A more sustainable solution to geosynthetic products for short-term reinforcing applications

Martin Pritchard[1], Dave Allen[2]

[1] Reader, School of the Built Environment & Engineering, Leeds Beckett University, Leeds, LS2 8AG, United Kingdom.
[2] Operations Manager, MetLase, Advanced Manufacturing Park, Brunel Way, Catcliffe, Sheffield, S60 5WG, United Kingdom.

Keywords: Geosynthetics, Limited-life geotextiles, Renewable resources, Soil reinforcement, Vegetable fibres geotextiles.

ABSTRACT

It is now very difficult to find a construction site that does not utilise any geosynthetic products. Materials used in the manufacture of geosynthetics are primarily synthetic polymers – generally derived from the by-products of the oil industry. As a result of the finite nature of these raw materials and their associated pollution streams, there is growing pressure to use renewable resources for sustainable production. Also, the majority of geosynthetic applications are only required to perform for a short period of time, thereby leaving an alien residual in the ground for many years to come. Natural (vegetable) fibres provide a more sustainable alternative to polymeric based materials, particularly for short-term applications – termed limited-life geotextiles (LLGs).

This paper presents an overview of an extensive study that has been undertaken on the development of reinforcing LLGs manufactured from renewable and biodegradable vegetable fibres for short-term applications. Initially, structural form is considered. It is shown that LLGs can have tensile strength of up to 100 kN.m^{-1}, which is directly comparable to a mid-range geosynthetic product. The shear interaction properties of the LLGs was then compared to a number of different commercially available geotextile structures – manufactured from both natural and synthetic materials. The results demonstrate that coefficient of interaction values of around unity can be achieved with these LLGs. This is about 20–25% more shear resistance than their synthetic equivalent. The difference stemming primarily from the coarseness of the vegetable fibres themselves but also from the novel structural form. In terms of longevity, durability tests have been undertaken on the LLGs in various ground conditions. The data obtained indicate that degradation rates are sensitive to fibre type, together with the amount of water present in the soil. Coir fibre performed the best in worst deterioration environment tested. A simple basal embankment analysis is then presented to demonstrate a potential end application for the short-term reinforcing LLGs. In this analysis, it is shown that the rate at which the underlying embankment soil gains in effective stress, due to the dissipation of excess pore water pressure, could be designed to correspond to the decline in tensile strength from the degrading LLG.

1. INTRODUCTION

The construction industry over the last two decades has experienced a global boom. This has placed a large demand on natural resources. It is now very difficult to find a construction site that does not utilise any geotextile products; over the last decade the geotextile market has been one of the most thriving sectors in the technical textile industry. By the end of 2017 it is predicted that just over five billion square metres of geotextiles would have been produced, with an associated market value of around £7 billion pounds (GBP). Geotextiles are used, on a vast array of construction sites, to perform one of five primary functions, namely: drainage, filtration, protection (erosion control), reinforcement and separation. Depending on the application, these functions can perform in isolation or simultaneously.

The environmental effects of geotextiles manufactured from synthetic materials are twofold; firstly, for short-term application, an alien residue is left in the ground that will not biodegrade once the geotextile has served its purpose; secondly, and more indirectly, by polluting the environment through the process of obtaining the raw materials, i.e. burning and flaring of oil and gas. With the need to embrace more sustainable development to meet the triple bottom line on economic, environment and social security. It has now become imperative to use more environmental friendly resources to manufacture construction materials.

At present, limited-life geotextiles (LLGs) are constrained to woven and nonwoven grid structures, and their main use is for erosion control. They are manufactured from a small range of fibres, primarily jute and coir, as illustrated in Table 1. Jute is easy to cultivate, widely available on a commercial scale, cheap, biodegradable and can hold five times its own weight of water. All these factors (especially the last two) make it ideally suited for the initial establishment of vegetation, which in turn provides a natural erosion prevention facility. By the time vegetation has become well established the jute has started to rot/break down and disappear (6 to 12 months), without polluting the land. Coir has also been used as geotextiles, but not to the same extent as jute, for erosion control applications. However, in some circumstances, such as river bank protection, coir has been found to be more suitable than jute due to it being more resistant to rotting due to its high lignin content.

Table 1: Properties of commercial erosion control vegetable fibre geotextiles

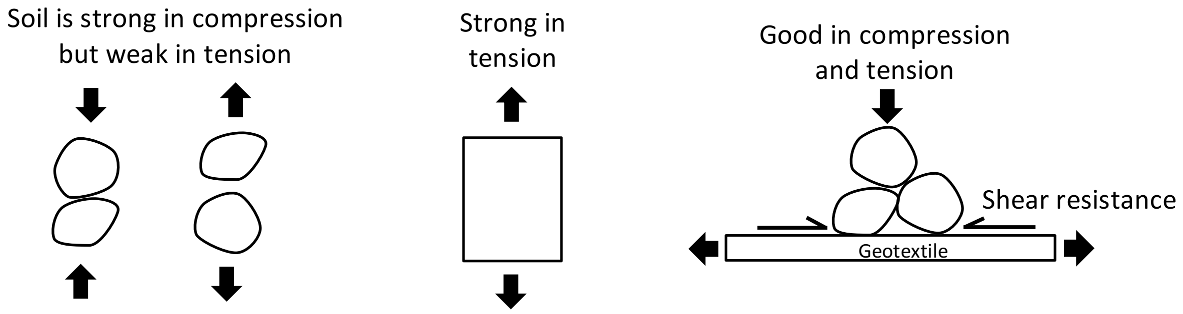
	Unit	Geo Jute	Geo Coir	Geo coir
Type		Woven	Woven	Nonwoven
Thickness	mm	3	5	12
Yarn count, warp	No.	78	130	–
Yarn count, weft	No.	42	70	–
Mass/unit area	$g.m^{-2}$	460	900	820
Open area	%	60	39	–
Wide width tensile, dry warp x weft	$kN.m^{-1}$	4.4 x 2.6	27.8 x 9.3	0.23 x 0.23
Wide width tensile, wet – warp x weft	$kN.m^{-1}$	1.8 x 0.9	21.4 x 6.8	–
Elongation at failure, dry – warp x weft	%	10 x 10	68 x 32	19 x 19
Elongation at failure, wet – warp x weft	%	11 x 11	82 x 49	–
Durability	years	1–2	5+	3

A pertinent factor for a geotextile, especially for reinforcement, is that it must possess a high tensile strength. The best way of obtaining this is for the fibres to have a high ratio of molecular orientation. This high strength ratio is achieved naturally by vegetable fibres, but for synthetic polymers the molecules have to be artificially orientated by a process known as stretching or drawing. It has been shown that flax, abaca and sisal fibres can have strengths in the range of 0.4 to 0.6 $N.tex^{-1}$, which is directly comparable to that of polyester of around 0.4 $N.tex^{-1}$ (Leflaive, 1988). Also, vegetable fibres are much coarser than their synthetic equivalent, inherently offering more shear resistance – another important characteristic for reinforcing geotextiles. Hence, nature provides ideal fibres to be used in short-term/temporary reinforcing applications – also termed vegetable fibre geotextiles (VFGs).

2. SOIL REINFORCEMENT

2.1 The concept

Soil is relatively strong in compression but weak in tension (Fig. 1a). The converse is true for a geotextile (Fig. 1b). Therefore, if they are used in intimate association with each other a composite material can be formed, which is good in both compression and tension (Fig. 1c). If this concept is then applied to an unreinforced soil mass, it can be shown that when a normal load is applied, the soil tries to deform laterally (Fig. 1d) as the soil particles cannot take any tensile load. However, when a geotextile is installed at vertical increments within the soil mass, and there is sufficient shear resistance along the soil/geotextile interface, the tensile load will be taken by the geotextiles. Effectively, this provides an in-built lateral confining stress which prevents deformation (Fig. 1e). This reinforcing soil concept can be extended to slopes and embankment stabilisation.



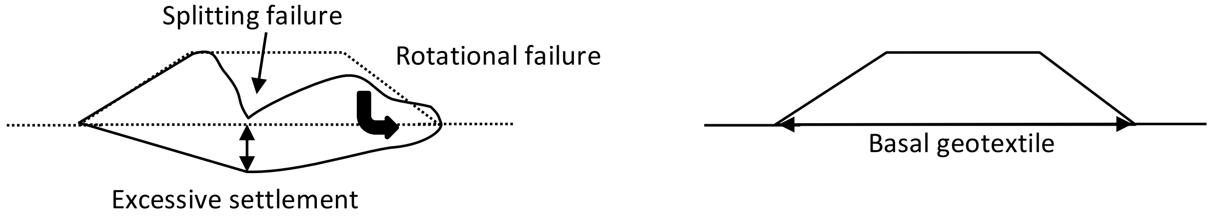
(a) Soil particles (b) Geotextile (c) Composite material

(d) Unreinforced element of soil deforms (e) Reinforced element of soil

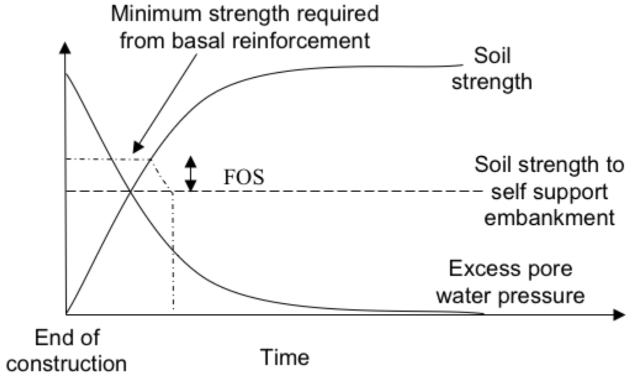
Figure 1: The concept of reinforced soil

2.2 Short-term application

Short-term reinforcing applications are frequently used to provide temporary support to engineered structures until excess pore water pressure has dissipated and the soil has consolidated. Typically, the geotextile only has to function during construction and for a short period afterwards. An example of such an application is basal reinforcement. When an embankment is constructed over soft compressible ground, the load from the embankment fill increases the pore water pressure in the underlying soil, especially at the centre of the embankment. This corresponds to a decrease in the shear strength of the underlying soil and can result in the embankment failure, e.g. splitting, circular rotation and excessive settlement (Fig. 2a). However, when a basal geotextile is used at the interface between the embankment fill and underlying soft soil, the restraining lateral load provided by the geotextile prevents the embankment from splitting or introduces a moment to resist rotation (Fig. 2b). Settlement can still be extensive in the underlying soil; the geotextile will however ensure it will be more uniform. This type of settlement can be compensated for during construction. The stability of the embankment will improve in time as the excess pore water pressure in the underlying soil dissipates. Effective stress will then prevail resulting in the stabilising force from the basal reinforcement being surplus to requirements. Typically, this timescale could be anywhere from a few months up to a few years but would ultimately depend on such factors as coefficient of vertical consolidation (c_v) of the underlying soil and length of the drainage path. To increase the rate of dissipation fin drains are typically installed. It is proposed this rate in soil strength gain can be design to correspond to the deterioration rate of the basal LLG with an appropriate factor-of-safety (FOS) being maintained (Fig. 2c).



(a) Failures (b) Reinforced embankment



(c) Soil strength/pore water pressure relationship for an embankment immediately after construction

Figure 2: Basal geotextile

2.3 Durability

The deterioration of any material is the influence the environment has on the properties with the passage of time; this is particularly true for natural materials, such as LLGs. There are numerous factors, which could affect the ageing process such as chemical (acid and alkaline) and biological (microorganisms) deterioration. The main question is how long a particular material can withstand the given degradation process, whilst maintaining the requisite properties throughout its design life. The answer is ultimately related to the hostile environment it is placed in and the chemical composition of the geotextile material.

2.4 Shear interaction

The shearing resistance at the soil/geotextile interface is extremely important to enable the soil to transmit the tensile forces from the soil to the geotextile such that the soil/geotextile composite is effective. The frictional resistance provided by the fabric structure is associated with the surface roughness features of the geotextile, i.e. soil sliding and the capability of the soil to embed the fabric. The latter is related to the geotextile's apertures relative to the particle size of the soil, which influences both bond and bearing resistance as shown in Figure 3. Bond resistance is developed when soil particles embed within the geotextile to retain soil particles in the apertures, such that adjacent soil above and below the geotextile surface are sheared against these retained particles. In comparison, bearing resistance emanates from restrictive movement of soil particles due to ridges in the geotextile surface, or at the end of the apertures, in the direction of shear.

The coefficient of interaction ($\propto$) is used to determine the efficiency of geotextiles in developing shearing resistance. The value is defined by the ratio of the friction coefficient between soil and geotextile ($\tan \delta$) to that of the friction coefficient for soil along ($\tan \phi$), as given in BS 6906: Part 8 (1991). Values for the coefficient of interaction typically range between 0.6 and 1 are often quoted (Richards and Scott, 1985). The widespread range is a result of such variants as the different soil strengths, geotextile types and the test method employed to derive the value.

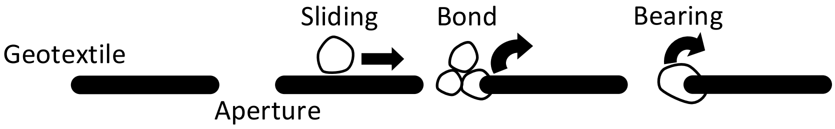


Figure 3: Shear forms of resistance along the surface of a geotextile

3. RESEARCH REVIEW AND METHODOLOGY

Processes for the selection, specification, production and utilisation of synthetic geotextiles are well established for soil strengthening applications. To-date, the use of vegetable fibres for soil reinforcement has not been investigated in depth because of preconceived ideas concerning the durability, strength, extensibility and manufacturing capability of these natural materials. Their use has therefore been confined to erosion control applications. There are however many ground engineering situations where reinforcing geotextiles are only required to function for a limited time period; whereas suitable synthetics have working lives longer than needed. Hence, are over designed but more importantly the manufacture and use of synthetic materials cause many forms of environmental pollution. From the wealth of knowledge available relating to the use of synthetic geotextiles within soil it is already known what should be expected from reinforcing LLGs; however, they have yet to be made, tried and tested.

The main aims for this work were to develop the technology appropriate for production of 'designer' LLGs for reinforcing applications; to characterise their behaviour; and, determine the extent to which they can be used to strengthen soil. The principal factors affecting the suitability of these LLGs can be identified as manufacturing feasibility, tensile properties, soil/geotextile interaction and durability. To be usable these materials must satisfy/fulfil all of the foregoing criteria to some degree. Therefore, the overall approach of this study was not to 'design' and 'test' for a specific reinforcing application, but to determine whether acceptable balances of properties and performance can be achieved. A potential use of a LLG for a short-term reinforcing application is then concluded, in this paper, by the development of a computational finite difference model. The aim of this model is to illustrate how effective stress conditions will govern in time as the excess pore water pressure dissipates. Hence, providing the timeframe the underlying embankment soil will become self-supporting without the need of a basal reinforcing geotextile.

4. RESEARCH METHOD

To enable a direct comparison with the novel LLGs developed as part of this research work, a commercially available woven coir geotextile (used for erosion control applications) and a warp knitted polyester grid (used for reinforcing applications) were also tested under the exact same conditions.

4.1 Structural form

The first aim of this research work was to develop a novel 'designer' geotextile structure made from vegetable fibres which would be suitable for reinforcing applications. This is because at the present time the range of LLGs is very limited, in that their main use is for erosion control. The principal criterion sought of the geotextile for erosion control is to have sufficient tensile strength to allow it to be laid on site and to provide, for a limited time only, some protection to the ground e.g. retain soil particles, protect grass seeds, hold water, etc. LLG structures for erosion control applications have been mainly plain weave jute or coir. Nonwoven structures made from jute, coir and flax have also been used for mulching applications. Both of these types of structures have their limitations (woven structures exhibit high elongation and nonwoven structures have low strength together with high elongation) and are unable to form geotextiles with the properties and flexibility possessed by knitted structures, particularly directionally structured fabrics (DSF). These fabrics incorporate high strength straight inlaid yarns to provide high uniaxial strength in the machine (warp) direction (Rankilor and Raz, 1994a–d).

Due to the coarseness and lack of pliability of vegetable fibre yarns, it prevents them from being used on warp knitting machines. Weft knitting machines are however capable of handling a much wider range of yarns types. The limitation of these machines, nevertheless, is that they cannot incorporate high strength inlay yarns in the machine direction due to the design of the mechanism which links the carriages on both beds. The initial aim of the research project was therefore to redesign this mechanism rather than constructing a completely new machine, as this would keep the costs low and enable the LLG to be mass produced very quickly. Thus, the LLG structure was designed to be manufactured with the following characteristics to reinforce soil:

1) The highest possible strength in one direction, together with low elongation combined with the ease of handling and laying on site.
2) Soil particle interlock and sliding resistance with the geotextile to such an extent that the soil/geotextile interface exhibits the same shearing resistance as the surrounding soil i.e. the soil/geotextile coefficient of interaction is in the order of unity.
3) A degree of protection to the high strength inlaid yarns to reduce installation damage.
4) Sufficient durability (with respect to degradation when buried in soil) to provide reinforcement over the requisite design life of the construction.

4.2 Tensile strength

A tensile testing apparatus was used to determine the tensile properties of the geotextiles. Output of load and extension was data logged to an accuracy of 10 data points every second. The overall dimensions (including apertures and abutments) of the samples were determined manually – the thickness was determined from the 'Shirley Thickness Gauge' using a circular plate 80 mm in diameter under a 1000 g weight. The tensile tests were conducted at the standard testing temperature and relative humidity of 20 ± 2°C and 65 ± 2% respectively BS 1051 (1972). The samples were also conditioned, at this temperature and humidity, for at least 24 hours before testing so that each sample was in a comparable state for testing. A gauge length of 200 x 50 mm was used as in BS EN ISO 13934-1, 1999 (strip method). As also recommended by standard five samples were tested in the strength (machine or warp) direction at a constant strain rate of 100 ± 10 mm per minute.

4.3 Coefficient of interaction

The geotextiles were tested in a 300 x 300 mm (plan dimensions) partially fixed direct shear box. The leading side of the lower shear box had the geotextile clamped to it. The geotextile was then laid over the lower half of the shear box containing the Leighton Buzzard sand (LBS), which was flush with the top of the lower shear box. A hydraulic ram was used to apply a vertical load and a load transducer measured the applied pressure, enabling a direct measurement of the vertical stress to 0.5 $kN.m^{-2}$. It was also possible to keep the normal stress constant, whilst the sample was dilating, by the load transducer. A 100 kN capacity proving ring was used to measure the shear force and this enabled the shear force to be recorded directly to 0.08 N (equivalent to a shear stress of 0.9 $kN.m^{-2}$). The relative horizontal displacement of the two halves of the shear box, the change in sample height during shearing and the vertical displacement of the top four corners of the upper half of the shear box were monitored by linear dial gauges reading directly to 0.01 mm. The tests were conducted at a strain rate of 0.3 mm per minute, up to 40 mm horizontal displacement.

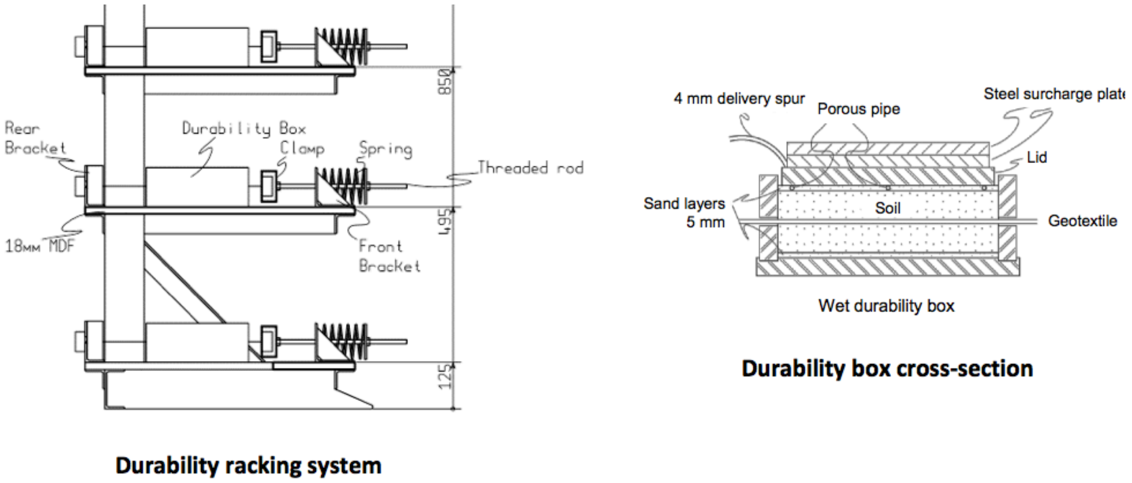
The upper and lower halves of the shear box were each compacted in three layers of equal thickness using a vibrating hammer and tamping plate to a predetermined thickness to produce nominal unit weight of 96% of the maximum nominal dry unit weight for the compacted LBS. This figure was chosen to represent the density likely to be achieved on site, whilst maintaining an accuracy of ±0.01 Mg.m^{-3} from the mean dry density in subsequent shear box tests, as recommended by BS 6906: Part 8 (1991).

Nominal effective normal stresses of 41, 68, 95 and 123 kN.m^{-2}, to represent the likely range of soil pressures which would apply to field situations, were applied to the samples. These represented the actual weight above the shear plane, i.e. the applied pressure plus the weight of the soil in the upper-half of the shear box, the upper-half of the shear box itself and the top platen.

The LBS was sheared with no geotextile in the shear box (referred to as 'plain' sand) to establish a datum. This enabled a direct comparison to be made when each of the geotextiles were sheared with the LBS, hence allowing their corresponding value of $\propto$ to be computed.

4.4 Durability tests

The durability of any geotextile product buried in the ground is of paramount importance, especially so for biodegradable vegetable fibre products. Physical and chemical deterioration conditions are commonly simulated in the laboratory under separate conditions. It is however recognised (Horrocks, 1996) that, in combination, these two effects can have a more detrimental impact on the product's lifespan. To replicate this, a novel testing rig was designed and manufactured (Fig. 4). This enabled the geotextile structures to be encapsulated in the test soils whilst subjecting them to both a tensile and confining load in a controlled environment. After set periods, the deteriorating samples were taken out of the soil and tested to determine the percentage loss in tensile strength.



Durability racking system

Durability box cross-section

Figure 4: Durability test rig

The test rig consisted of the durability boxes positioned on a loading frame; all of which were housed in a controlled room which had a temperature and relative humidity of 20–22 °C and 60–65% respectively, in accordance to BS EN 12224 (2000). Each box was designed to contain three strips of geotextile surrounded by 35 mm of soil. The geotextile strips encapsulated in the soil were 50 mm wide by 200 mm long, which is in accordance with BS EN ISO 13934-1, 1999 (strip method).

Each geotextile strip was loaded by a spring mechanism via a bracket fixed to the racking system to 5% of the geotextile's maximum strength. The spring was adjusted at regular intervals to compensate for any creep in the geotextile, hence maintain a constant load. To ensure soil/geotextile contact throughout the test period an effective normal stress of 2 kN.m^{-2} was applied as a surcharge on the box lid. To simulate natural weathering conditions (i.e. wetting/drying cycles) that occurs in-situ during installation and over the working life of geotextile products, an irrigation system was used to saturate the soil contained within the durability boxes every 14 days.

5. RESULTS & DISCUSSION

5.1 Structural form

Modifications were carried out using a mechanically operated Dubied DC-2 5-gauge V-bed weft-knitting machine to produce a novel base structure (Patent No. GB 2339803). The main modification to the machine involved removing the bow linking the front and rear carriages as this prohibited vertical inlay. The purpose of the bow was to maintain the synchronisation of the front and rear carriages as they traverse the needle beds. The front and back carriages now being connected by two endless chains connected via a series of double and single sprockets positioned at both ends of the machine.

In reference to the manufacturing design characteristics noted in Section 4.1, variations of this base structure were then developed to provide the specific properties required from geotextiles to strengthen soil, essentially:

1) The geotextile was designed to have the highest possible number of straight high strength inlay yarns in one direction, with the base fabric structure, made from thinner more flexible weaker/cheaper yarns, holding the inlay yarns in place.
2) Coarse yarns together with abutments and apertures in the geotextile were created to produce high shear resistance in the machine direction.
3) A sacrificial base structure, formed from a cheaper more degradable yarn, was used to encapsulate the high strength yarns. By providing protection to the high strength inlay yarns the necessity to introduce a large reduction factor into the design, to account for installation damage from certain types of fill/plant, is minimised.
4) To achieve different durability rates high strength inlay yarns could be wholly or partly changed for a more durable yarn in aggressive ground conditions.

Figure 5 illustrates the base structure that was developed to address the above manufacturing design characteristics. Essentially the structure is a directionally structure 1x1 knitted rib, with alternate wales of face loops on each side. The inlay yarns are encapsulated within the knitted structure by the cross meshing between the face and reverse wale loops. This ensures the structure remains flat when cut and has a good resistance to tear. Variations in both the inlay and knitting yarns were possible. To reduce the number of variables, three combinations of the base knitted structure were used in this testing programme, namely: (1) sisal inlay/knitted flax; (2) sisal inlay/knitted jute and (3) jute inlay/knitted flax. Table 2 summarises the fabric characteristics of these novel LLGs together with the two commercially available geotextiles (4 & 5).

Figure 5: Sisal inlay/knitted flax 1x1 rib base structure

Table 2: Fabric characteristics of the geotextiles

No.	Material	Inlay yarns per m	No. of courses per cm	No. of Wales per cm	Stitch density cm^2	% inlay yarn	% knitting yarn
1	Sisal inlay/knitted flax	110	8	4	32	52	48
2	Sisal inlay/knitted Jute	110	8	4	32	53	47
3	Jute inlay/knitted flax	110	8	4	32	40	60
4	Woven coir	90	0.9*	0.8$^{\#}$	N/A	59	41
5	Warp knitted polyester grid	80	6	0.8	N/A	98	2

* No. of warp yarns per cm $^{\#}$ No. of weft yarns per cm

5.2 Tensile strength

Figure 6 shows the ultimate tensile strength of the five geotextiles tested in the machine (warp) direction, with corresponding values shown in Tables 3. The main parameters under consideration are the load the geotextiles can take for every given metre (kN.m^{-1}) and the percentage strain resulting from the load.

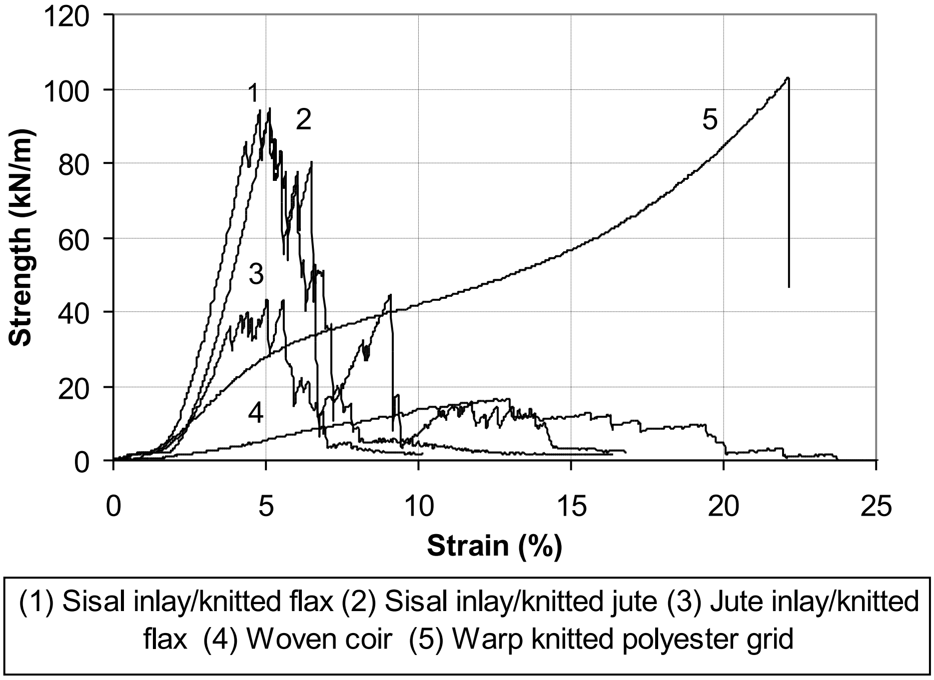


Figure 6: Tensile strength properties of five geotextiles

Table 3: Physical properties of the five geotextiles

No.	Material	Tensile strength kN.m^{-1}	Strain %	Elastic modulus kN.m^{-1}	Mass g.m^{-2}	Thickness mm
1	Sisal inlay/knitted flax	97.6	5.0	19.35	1380	5
2	Sisal inlay/knitted Jute	97.4	5.3	18.52	1310	5
3	Jute inlay/knitted flax	43.8	5.4	8.18	1180	5
4	Woven coir	16.6	13.2	1.26	900	4
5	Warp knitted polyester grid	106.2	22.0	4.83	430	1.5

It can be seen that the tensile strength of sisal inlay geotextiles (1 & 2) are comparable to the warp knitted polyester geotextile (5). The jute inlay geotextile (3) has approximately 50% of the strength of sisal. Woven coir (4) is the weakest of the geotextile materials tested with only 20% of the tensile strength of sisal (1). This is due to the fact that coir is weaker as a result of its chemical composition and this fabric structure has less inlay yarns to carry the load. On examination of the plot, sisal and jute fail in the same manner. A 'saw toothed' failure mode was created as individual inlay yarns break and the load is passed to the remaining yarns. The warp knitted polyester and woven coir geotextiles have significantly higher ultimate strain capacities, which would ultimately result in more unfavourable deformation in the reinforced structure.

5.3 Coefficient of interaction

The coefficient of interaction is dependent on both the geotextile and soil type. Ideally the coefficient should be as close to one as possible. From the LBS shear interaction results (Fig. 7 and Table 4), coir had the highest coefficient at 0.99 and the synthetic geotextile had the lowest at 0.80. The structures manufactured from sisal, jute and flax were all found to have coefficients in the range of 0.91–0.97.

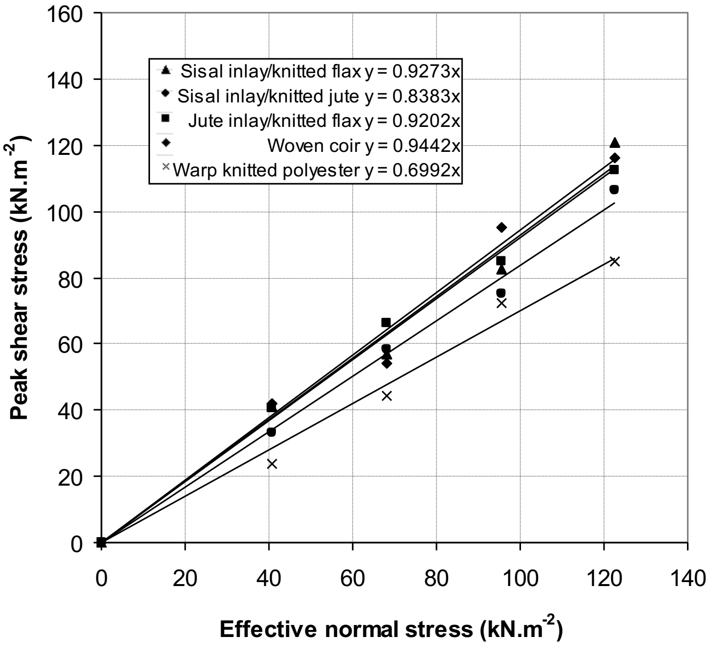


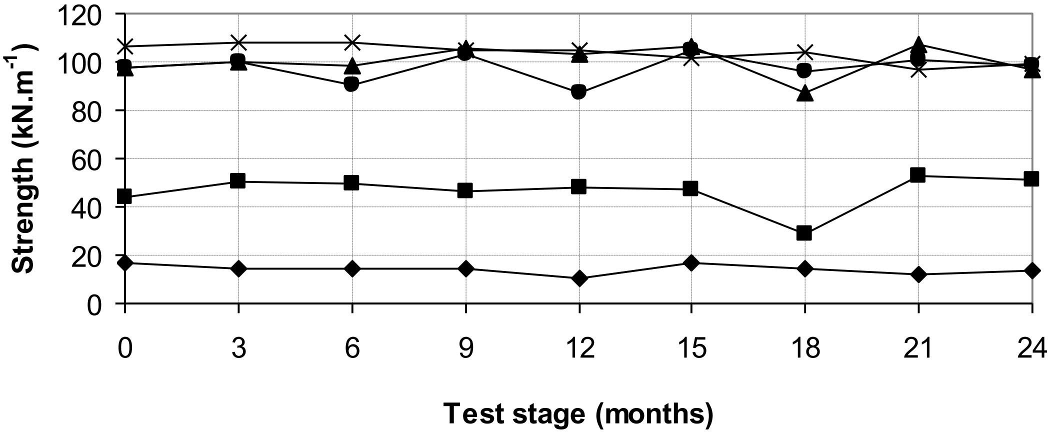
Figure 7: Interface LBS–geotextile frictional values

Table 4: Shear strength characteristics

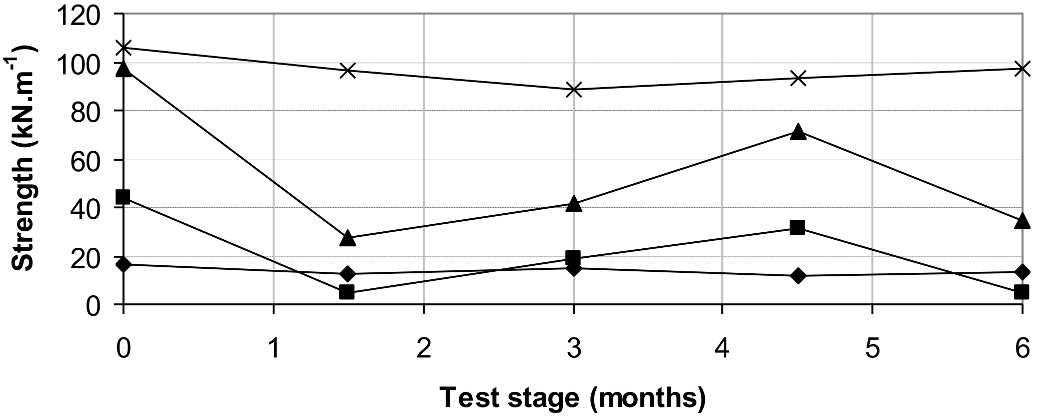
No.	Material	Peak angle of bond friction (°) Φ'_p	Coefficient of interaction α
	LBS – LBS (no geotextile)	44.0	1.00
1	Sisal inlay/knitted flax – LBS	42.8	0.97
2	Sisal inlay/knitted jute – LBS	40.0	0.91
3	Jute inlay/knitted flax – LBS	42.6	0.97
4	Woven coir – LBS	43.4	0.99
5	Warp knitted polyester grid – LBS	35.0	0.80

5.4 Durability tests

Figure 8a shows the results from the tests carried out at the soils natural moisture content of 0.1% (termed dry). The results indicate that no reduction in tensile strength occurs with time. This was anticipated as no real moisture is present to sustain a microbial community.



(a) Dry durability boxes



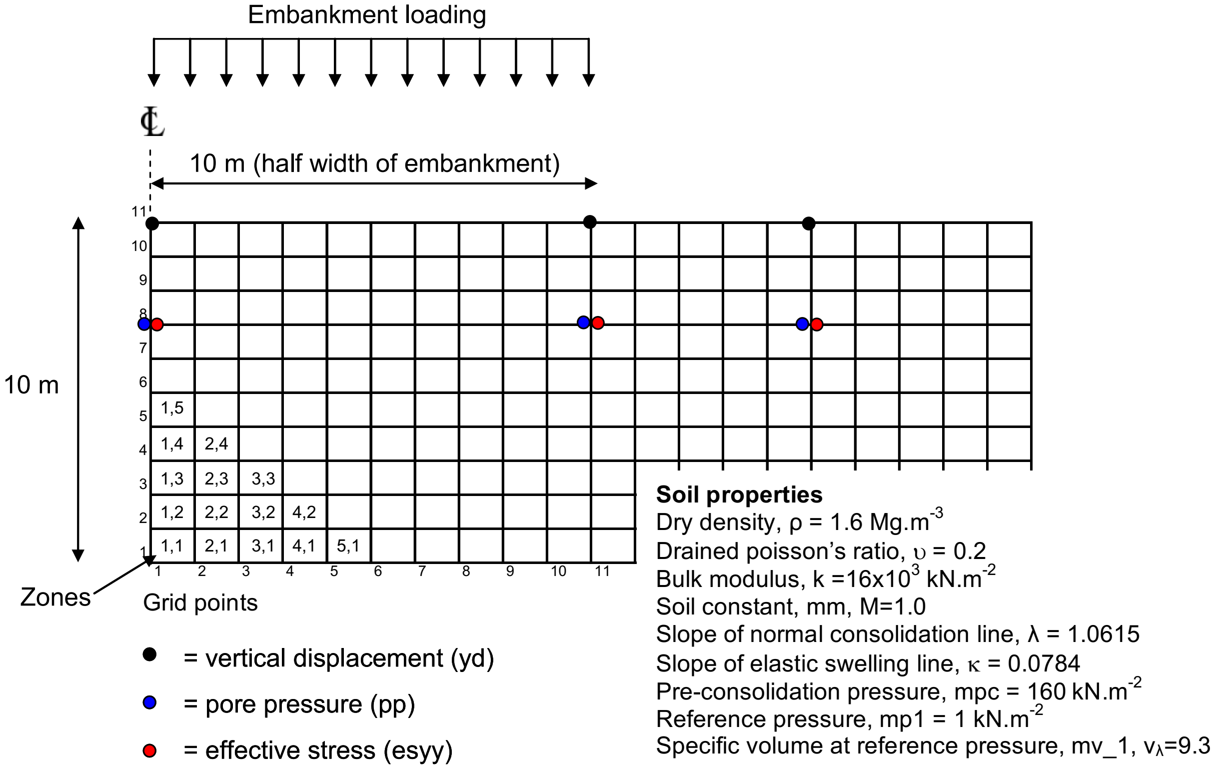
(b) Wet durability boxes

Figure 8: Geotextile strengths – durability boxes

Figure 8b shows that over the test period there were significant initial reductions in tensile strength of both the sisal and jute inlay geotextiles. After 1½ months the jute inlay geotextile had only retained about 11% of its initial strength. The sisal inlay geotextile performing slightly better, retaining 28%. The behaviour of the geotextiles at 3 and 4½ months did not however fit a logical deterioration trend, but at 6 months the geotextile had not really lost any further strength. The overall reductions of around 70% and 90% for sisal and jute inlay geotextiles were obtained at the end of the testing period respectively. After an initial reduction in strength, the woven coir geotextile retained on average 82% of its initial strength throughout the duration of the test period. This is related to its high lignin content, which is difficult to break down and can persist for years in soil (Gray and Williams, 1971). The synthetic grid also appears to have lost on average 9% of its initial strength over the testing period.

6. EMBANKMENT ANALYSIS

A numerical example is presented below to illustrate how the soft underlying soil gains in strength over time; hence, demonstrating that a basal geotextile would only be required for a limited time period. The finite difference software package that was used to develop a numerical solution was FLAC, which stands for Fast Lagrangian Analysis of Continua. This software package was developed by the Itasca Consulting Group, Inc. In this model, the foundation soil was 10 m deep and groundwater was at ground level. The analysis was simplified by taking into account half symmetry and using an applied surcharge to simulate embankment loading (Fig. 9).

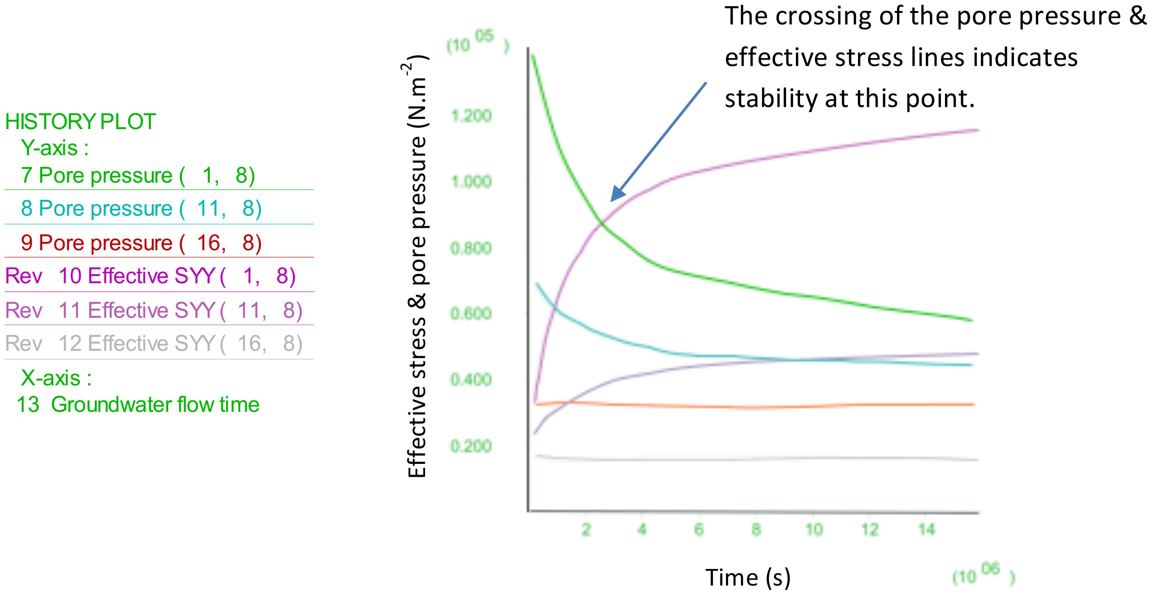


Soil properties
Dry density, ρ = 1.6 Mg.m^{-3}
Drained poisson's ratio, υ = 0.2
Bulk modulus, k =16x10^{3} kN.m^{-2}
Soil constant, mm, M=1.0
Slope of normal consolidation line, λ = 1.0615
Slope of elastic swelling line, κ = 0.0784
Pre-consolidation pressure, mpc = 160 kN.m^{-2}
Reference pressure, mp1 = 1 kN.m^{-2}
Specific volume at reference pressure, mv_1, v_λ=9.3

Figure 9: Model parameters

Surcharges relating to embankment heights of 3, 6 and 9 m were considered, and these were modelled as being applied instantaneously. The underlying soil was modelled as a Cam-clay material, using the properties shown on Figure 9. Mechanical boundary conditions corresponded to fixed ‘x’ and ‘y’ displacements along the base of the grid to simulate a ridged base and roller boundaries along both vertical boundaries so that displacements are unrestricted. As the lower boundary was considered impermeable, drainage occurred only at the soil surface. During computational run the pore water pressure, effective stress and displacements in the soil were monitored at the three locations shown on Figure 9, i.e. at centre, toe and outside the embankment, with associated grid points 1,8; 11,8 and 16,8 respectively.

Figure 10 contains a combined plot of pore water pressure and effective stress for the three locations considered for the simulated embankment at 3 m high (similar plots were obtained for the other heights). The monitoring of pore water pressure showed that over time the excess pore water pressure generated by the simulated embankment load dissipated. As this occurred, the effective stress increased illustrating the fact that the soil gained strength as consolidation and drainage took place. The point at which the effective stress line crosses the corresponding pore pressure line, indicates that the soil at this location has gained sufficient strength to become stable. Hence, sufficiently strong to support the embankment without the need of a basal reinforcing geotextile. As further drainage/consolidation occurs, an equivalent improvement in stability is achieved. The time taken for this to occur, i.e. when effective stress equals pore water pressure, is summarised in Table 5 for the different simulated embankment heights.



The crossing of the pore pressure & effective stress lines indicates stability at this point.

Figure 10: Pore water pressure and effective stress plots for a 3 m high embankment

Table 5: Stability results for various embankment heights

	Centre		Toe	
Height (m)	Time (days)	Effective stress = pore pressure (kN.m^{-2})	Time days	Effective stress = pore pressure (kN.m^{-2})
3	20	44	14	31
6	27	65	102	36
9	30	88	104	480

For the 3 m high embankment, stability is achieved in 20 days at the centre of the embankment, and 14 days at the toe. As embankment height is increased the time for stability also increases. In addition, the time to reach stability at the toe becomes the controlling factor for embankments over 3 m. This is due to the pore water migrating through the underlying soil to extremities of the embankment. Thus, the soil at the toe of the 9 m took the greatest amount of time to stabilise – being just over three month (i.e. 104 days). In reality, some form of safety factor would also be accommodated within the design. This will result in the stability of the underlying soft soil occurring just after the crossing of the effective stress and pore pressure lines (as illustrated diagrammatically in Figure 2). As noted in Section 2.2, the installation of fin drains in the underlying soft soil would increase the rate of pore pressure dissipate. The underlying soil would then take less time to stabilise, permitting the design life of the LLG to be relatively short.

7. CONCLUSION & RECOMMENDATIONS

As part of this research project a novel directionally structured weft knitted vertical inlay geotextile structure was manufactured from various vegetable fibres for short-time soil reinforcement applications. This structure was principally design to have the highest possible strength in one direction, together with providing good soil/geotextile shear interaction.

In terms of:

- **Tensile strength**, the novel sisal inlay LLGs were directly comparable to a mid-range geosynthetic product tested under identical conditions; with strength values of around 100 kN.m^{-1}. Also, the novel LLGs were up to six times stronger than the commercially available woven coir geotextile, currently used for erosion control applications.
- **Shear resistance**, all the LLGs tested outperformed the synthetic geotextile; offering between 20 and 25% more shear resistance.
- **Durability**, coir fibre retained the highest degree of strength (i.e. just over 80% of its initial strength) when subjected to the worst deterioration environment under consideration, i.e. cycles of wetting/drying.

From the simplistic finite difference embankment analysis, it has been shown that the timescale for effective stress conditions to govern ranged between 20–30 days at the centre of the embankment to 14–104 days at the toe, depending on the height of the embankment under consideration. Potentially, this gain in strength timescale could be design to correspond to the decline in tensile strength of the reinforcing LLG.

It is recommended that a hybrid of the novel LLGs is manufactured and tested, containing both sisal and coir inlay yarns. The sisal yarns providing high initial strength, whilst the coir yarns providing longevity. Also, an instrumented site trial to physically test the performance of these LLGs in a natural environment would be extremely beneficial to actually determine their suitability and performance in-situ.

Although vegetable fibres have always been available no one visualised their potential as a form of geotextile until synthetic fibres enabled diverse use and applications for geotextiles to emerge. The key to developing geotextiles from vegetable fibres is the concept of designing by function, i.e. to identify the functions and characteristics required to overcome a given problem and then manufacture the product accordingly. Provided the function can be satisfied technically and economically then these can compete with synthetic materials and in some situations, they will have superior performance to their artificial counterparts as well as being far more sustainable.

REFERENCES

BS 6906:8 (1991) **Determination of sand-geotextile frictional behaviour by direct shear**. British Standards Institution, Milton Keynes.

BS 1051 (1972): **Glossary of Terms Relating to the Conditioning and Testing of Textiles**. British Standards Institution, Milton Keynes.

BS EN ISO 13934–1, (1999) **Determination of maximum force and elongation at maximum force using the strip method**. British Standards Institution, Milton Keynes.

BS EN 12224 (2000) **Geotextiles and geotextile-related products. Determination of the resistance to weathering**. British Standards Institution, Milton Keynes.

BS EN ISO 13934–1 (1999) **Determination of maximum force and elongation at maximum force using the strip method**. British Standards Institution, Milton Keynes.

GB 2339803 (2002) **Directionally structured fibre geotextiles**. Patent, October.

Gray, T.R.G. & Williams, S.T. (1971) **Soil microorganisms**. University reviews in botany. Oliver & Boyd, Edinburgh.

Horrocks, A.R. (1996) **The Effects of Stress on Geosynthetic Durability**. Proceedings of the First European Geosynthetics Conference Geosynthetics Applications Design and Construction, Maastricht, Netherlands, 30th Sept. to 2nd Oct., pp. 629–636.

Ingold, T.S. (1994) **Geotextiles and geomembranes manual**. Elsevier science, Oxford.

Leflaive, E. (1988) **The use of natural fibres in geotextile engineer**. Proceedings of the 1st Indian geotextiles conference on reinforced soil and geotextiles, New Delhi, India, Indian Geotextiles Society, Bombay, pp. 81–84.

Rankilor, P. (1994) **UTF Geosynthetics manual: A technical manual for the design of UFT geosynthetics into civil and marine engineering projects**. UCO technical fabrics, Belgium.

Rankilor, P.R. and Raz, S. (1994a) **Geotextiles and knitted structures – III**. Man-made Textiles in India, Nov. pp. 493–497.

Rankilor, P.R. and Raz, S. (1994b) **Geotextiles and knitted structures – I**. Man-made Textiles in India, Sept., pp. 409–412.

Rankilor, P.R. and Raz, S. (1994c) **Geotextiles and knitted structures – IV**. Man-made Textiles in India, Dec., pp. 531–534.

Rankilor, P.R. and Raz, S. (1994d) **Geotextiles and Knitted Structures – V**. Man-made Textiles in India, Jan.

Richards, E.A. and Scott, J.D. (1986) **Stress-strain Properties of Geotextiles**. Third International Conference on Geotextiles, Vienna, Austria, Vol. III, pp. 873–878.