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Matching performance requirements to product properties for a new range of geogrid reinforcements

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ABSTRACT: Geogrid reinforcements are used to reinforce soil structures in a wide range of Civil Engineering applications and an increasing number of environmental protection situations. The performance requirements for these end uses vary greatly from the point of view of national and international material specifications and design code testing methodologies. Thus matching the properties of available products to the various performance requirements proves to be a complex and difficult process for manufacturers and end users alike. In this paper, the performance requirements of various reinforcement applications in civil engineering and environmental protection are shown to be dominated by the nature of the "Operational Environment" and "Actions" to which Geosynthetic Reinforced Soil Structure are subjected. The range of testing required to identify the product properties to match the range of performance requirements is then discussed and the need to correlate these is highlighted. Each stage of the testing and analysis is described and the applicability of the recently developed Isochronous Strain Energy Approach to the analysis, particularly to the comparison of test data from different test methodologies, is demonstrated. On these bases, the process of matching the isothermal load-strain-time behaviour to different end uses of geosynthetic reinforcements in general, and the new range of geogrids in particular, are presented.

1 INTRODUCTION

A new range of uniaxial and biaxial geogrids made of welded flat bars has recently been introduced to the international market. This product range is called Secugrid® and it is manufactured by the NAUE Fasertechnik group in Germany. This form of construction allows different pre-stressed / pre-strained polymers (to date, polyester [PET] and polypropylene [PP]), to be formed into monolithic bars of various sizes, shapes and spacings which are then fixed into a grid arrangement by welding at cross-over points. This product construction offers a high degree of flexibility but for reasons of technical and cost efficiency the range of products manufactured must be optimised to suit designated applications in civil engineering and environmental protection. To achieve this, requires that a considerable amount of testing be undertaken in order to comply with the many international and national standards that now exist. This has been done but in parallel, a more fundamental approach was developed which matches performance requirements to product properties. Although applied to this specific product range, it is suggested that this approach has general applicability.

2 PERFORMANCE REQUIREMENTS IN CIVIL ENGINEERING AND ENVIRONMENTAL APPLICATIONS

Polymeric reinforcements employed in the construction of Reinforced Soil Structures are called *Geosynthetics*. These Geosynthetic Reinforced Soil Structures [GRSSs] represent a wide range of construction forms. Bonaparte et al (1985) sub-divided them into two broad categories, viz. *Earth Structures* and *Load Supporting Structures*.

Earth Structures include walls, bridge abutments, steep slopes and embankments, which are not generally stable under their own weight and may or may not require to support significant external loads. Thus the primary design criterion is the stability of the structure under its self-weight. The geosynthetic reinforcement layers provide lateral tensile strength and they increase the confining pressure acting on the soil. This permits the construction of slopes at angles greater than the mobilised angle of friction of the backfill.

Load Supporting Structures include road and airfield pavements, railroad tracks, load supporting pads and foundations. These structures are usually stable under their own weight, and the primary design criterion is the ability of the structure to support the externally applied loads, with limitations placed on the associated deformations. The reinforcement function of the geosynthetic is to provide lateral tensile strength and to increase confining pressure within the fill. This increases the ability of the system to carry additional externally applied loading or to carry loads with less deformation.

The geosynthetic reinforcements may be produced from a wide range of polymeric materials, manufactured in a variety of forms, including sheets, strips and grids. Their load-strain properties are time and temperature dependent and the load transfer mechanism between the soil and the geosynthetics is dependent on surface friction, bearing stresses or possibly a combination of these. Many applications include facings which are connected to the reinforcement layers to prevent surface erosion and local deformations.

The most common construction procedure associated with GRSSs is to place successive layers of Geosynthetic reinforcements between compacted layers of fill. During compaction of the fill the geosynthetic is stretched. For Geogrids, soil particles are forced into the apertures. When the compaction load is released, the grid attempts to return to its initial condition, but is resisted from doing so by the presence of the soil particles in the apertures. This develops locked-in strains and so locked-in stresses in the grid. The locked-in strains have a similar effect to a confining stress on the soil and therefore increase the strength of the soil.

GRSSs are designed to resist several types of loadings during their design lifetime. These loadings can be either internal loads (essentially self-weight) or external loads (e.g. traffic, temporary or permanent surcharges, seismic or shock loading). The structures are expected to resists these loadings without excessive deformation or failure of their components.

As mentioned above, one of the main functions of geosynthetic reinforcements is to resist these loadings and perform within satisfactory strain limits over the whole design lifetime. The reinforcements may be subject to a combination of loadings. Given the elasto-visco-plastic nature of geosynthetics, any testing to characterize their load-strain-time and temperature behaviour requires a close simulation of the loading conditions. However, it is very difficult to represent the actual combinations of loads and deformations and to apply these combined loadings for the design lifetime of the structure.

2.1 *Operational Environment*

The operational behaviours of GRSSs may be characterised at three levels. The first is their behaviour under working loads and imposed deformations, so-called Working Conditions. Second is their behaviour at limiting deformation conditions, the so-called Serviceability Limit State. Third is at collapse, the so-called Ultimate Limit State. McGown et al (1998) suggest that some or all of the following aspects of their operational behaviours require to be considered:

- Local instability of the lateral face of the reinforced fill
- Settlement of the reinforced fill, other fills and subsoil
- Rupture and deformation of the facing units, connections and reinforcements
- Pull-out and slippage of the reinforcements
- Sliding of the reinforced mass along its base
- Overturning of the reinforced mass
- Bearing failure or deformation of the subsoil and
- Overall stability of the structure.

2.2 *Actions*

All of these operational or limiting behaviours may be directly related to the nature of the Actions resisted by the structure. Eurocode 1 (1996) suggests a categorisation into *Direct Actions*, which are loads or forces applied to the structure, and *Indirect Actions*, which are imposed or constrained deformations, Figure 1.

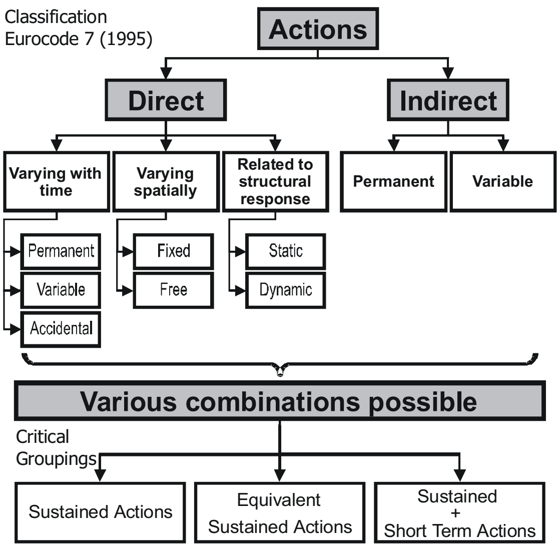

Figure 1 Classification and grouping of Actions

Within these two categories, there are many Types of Actions, including *Permanent Actions*, (likely to act throughout a given design situation); *Variable Actions*, (likely to vary but with a mean value of significance); *Accidental Actions*, (likely to be of short duration and unexpected but of sufficient magnitude to cause severe consequences); *Fixed Actions*, (likely to be of known magnitude and direction with a fixed distribution over the structure); *Free Actions*, (likely to be of known magnitude and direction but a variable distribution over the structure); *Static Actions*, (likely to be stable and not cause significant acceleration of the structure or any of its components); *Quasi-static Actions*, (likely to be essentially static but have some dynamic effects), and *Dynamic Actions* (likely to cause acceleration of the structure or of its components).

For simplicity in the design, it is suggested that the various types and combinations of Actions acting on the GRSSs should be split into only three general categories, viz. Sustained Actions, Equivalent Sustained Actions and Sustained plus Short-term Actions, McGown (2000). Sustained Actions and Equivalent Sustained Actions represent all types and combinations of actions that can be reasonably represented as long-term sustained loads or deformations and are termed Single-Stage Actions. Sustained plus Short-Term Actions are those Actions which must be treated in design as a series of loads or deformations acting for different periods of time, either combined or acting separately, and are termed Multi-Stage Actions.

It should be appreciated that Actions may also vary considerably with time and magnitude, Kupec (2001).

3 TESTING METHODS TO OBTAIN DESIGN PARAMETERS

Thus where introducing a new Geosynthetic reinforcement product a great deal of testing has to be undertaken. So-called *Index* tests are generally required for specification (quality control) purposes but for design purposes more complicated, (sometimes confined in-soil), methods are required. These are termed *Performance* tests, Murray and McGown (1982, 1987 and 1992).

Index test are in general short-term tests, e.g. Constant Rate of Strain [CRS], Puncture and Cone Penetration. Due to the elasto-visco-plastic nature of geosynthetics they are likely to be dominated by their elastic strain energy component, McGown (2000). Performance tests are more expensive and time consuming than Index tests and may have durations up to 10,000 hours. In general, Performance test data are recommended for use in designs.

Due to the load-strain-time-temperature dependencies of Geosynthetics, different "Strengths" are obtained from Index and Performance testing. Slight variations in test conditions can affect the results greatly, Kabir (1984).

4 THE ISOCHRONOUS STRAIN ENERGY APPROACH

The Isochronous Strain Energy [ISE] Approach was developed by Khan (1999) and several publications dealing with this have followed, including McGown (2000), Kupec (2000) and Heerten et al (2001).

The ISE Approach is based on the principles of elasto-visco-plastic behaviour of engineering polymeric materials. It requires test data from single-stage loading tests to be represented in the form of Isochronous Load-Strain curves. The areas under these curves then represent for any specified strain level and time, the "Absorbed Isochronous Strain Energy" $[A]_t$. The Absorbed ISE at any strain level and time, in fact consist of two components, viz. the "Immediately Recoverable ISE" $[R]_t$ and the "Locked-in ISE" $[L]_t$. These components may be represented in a $[R]_t$ - $[L]_t$ plot to show how they vary with time.

Khan (1999) applied the ISE Approach to the analysis of test data obtained by other investigators and showed that it was possible to correlate data obtained from a wide range of test methodologies. Thus he showed that for all practical purposes, the "ISE Capacity" $[C]_t$ of geosynthetics determined from different loading test conditions could be correlated. Kupec (2000) later showed that the ISE Approach could be successfully employed to analyse multi-stage loading test data.

5 USE OF THE ISE APPROACH TO PREDICT THE LOAD-STRAIN BEHAVIOUR

As stated previously, given the elasto-visco-plastic nature of geosynthetics, in order to characterize their load-strain-time and temperature behaviour for the purpose of obtaining appropriate design input parameters, a close simulation of the loading conditions is required during testing. However, that is not easily accomplished. Given the wide range of Actions that may require to be resisted by the Geosynthetic, it may require a wide range of test protocols to be employed. This is both time consuming and expensive. Thus a means reliably predicting the response of Geosynthetics to the range of Actions, likely to exist, is required which is not dependent on undertaking many different testing regimes. It is suggested that the ISE Approach can be used for this purpose and in this Paper it has been applied to a new range of grid reinforcements.

5.1 *Developing ISE Capacity and ISE Components*

The first step is to carry out a series of single-stage loading tests. These could be CRS tests at different strain rates or a number of other test methods, but the simplest means was to use sustained loading (creep) tests. These tests were carried out at different load levels in order to allow the Isochronous Load-Strain curves to be constructed, Figure 2(a) and (b). As stated previously, the areas under these curves for different strain levels and times can then be used to construct the ISE Capacity at specified strain levels over the range of times relevant to the application, Figure 3.

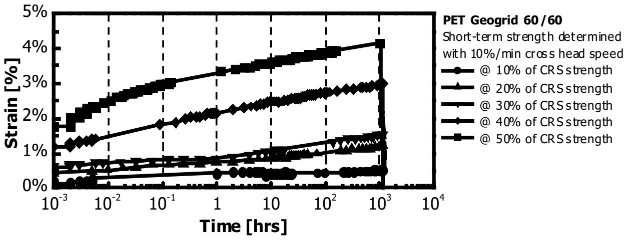

Figure 2(a) Results from sustained loading (creep) tests

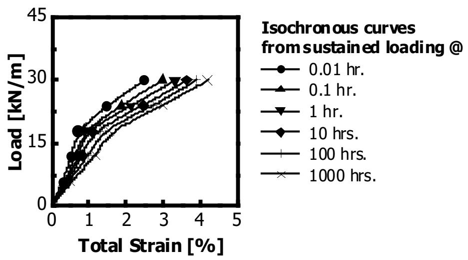

Figure 2(b) Isochronous Load-Strain curves from sustained loading (creep) tests

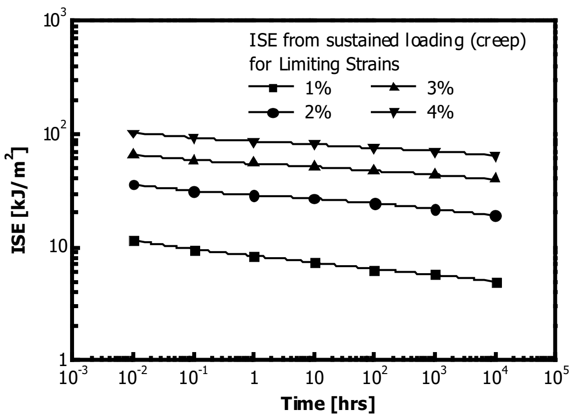

Figure 3 Absorbed ISE-Time plots for different limiting strains

At the end of the loading period the test specimens were unloaded in the same manner as initially loaded. From the initial loading and unloading data, the Immediately Recoverable ISE was computed. Taking this from the Absorbed ISE at any strain level and time allows the Locked-in ISE to be identified, Fig. 4.

$$[L]_t = [A]_t - [R]_t \tag{1}$$

From these data the $[R]_t$ - $[L]_t$ plots were produced for different strain levels, Figure 5. These plots contain the fundamental data upon which the prediction of the response of the geogrids to Actions can be based.

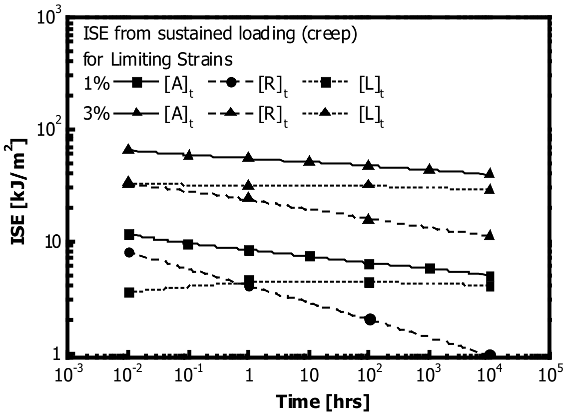

Figure 4 Variation of $[A]_t$ and the ISE Components, $[R]_t$ and $[L]_t$ with time

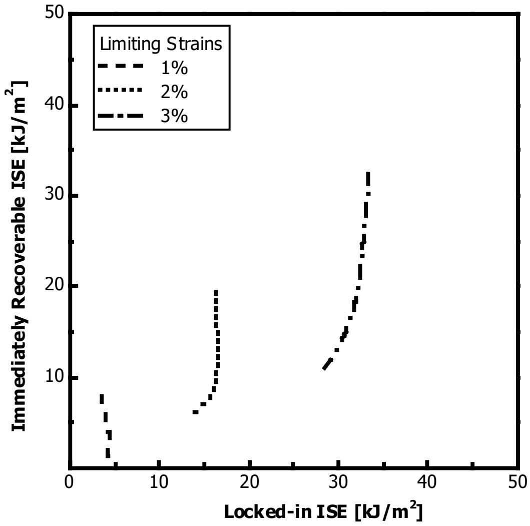

Figure 5 ISE components in the $[R]_t$ - $[L]_t$ plot

5.2 *Predicting the Response of a Geosynthetic to Single-Stage Loading*

For any specified Single-Stage Action or test loading condition, the response of the Geogrids was predicted on the basis of the ISE Components up to the limiting value of the ISE Capacity for any specified strain limit (or rupture) at any time. Figure 6 shows how the $[R]_t$ - $[L]_t$ plot was used to predict a single-stage loading on the geogrids, e.g. CRS testing. Thus providing the Action or test conditions are specified then the load-strain response of the Geogrids can be predicted for single-stage loading conditions.

5.3 *Predicting the Response of a Geosynthetic to Multi-Stage Loading*

For multi-stage loading the approach is to treat each stage in sequence. Thus if the geogrid is subject to a sustained load plus a cyclic load, the $[R]_t$ - $[L]_t$ plot can be used to predict the response as shown in Figure 7.

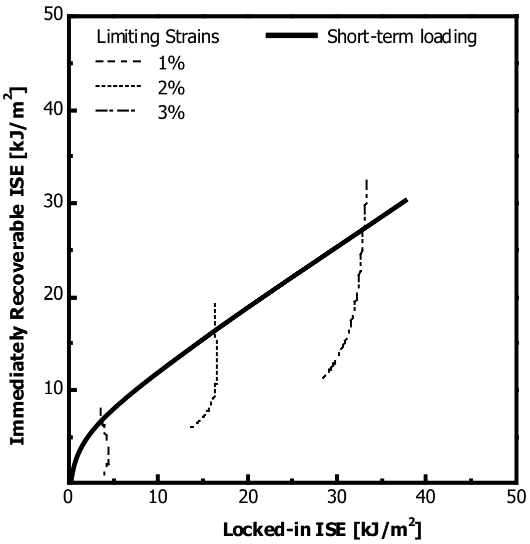

Figure 6 Predicted load-strain response from the $[R]_t$ - $[L]_t$ plot for single-stage loads (CRS)

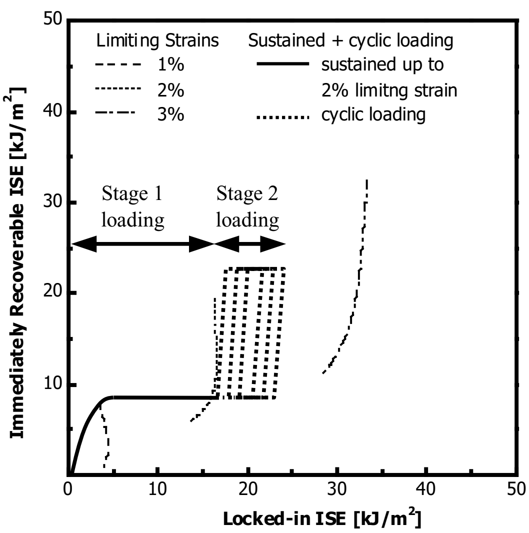

Figure 7 Predicted load-strain response from the $[R]_t$ - $[L]_t$ plot for multi-stage loads (combined sustained plus cyclic)

5.4 *Application of the ISE Approach to Residual Strength*

The Residual Strength Approach to the characterisation of geosynthetic behaviour was introduced by Greenwood (1997) and a number of publications have followed based on this approach, e.g. Greenwood et al (2001). It assumes that a load in excess of the long-term rupture load obtained from sustained loading can be applied to the geosynthetic for short periods of time. This load is predicted to be close to the short-term tensile load obtained from Index testing methods, e.g. CRS test.

In fact, what is being suggested is that the rupture load under multi-stage loading can be correlated closely with the rupture load from a single loading condition. The ISE Approach would confirm that for particular sets of multi-stage loadings this indeed is correct. However, it also shows that for other sets of conditions this may not be the case.

Thus the ISE Approach based on the fundamental concept of elasto-visco-plastic behaviour of engineering polymers shows that there is some validity to the Residual Strength Approach. However, its validity is strictly limited to specific combinations of single-stage loads. The ISE Approach also shows that it is not possible to generalise this Residual Strength Approach to all multi-stage loading conditions, (i.e. to all Multi-Stage Actions).

6 CONCLUSIONS

Current practice does not effectively measure the fundamental elasto-visco-plastic nature of geosynthetics rather; it is based on a series of test methods related to empirically based approaches. Thus the current characterisation of the isothermal load-strain-time behaviour requires that a very wide range of tests be undertaken to obtain data which cannot be correlated or directly compared. It is suggested that the ISE Approach provides a means of correlating and predicting these various data. For the geogrids tested it has been shown that it is able to predict their isothermal load-strain-time behaviour for widely different conditions. It is suggested that this may be accomplished for all geosynthetic materials.

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