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Testing related to the introduction of a new geogrid with welded flat bars for use as a soil reinforcement

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ABSTRACT: When introducing a new geosynthetic soil reinforcing product, a range of test data is required for specifying authorities and design codes/methods and there are no general correlations between them. As a result, manufacturers have to undertake a wide range of testing and specifiers/designers then find it difficult to identify which of the data available is critical. In this paper, the recently developed Isochronous Strain Energy Approach for the load-strain-time-temperature behaviour of geosynthetics is presented and it is shown how this can be used to characterise geosynthetic products generally and a new geogrid with welded flat bars in particular.

1 INTRODUCTION

A wide range of predominantly synthetic polymers mixed with a variety of additives are formed into geosynthetics using a number of manufacturing processes. The combination of different polymer mixes and manufacturing processes results in products possessing diverse micro and macrostructures. As a result, these products exhibit a very wide range of physical and engineering properties. Specifiers and Designers of geotechnical structures incorporating these products require to obtain test data from the products for the purposes of quality control and design. So-called "Index" tests are generally appropriate for specification (quality control) purposes but for design more complicated, (sometimes confined in-soil), methods are required. These are termed "Performance" tests, Murray and McGown (1982, 1987 and 1992).

Various national and international design codes/ methods and specification authorities have recognised the need for both Index and Performance tests but to date there is a lack of standardisation in these test methodologies and to some extent in the interpretation/presentation of the test data. Thus when introducing a new product range, manufacturers require to obtain a wide range of test data using different test methodologies and data presentation techniques in order to satisfy the various national and international specifications and design codes/ methods.

The test methodology and terminology used to identify the basic characteristics are generally agreed internationally, but particularly for design input data, this is not the case. Additionally, there are few general correlations between the data obtained from different test methods. This has had the effect of putting a great deal more emphasis on the provision of Index test data than on the provision of the more complex and more expensive Performance test data.

Recently a new approach to the characterisation of the load-strain-time-temperature behaviour has been developed, McGown (2000), which allows correlation of data from a wide variety of test methodologies. This is called the "Isochronous Strain Energy" [ISE] approach. In this paper the ISE approach and the test methodologies to be used in relation to the introduction of geosynthetic reinforcing products in general are described and then applied to a new range of geogrid products made from welded flat bars.

2 CHARACTERISING THE LOAD-STRAIN-TIME-TEMPERATURE BEHAVIOUR OF GEOSYNTHETICS

2.1 *Loading regimes*

Whether for specification or design purposes it is always necessary to identify the load-strain behaviour of geosynthetic soil reinforcing products at specified times and temperatures. This usually involves testing the products under Constant Rate of Strain and Sustained Loading (Creep) test conditions at various specified temperature conditions. Tests on ex-works materials provide data which can be used to identify what is termed the "Reference Strength". Tests must then be carried out on materials that have been damaged or environmentally exposed in order to establish what level of degradation of the load-strain properties of the geosynthetic will occur with time under operational conditions. This then allows Factors of Safety for Limit Equilibrium designs and Partial Factors for Limit State designs to be assessed. "Design Strengths" are then obtained by applying these Factors of Safety or Partial Factors to the Reference Strengths.

To date the complex loading regimes applied to Geosynthetic Reinforced Soil Structures [GRSSs] are represented as quasi-static long-term loading. In fact the Actions to which GRSSs are subject may be permanent or variable; accidental free or fixed; static or dynamic, Eurocode 7 (1995). In view of the wide range of Actions that can affect GRSSs, their performance can be very difficult to assess. Thus for simplicity in specifications and designs it is suggested that the various types of Actions should be split into only three general categories, viz. "Sustained Actions", "Equivalent Sustained Actions" and "Multi-Stage Actions". The first two may be represented as long-term sustained loads or deformations, i.e. "Single Stage Actions", however the third must be treated as a series of loads or deformations acting for different periods of time, i.e. Multi-Stage Actions.

Test data related to the performance of geosynthetics subject to Single-Stage Actions can be obtained from "Single-Stage Loading" tests. For situations where Multi-Stage Actions are applied, then "Multi-Stage Loading" tests are required, however, these are still at the development stage. Hence in this paper, only Single-Stage Loading test data will be referred to in respect of the determination of Reference Strengths, Factors of Safety/Partial Factors and so Design Strengths.

2.2 *Reference strength*

For Single-Stage Loading the Reference Strength of geosynthetics is defined in existing specifications and design codes/methods in different ways. Some define it as the factored strength determined from short-term Constant Rate of Strain [CRS] testing, whilst others define it as the long-term, sustained load (creep) strength at rupture or at a limiting strain. For example, DIBt (1998) and AASHTO (1997) use the maximum load at rupture of the ex-works materials under Constant Rate of Strain [CRS] testing as the basis of defining the Reference Strength of geosynthetics. The Reference Strength to avoid long-term creep rupture, is then obtained by dividing the CRS rupture strength by a Reduction Factor. The DIBt (1998) and the AASHTO (1997) design methods specify 33% per minute and 10% per minute strain rates respectively, for the CRS tests employed. Thus as suggested by Kabir (1984) and Yeo (1985), these tests are likely to provide different strengths due to different test conditions. Hence, it can be stated that to avoid long-term creep rupture, a single value of the Reduction Factor will not be applicable to data obtained from different test methodologies. Indeed, it is apparent that Reduction Factors are likely to be specification and design code / method specific.

Additionally, Troost and Ploeg (1990), BS8006 (1995) and Jewell (1996) defined the Reference Strength as the load to cause creep rupture of ex-works specimens at the end of their design life [t_{dl}]. Typically, many geosynthetics exhibit a wide range of creep rupture strains for different sustained (creep) load levels. Hence, the Reference Strength, defined on the basis of load at creep rupture for a specific design life time, can be very difficult to select if it has to be related to a specific strain level developed at creep rupture, McGown et al (1998).

Some other design methods define the Reference Strength as the load obtained from the Isochronous Load-Strain curves, corresponding to a Performance Limit Strain, for example the HA 68/94 Design Method (1997) and the TBW Method (1998). The strength at the "Performance Limit Strain" is always less than the strength at creep rupture, hence it is a conservative choice.

Overall it may be suggested that currently the so-called Reference Strength of a geosynthetic should be viewed as a range of values which depend on the application and the test methodology specified in the code/method.

2.3 *Factors of safety and partial factors*

To date, most specification and design codes/methods, suggest the use of Factors of Safety or Partial Factors obtained from CRS tests. For example, Watts et al (1990) and Koerner et al (1990) used CRS tests to identify damage effects on geosynthetics. They determined the Damage Factors for various geosynthetics by comparing the CRS loads for rupture "before" and "after" damage effects BS8006 (1995), AASHTO (1997), HA 68/94 (1997), TBW (1998) and DIBt (1998) adopt the same method for the determination of Partial Factors for geosynthetics.

The above procedure implicitly assumes that the effects of construction damage or environmental degradation on the properties of geosynthetics are the same in both the short-term and the long-term. Furthermore, it is likely that Factors of Safety and Partial Factors will be strain level and time dependent. Therefore specifying a single value of a Factor of Safety or Partial Factor is likely to be inappropriate.

2.4 *Design strength*

In view of the differences identified in the definitions of Reference Strength and in the means of determining Factors of Safety or Partial Factors, it is apparent that Design Strengths will be different from specification to specification, code to code and method to method, for any particular geosynthetic. Further, it is likely that the geosynthetic strains corresponding to the Design Strengths for the Ultimate and Serviceability Limit State in Limit State Analyses will differ.

3 CHARACTERISING THE LOAD-STRAIN-TEMPERATURE BEHAVIOUR OF GEOSYNTHETICS SUBJECT TO SINGLE STAGE ACTIONS USING THE ISE APPROACH

3.1 *Definition of Isochronous Strain Energy*

For a Single-Stage Loading test, e.g. CRS or sustained loading (creep) test, under isothermal conditions, the external work done per unit width of a geosynthetic may be taken to be equal to the Absorbed Strain Energy at any time (t). From Isochronous Load-Strain plots developed from these test data, the areas under the curves can be calculated to give the Isochronous Strain Energy [ISE] for the geosynthetics at different times, Fig. 1, McGown (2000). The unit of ISE for geosynthetics is:

Force per unit width times unit strain
= (kN/m) × (m/m) = kN/m

To avoid confusion with existing definitions of strain energy it is suggested that another unit for ISE is used as follows:

ISE = (kN/m) × (m/m) = (kNm/m^2) = kJ/m^2

3.2 *The components of ISE*

Figure 2 represents the load-strain-time behaviour of a geosynthetic in terms of the "Absorbed ISE" [A]t. Upon application of load [P]$_1$ at time [t$_0$], as shown in Fig. 2(a), there will be an Absorbed ISE [A]$_{t_0}$ (point 1) within the geosynthetic. Thereafter, over a period of time between [t$_0$] and [t$_1$] more Strain Energy will be absorbed by the geosynthetic, i.e. the Absorbed ISE will increase to [A]$_{t_1}$, (point 2), Fig. 2(b). At time [t$_1$] when the load is removed, a part of Absorbed ISE will be recovered and this is termed the "Immediately Recoverable ISE" [R]$_{t_1}$, (point 2 to 3), Fig. 2(c). At this point of time, i.e. time [t$_1$], the Absorbed Strain Energy remaining in the geosynthetic is termed the "Locked-in ISE" [L]$_{t_1}$, Fig. 2(c). If no further load is applied to the geosynthetic, then with time part of this Locked-in ISE will be recovered due to viscous rebound, however, part will be irrecoverable, the so-called "Irrecoverable Locked-in ISE" [L]$_{irr}$.

Clearly, this indicates that at any time the Absorbed ISE comprises two components, which are:

i) Immediately Recoverable ISE [R]$_t$ and
ii) Locked-in ISE [L]$_t$, part of which is recoverable with time.

It should be noted that these components vary with time for any limiting strain or rupture condition, as shown in Fig. 3.

4 DETERMINING THE ISE CAPACITIES AND COMPONENTS FROM TEST DATA

4.1 *Determining ISE capacities*

CRS testing needs to be carried out at different rates of strain at a specified temperature, to allow the

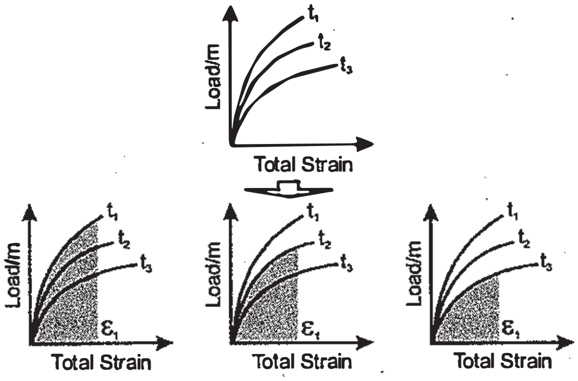


Figure 1. Calculation of Isochronous Strain Energy from Isochronous curves.

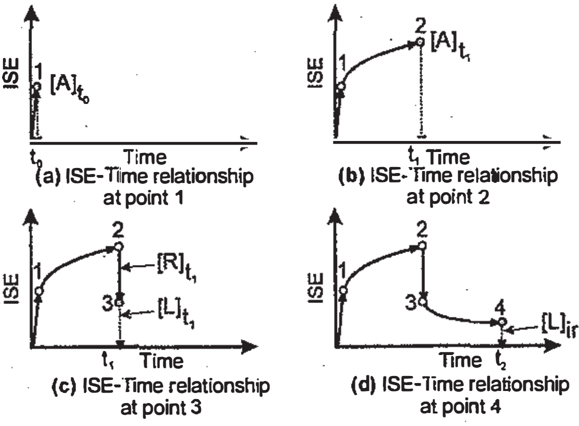


Figure 2. Load strain-time behaviour in terms of ISE.

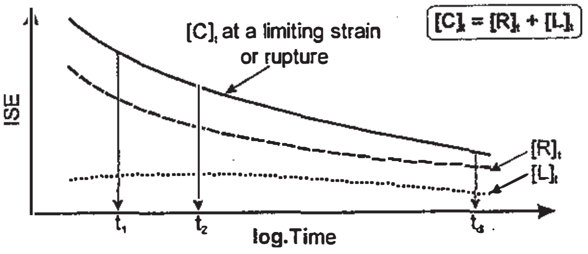


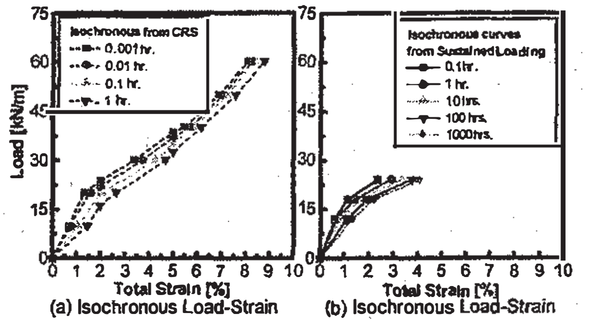
Figure 3. Variation of ISE components with time.

Isochronous Load-Strain curves to be drawn as shown in Fig. 4(a). Sustained load (creep) tests carried out at different load levels may similarly be used to plot Isochronous Load-Strain curves, Fig. 4(b). The areas under these Isochronous Load-Strain curves may then be plotted together in an ISE-log.Time plot, as shown in Fig. 4(c). If these data are re-plotted to a log-log scale and the best-fit curves drawn through the data, it will be seen that the data from the CRS and creep tests will lie close to the same best-fit curves. The best-fit curves at each strain level represent the ISE Capacity [C]t for this material.

Strictly speaking, for a particular strain at a specific time, the load required to achieve this strain in a CRS test will be different from the load required in a sustained load (creep) test. Therefore theoretically, the ISE Capacity $[C]_t$ at a particular limiting strain $[\varepsilon]_L$ and at a specific time from CRS tests should be always different from data from sustained load (creep) tests. However, for relatively short-term tests, the response of geosynthetics to loading is dominated by their initial elastic and plastic strains and a limited amount of rapidly developed primary creep. The result is that for all practical purposes, the ISE Capacity $[C]_t$ determined from different short-term test methods will be very similar and can be represented by the same best-fit curves. Therefore, such curves can be used to compare and correlate the data obtained from CRS and other short-term tests, such as sustained load, sustained strain (stress relaxation) and cyclic loading tests, McGown (2000).

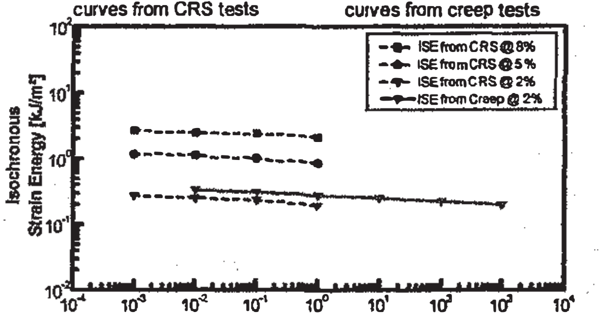
4.2 *Determining the ISE components*

Calculation of the ISE components requires the identification of the "Isochronous Load-Locked-in Strains". To do so the "Isochronous Load-Total Strain" and "Isochronous Load-Immediately Recoverable Strain" curves require to be developed from loading/unloading tests. The "Total Strain" at any time is equal to the summation of "Immediately Recoverable Strain" and "Locked-in Strain", therefore the Isochronous Load-Locked-in Strain curves are obtained by the method shown in Fig. 5. The ISE capacity and its components for any SingleStage Loading regime, i.e. $[C]_t$, $[R]_t$ and $[L]_t$, are then determined from the areas under the respective Isochronous Load-Strain curves for different times and strains, as shown in Fig. 1.



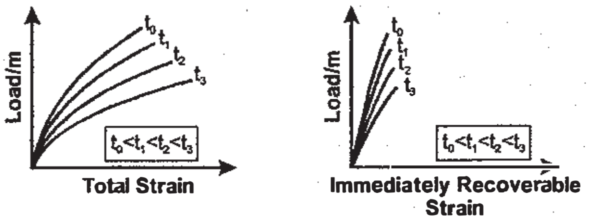
(a) Isochronous Load-Strain curves from CRS tests

(b) Isochronous Load-Strain curves from creep tests



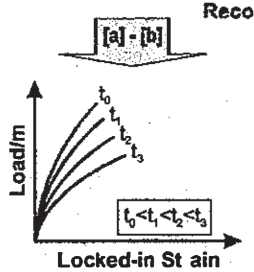
(c) ISE Capacity $[C]_t$ – log.Time curves from different loading paths

Figure 4. Test data from different load-strain paths and their correlation in the ISE-log.time plot.



(a) Load-Total Strain curves

(b) Load-Immediately Recoverable Strain curves



(c) Load - Locked-In Strain curves

Figure 5. Construction of Isochronous Load-Locked-in Strain curves.

5 DETERMINING TEST DATA FROM THE ISE CAPACITY AND COMPONENTS

It is clearly the case that if a product is characterised using CRS tests and sustained load (creep) tests and the data analysed to obtain the ISE Capacities and ISE Components at various isothermal conditions, then it is possible to reverse the process. Thus given the availability of such ISE data, the load-straintime-temperature behaviour of geosynthetics may be derived for any specified conditions. Therefore ISE Capacity and ISE Component data provide the basis for Manufacturers, Specifiers and Designers to predict the performance of geosynthetic reinforcements under different test methodologies in a manner not previously possible.

6 CHARACTERISATION OF A NEW GEOGRID WITH FLAT WELDED JUNCTIONS

6.1 *Basic properties of the geogrid*

To increase the current range of geosynthetic reinforcement, a new range of geogrid reinforcements has been developed in Germany. It is made from pre-stressed / pre-strained monolithic flat polyester (PET) bars with welded joints. These are intended to provide low elongation at high strength with low creep characteristics. The product range covers uniaxial and biaxial geogrids with tensile strengths up to 600kN/m when tested under CRS conditions at 20°C.

6.2 *Choice of representative test specimen*

The size and shape of representative samples of geogrids are dominated by their macro structure. The gauge length of test specimens is taken as the distance between the centre of the elements and a minimum dimension of 100mm in any direction of testing is generally considered satisfactory to account for the local variability of most geogrids. However, many test standards also require that at least three complete tensile elements (ribs) and at least one row of nodes or cross-members along the width, (excluding the nodes or cross-members by which the sample is being held in the clamps), should be included. In addition, all ribs must be cut at least 10mm away from any node. The test procedures outlined in ISO 13431 (1999) state that at least three test specimens for each product should be tested. Recently, Wrigley et al (1999) suggested that the number of test specimens required to characterise a product can be reduced using timetemperature superposition,

For the new geogrid product the testing recommendations of ISO 13431 (1999) and BS 6906 (1987) have been employed. A gauge length of 210mm was selected which included 6 cross members. Specimens were held in specially developed friction clamps as roller clamps proved unsatisfactory. CRS tests were conducted at different rates of deformation and repeated three times. Specimen rupture occurred well within the clamped area and across the specimen. Sustained loading (creep) tests were conducted on 10, 20, 30 and 40% of the 10%/min short-time CRS strength. The sustained loads were applied over periods of 1, 10, 100 and 1000 hours and unloaded for a tenth of the loading time or at least 10 hours. The sustained loading (creep) tests were repeated three times to observe the specimen variation. The test data indicate that specimen reproducibility from CRS and sustained loading (creep) tests was 95% at any time.

6.3 *Derivation of ISE capacity and ISE Components*

To obtain the ISE capacity, $[C]_t$, and ISE Components the short-term and long-term test data were employed in the manner described previously, see Fig. 4. The ISE Capacity $[C]_t$ - log.Time plot was constructed, Fig. 6, and the ISE Components derived as shown in Fig. 7.

6.4 *Use of ISE capacity and ISE Components to derive test data*

The test data presented in Figs. 6 and 7 were extrapolated by two log cycles. The data were then used to predict the material behaviour for test conditions not included in the test programme, as shown in Fig. 8, and as suggested would be possible in the previous sections. Test data from environmental degradation and construction damage are not yet available so that Factors of Safety and Partial Factors cannot be calculated to obtain the Design Strength at any condition and time but they will be obtained in a similar manner following further testing.

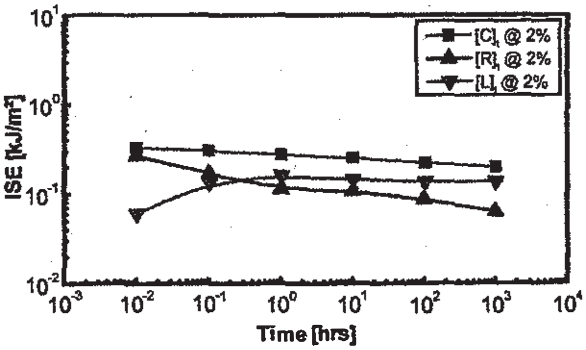


Figure 6. ISE capacity $[C]_t$–log. Time and variation of the ISE Components.

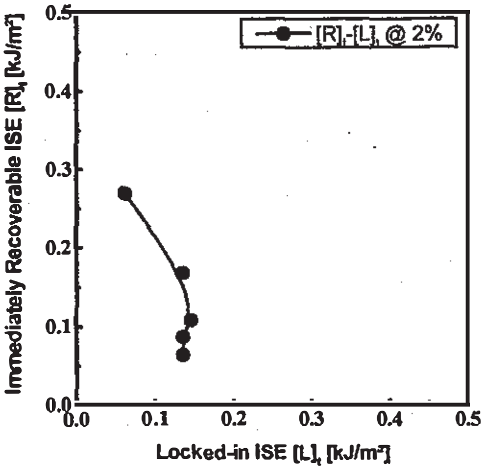


Figure 7. ISE Components $[R]_t$ - $[L]_t$ plot.

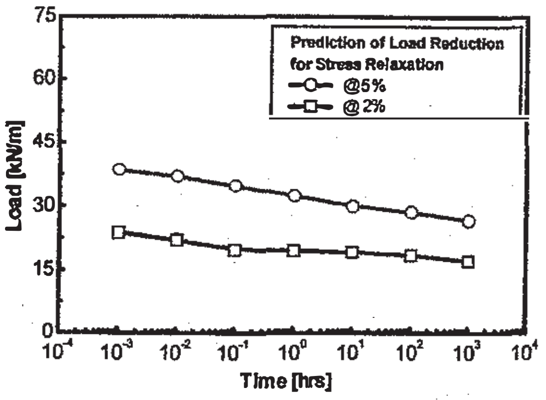


Figure 8. Prediction of material behaviour.

7 DISCUSSION

The need to have a wide range of test data from different test methodologies in order to comply with various national and international specifications and design codes/methods has caused Manufacturers to focus more on Index testing than on Performance testing. The range of data then available and the lack of correlation between the data has caused confusion to many Specifiers and Designers. In this Paper the use of the Isochronous Strain Energy to correlate test data and provide a fundamental characterisation of the load-strain-time-temperature behaviour of geosynthetics has been identified. The application of this approach to a new geogrid with welded flat bars has been demonstrated. The use of ISE Capacity and ISE Component data to provide data for any specified test methodology, within the range of time and temperature of the ISE data was also indicated. Thus it is suggested that the ISE approach is a fundamental and useful means of characterising geosynthetic reinforcements.

In order to comply fully with Specification and Design, other data will be required relating to soil-geosynthetic interaction and perhaps to junction strength in respect of geogrids. Recommendations on the approach to be taken to soil-geosynthetic interaction have been provided previously by McGown et al (1998). To date no recommendation can be made with respect to junction strength. Tests have been suggested for this, Koerner (1994), but the applicability of these is still very much open to question.

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