out on each of the three geotextiles.

Table 1. Results of index testing.

Property	units	Geotextile Type		
		A	B	C
Mass per unit area	g/m^2	1,000	1000	1000
CBR puncture resistance	N	11,443	7,974	7,353
CBR displacement	mm	58	73	86
Tensile strength (MD)	kN	41	38	24
Tensile strength (XMD)	kN	110	78	66
Elongation (MD)	%	101	165	240
Elongation (XMD)	%	52	124	135
Cone drop perforation	mm	1.4	1.0	0
Thickness under 2 kPa	mm	6.22	7.14	11.35
Thickness under 200 kPa	mm	4.26	4.98	5.37

The results clearly show the difference in the mechanical properties of the three geotextiles. The CBR puncture resistance of Geotextile A is significantly higher than the values of the other two geotextiles. It is interesting to note that while the CBR puncture resistance of Geotextiles B and C are similar, the tensile strengths are significantly different.

If it is considered that the CBR puncture resistance is the best indicator of on site performance then it would be expected that Geotextile A would be considerably better than both Geotextiles B and C, and that the latter two would be similar. However, if it is postulated that the tensile strength in the machine direction gives the best indication of protection performance, Geotextile A would only marginally be better than Geotextile B, and Geotextile C would be significantly worse. However, it is interesting to note that there is a correlation between CBR puncture resistance and the tensile strength in the cross machine direction.

6.2 *Performance testing*

Once the cylinder tests were complete, the lead plate was examined and the three worst indentations were measured. As detailed in the testing procedure (Environment Agency, 1998) the mean strains were calculated for each of the three largest dents. The results are summarised in Table 2 in accordance of the EA methodology (1998). For comparison purposes it is acceptable to use the mean values of strain measured for the test on each geotextile. This produces mean % strain values of 0.10, 0.42 and 0.58 for geotextiles A, B and C respectively.

Table 2. Summary of performance testing results.

Mean strain per dent	Geotextile Type		
	A	B	C
Dent 1	0.11 %	0.54 %	0.79 %
Dent 2	0.10 %	0.40 %	0.66 %
Dent 3	0.09 %	0.33 %	0.30 %

7 DISCUSSION

7.1 *Test results*

It is clear from these results that field performance of the three geotextiles will differ. Cylinder testing of Geotextile A resulted in the lowest calculated strains and Geotextile C the largest strains. At present, the majority of the UK industry considers the pass/fail criterion to be 0.25 % (i.e. following the ‘Quo Vadis’ guidance), and this means that only Geotextile A would be suitable for this particular project. However, as discussed in Section 3.2, the pass/fail criterion is far from being certain.

Comparing the performance test results with those from the index tests, reveals that the CBR puncture resistance and cross machine direction tensile test results demonstrate the same trend (i.e. Geotextile A has a significantly higher value than B and C, with B higher than but closer to C). The machine direction tensile strength test produces only a small difference between A and B, while the cylinder test produces a significant difference. The main conclusion that can be drawn from the cylinder tests is that geotextiles with the same unit weight can exhibit markedly different protection performance.

7.2 *Inter- fibre friction theory*

It is proposed that the protection performance of a needle punched non-woven geotextile is strongly related to inter-fibre friction (Figure 2). The mechanism of loading a geotextile/geomembrane system can be considered to comprise of two stages; initial geotextile compression, and combined subsequent geotextile compression and geomembrane deformation. These two stages are shown in Figures 3 and 4. During the initial loading from the waste, the geotextile protector will compress (Figure 3). As this happens, two zones of influence are developed. Firstly, Zone 1 is located beneath the lowest part of the stone. In this zone, the geotextile fibres mat down during compression, and there is no re-alignment or development of inter-fibre friction, see Figure 5.

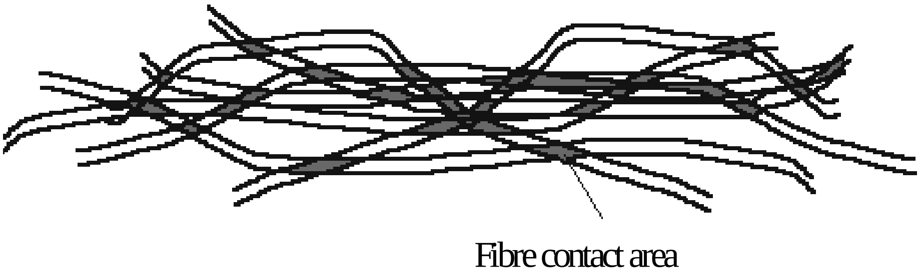

Figure 2. Schematic showing fibre contact area.

In areas surrounding the base of the stone (Zone 2), the vertical force from the waste can be resolved into components acting normal and parallel to the stone/geotextile interface. These result in shear forces being induced into the geotextile, and these will be transmitted into a combination of tensile forces along the fibres and frictional forces between fibres. The more force that can be distributed in this manner, the less compression the geotextile will undergo for a particular load.

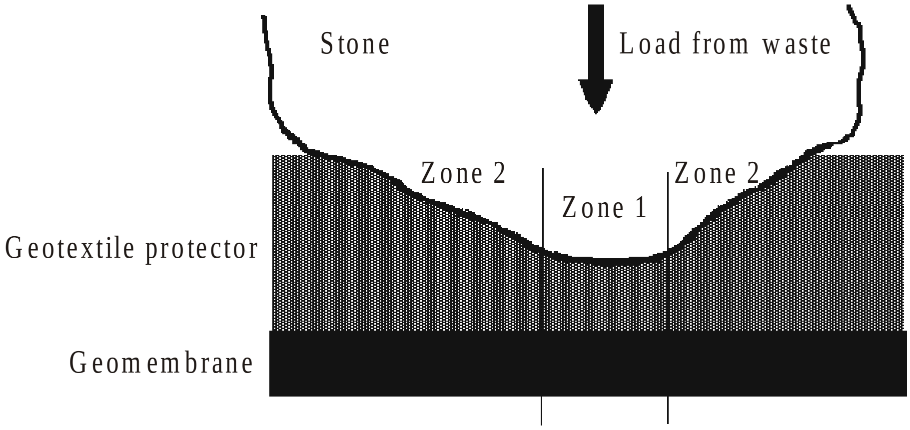

Figure 3. Stage 1 – Initial geotextile compression

Once the geomembrane beneath the geotextile begins to deform (Figure 4) additional frictional forces are generated at the geomembrane/geotextile boundary (Zone 3). The most efficient structure of geotextile fibres would be a matrix of stiff, high surface friction fibres intertwined such that a stone receiving a lateral load would transfer this load through the fibres to produce an evenly distributed load to the geomembrane.

The vertical and horizontal components of this load would be translated through the matrix of fibres. Settlements and strains would occur until equilibrium was reached, but their magnitude would be reduced. This model of geotextile behaviour under stone load would explain the observed correlation between performance and CBR puncture resistance. The proposed model can also be used to explain why unit weight can not by itself result in adequate protection performance.

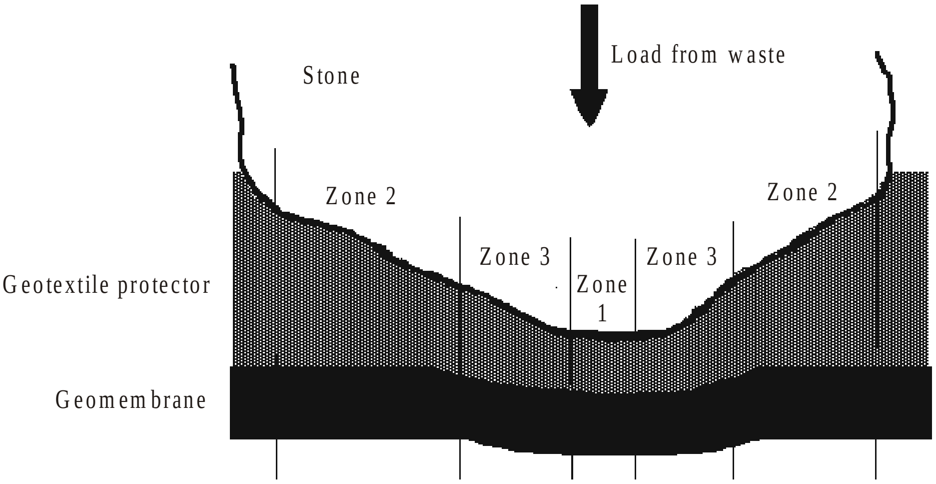

Figure 4. Stage 2 – Subsequent geotextile compression and geomembrane

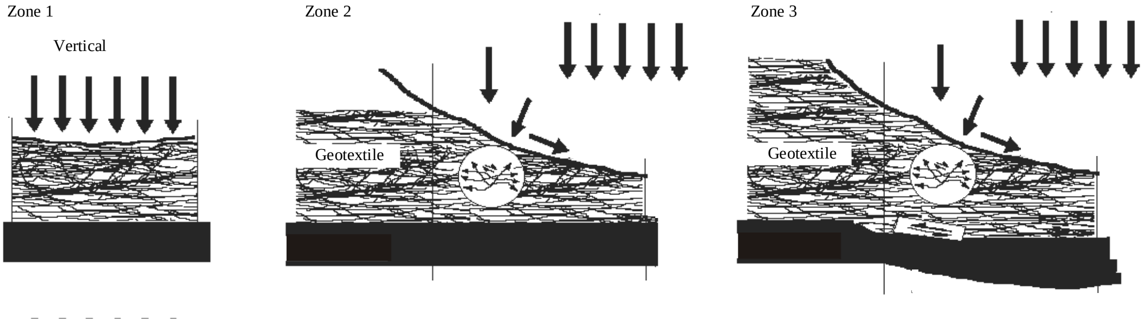

Figure 5. Schematic of the three zones of influence.

Use of poor quality fibres in conjunction with a minimum amount of needling, will produce a geotextile that can not generate significant tensile forces along the fibres or high friction between fibres. Hence, load will be transferred to the geomembrane, thus increasing strains. In addition, the loose assemblage of fibres means that large strains will be required to mobilise the tensile and friction fibre forces, and this will again lead to larger strains in the underlying geomembrane.

8 CONCLUSIONS

Selection of adequate geotextile protection for geomembranes is a fundamental aspect of landfill barrier design if the long-term integrity of these systems is to be ensured. Environmental stress cracking can occur in HDPE materials and therefore the strains in a geomembrane must be restricted to an acceptable level, although to date the value for the limiting strain is not known with any accuracy. The approach followed in the USA of only considering mechanical damage is highly questionable, and does not address the concerns regarding stress cracking.

Specifying geotextile protection layers by unit weight is inappropriate. Other factors such as fibre type and quality, and manufacturing method (e.g. type and amount of needling), have a controlling influence on performance. The investigation presented in this paper has clearly shown that three geotextiles with the same unit weight can exhibit significantly different performance. Of the index tests, CBR puncture resistance gives a better indication of protection performance than either unit weight or machine direction tensile strength, and is therefore a useful tool for comparing materials. However, an assessment of likely field performance can only be obtained in a test such as the cylinder test that incorporates site specific materials, and consideration of long-term loading and temperature effects. The role of fibre interaction is considered to be central to the performance of geotextile protection layers. Research is ongoing in this area.

The combination of specifying geotextiles by unit weight and only considering mechanical damage to the geomembrane, have important implications for the time dependent development of geomembrane strains, and hence failure, and the future development of geotextile products.

ACKNOWLEDGEMENTS

Thanks are due to Vince Caddick at GEOfabrics for carrying out the laboratory testing.

REFERENCES

EN 918. 1996. Geotextile and geotextile related products, Dynamic perforation test (cone drop test).

EN 965. Geotextile and geotextile related products, Determination of mass per unit area.

EN 964-1:1995. geotextile and geotextile related products, Determination of thickness at specified pressures part 1 – single layers.

EN ISO 10319. 1996. Geotextile and geotextile related products, Wide width tensile test.

EN ISO 12236. 1996/Geotextile and geotextile related products, Static puncture test (CBR test).

Berg, R.P. & Bonaparte, R. 1993. Long-term allowable tensile stress for polyethylene geomembranes. *Geotextiles and Geomembranes*, 12, pp. 287-306.

Dixon, J.H., von Maubeuge, K. 1992. Geosynthetic protection layers for the lining systems of landfills. *Ground Engineering*, December, 28-30.

Duval, D.E. 1993. Creep stress rupture of a polyethylene geomembrane under equal biaxial stress. *Proc. Geosynthetics* '95, IAFI, pp. 817-830.

Environment Agency 1998. A method for cylinder testing of protectors for geomembranes. *Environment Agency, UK*, pp. 61.

Gallagher, E.M., Darbyshire, W., Warwick, R.G. 1999. Performance testing of landfill geoprotectors: Background, critique, development, and current UK practice. *Geosynthetics International*, 6, 4, 283-301.

Narejo, D., Koerner, R.M. & Wilson-Fahmy, R.F. 1996. Puncture protection of geomembranes Part II: Experimental, *Geosynthetics International*, Vol. 3, No. 5, pp. 629-653.

Shercliff, D.A. 1996. Optimisation and testing of liner protection geotextiles used in landfills. *Geosynthetics: Applications, Design and Construction*, De Groot, Den Hoedt and Teraat (eds.), Balkema, Rotterdam.

Smolkin, P.A. & Chevrier, A.F. 1997. Design of geomembrane protection in landfills. *Proc. 50th Canadian Geotechnical Conference*.

Wilson-Fahmy, R.F., Narejo, D. & Koerner, R.M. 1996. Puncture protection of geomembranes, Part I: Theory. *Geosynthetics International*, Vol. 3, No. 5, pp. 605-628.