Current Approaches to the Determination of the Design Stiffness and Strength of Polymeric Biaxial Geogrids

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Polymeric biaxial geogrids are formed by arranging tension resistant members, often termed ribs, in two orthogonal directions with junctions formed at their cross-over points. They are used as reinforcement elements in a wide variety of ground engineering applications. Various methods of manufacture are employed, with five main types of junctions now identifiable, viz. integral, welded, heat bonded, chemically bonded and entangled junctions. When subject to various loading regimes, the stiffness and strength of these geogrids depend on a number of factors, including the nature of the polymer used to form the ribs and the junctions, the size and number of ribs and junctions as well as the methods of forming the junctions. Determination of the load-strain behaviour of biaxial geogrids is currently undertaken using a variety of uniaxial test procedures. In this paper, the current approaches to the identification Design Stiffness and Strengths are fully set out and shown to be specific to the particular design codes/methods in which they are employed and to be highly variable. The danger of employing the incorrect values is highlighted. To overcome some of the current deficiencies in the testing methods for biaxial geogrids, new biaxial test methods using large, representative-sized samples have been developed. Details of the new biaxial testing methods are presented and test data obtained for different types of biaxial geogrid are included. The significance of the differences between the various types of testing are discussed.

1. Introduction

Since the widespread introduction of geosynthetics in the late 1960's, innovations in design methods and construction techniques in reinforced soil structures have followed. In response to these innovations, the geosynthetics manufacturers have put considerable effort into developing their existing product ranges and into the introduction of new products. However, materials testing research and the standardisation of materials testing methods have struggled to keep pace. As a result, the characterisation of the product ranges available for use by the construction industry is less than satisfactory. Thus the full technical and cost benefits to be derived from the use of polymeric geosynthetics in ground engineering works is not being fully realised.

In recent years, development of existing biaxial geogrids has occurred and new types introduced. Thus it is appropriate at this time to consider the deficiencies associated with the current approaches to the determination of the design stiffness and strength of the available range of biaxial geogrids and to make recommendations, based on ongoing research, which will rectify these. Therefore in this paper, the nature of the various types of polymeric geogrids available are identified. The current approaches to the characterisation of their tensile properties based on uniaxial test methods are presented. Details of new, more appropriate, biaxial test methods are detailed. Comparisons are made between the uniaxial and biaxial properties obtained from the testing of a range of products. The significance of the differences in properties identified with respect to the design of reinforced soil structures is then considered.

2. Geogrid Types

Geogrids consist of two orthogonal sets of polymeric, tension resistant components, often termed ribs, with junctions formed at their cross-over points. The resulting apertures between the ribs, are usually of sufficient size to allow the particles of the surrounding soils to penetrate between the ribs.

The ability of the surrounding soils to transfer stresses and strains into the geogrid relies upon frictional resistance on the surface of the ribs and junctions and on the development of bearing stresses on the edges of the ribs. The level of interaction between the surrounding soils and the geogrid thus relies on the surface frictional properties of the ribs and junctions and on the ability of the junctions to transfer the edge bearing stresses into the ribs. In the latter case the operational shear strength of the junctions is critical.

Currently the ribs may be formed by a wide variety of manufacturing techniques using a range of different polymers, including polyester, polypropylene and high density polyethylene. Further, there are five different types of junctions presently produced, viz., integral, welded, heat bonded, chemically bonded and entangled junctions.

Geogrids properties are currently characterised in terms of the tensile stiffness and strength of their ribs, junctions and the overall product. The properties of the ribs, junctions and overall products may vary significantly in the two principal directions. Thus two classes of geogrids may be identified; Uniaxial geogrids, which develop tensile stiffnesses and strengths primarily in one direction, and Biaxial geogrids, which develop tensile stiffnesses and strength in the two orthogonal directions.

2.1 Uniaxial Geogrids

Uniaxial geogrids usually exhibit a high stiffness in the machine direction [MD] with a very low to negligible stiffness in cross-machine direction [XMD]. However, it should be noted that there are products which have their maximum properties in the XMD. The main functions of the secondary cross-members and junctions are to provide geometrical stability during transport and installation, but they may also provide the possibility of interlock with the soil in which they are placed. Uniaxial geogrids are intended for use in plane strain applications, where the secondary direction has little or no tensile loading, i.e. plane strain applications.

2.2 Biaxial Geogrids

Biaxial geogrids exhibit significant stiffness and strength in two orthogonal directions. In these materials, the ribs and junctions provide geometrical stability during transport and installation and may provide the possibility of interlock with the soil in which they are placed.

Anisotropic biaxial geogrids exhibit dissimilar stiffnesses in the two principal directions. They are used in anisotropic loading conditions, i.e. where there is a primary and a secondary degree of loading/strain.

Isotropic biaxial geogrids exhibit very similar stiffnesses and strengths in the two orthogonal directions. They are used in isotropic loading conditions, i.e. where there is almost an equal degree of loading/strain in two orthogonal directions.

2.3 Rib Types

The rib types used in the available products include preformed, predrawn polymeric bars, coated or uncoated bundles of predrawn polymeric fibres and ribs produced by drawing out punched sheets of amorphous polymers. The cross sections of the latter are variable, whilst the others are generally uniform.

2.4 Junction Types

The junction types in use are entangled fibres or filaments, heat or chemically bonded ribs, laser or microwave welded ribs or integral junctions formed during the uniaxial or biaxial drawing of punched sheets.

All types of junctions provide geometrical stability during transport and installation and to some degree enable interaction with the fill in which they are placed. Geogrids formed with entangled or heat or chemically bonded junctions generally only possess sufficient junction strength to transfer stresses from one set of bars to another, when they are subject to significant normal confining stresses. In contrast, geogrids formed with welded or integral junctions most often exhibit sufficient unconfined junction strength to transfer stresses from one set of bars to another under either uniaxial or biaxial loading/strain conditions.

2.5 Overall Product Types

All geogrid products have ribs in two orthogonal directions but the number and/or dimensions of the ribs may be similar or highly dissimilar. For geogrids with integral junctions all the ribs and junctions lie in the same plane. However, for the other types of geogrids, one set of ribs is usually offset from the other orthogonal set with the junctions between.

3. Stiffness and Strength of Geogrids

3.1 General

Specifiers and Designers employing geogrid reinforcements in soil structures, require to obtain test data for the purposes of specifications and design. So-called "Index" tests are generally appropriate for specifications (Quality Control), but for design more complicated, sometimes confined in-soil, test methods are required. These are termed "Performance" tests, Murray and McGown (1982).

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 in the interpretation and presentation of the test data. 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 generally applicable correlations between data obtained from different test methods. This has had the effect of putting a great deal more emphasis on the provision of more easily obtained Index test data than on the provision of the more complex Performance test data.

3.2 Available Test Methods

A wide range of uniaxial loading tests have been adopted or specially developed over the last three decades to determine the uniaxial properties of geogrids, e.g. CRS, sustained loading (creep), Stress Relaxation and Cyclic testing, ASTM D4595-86 (1994), BS 6906 (1987) and ISO 13 431 (1999). These tests utilise different specimen sizes and shapes, loading methodologies, rates of load application and test temperatures, McGown et al (1981). Test specimen sizes vary but should always be of sufficient size and shape to be representative of the component ribs, junctions and/or the macro-structure of the product. Nevertheless, even when this condition is satisfied, each test may investigate the response of different features of the micro and macro-structures of geogrids. Indeed, changing a single test condition or the test environment may induce significant changes in the load-strain response. For example, for wide width test specimens loaded at a given test temperature, a change in the rate of strain in monotonic tests may have significant effect on the measured properties. Similarly, changing the test temperature whilst using the same rate of strain, may have a significant effect Kabir (1984) and Yeo (1985).

The behaviour of geogrids under CRS and Creep testing has been widely studied and the influence of time and temperature clearly identified, Kabir (1984), McGown et al (1984), Yeo (1985) and Wrigley et al (1999). To a lesser extent, the behaviour of geogrids under Stress Relaxation testing has been studied and the influence of time and temperature similarly identified, Soong et al (1994). Cyclic testing has been systematically investigated by Müller-Rochholz et al (1994) and Khan (1999). Significantly, all these test data produce different load-strain-time-temperature responses even for a particular geogrid product type.

4. Uniaxial Testing of a Range of Biaxial Geogrids

4.1 General

The testing of individual ribs is essentially only for Quality Control purposes. The currently available testing techniques can be used to test these with confidence providing only that the clamping techniques employed are satisfactory. Thus no single rib testing is reported on this paper.

The testing of single junctions is the subject of some ongoing research and discussion but it is again essentially a Quality Control issue. A recent paper by Kupec et al (2004) discusses in detail the testing procedures now available and compares the applicability of these different test methods to the various types of junctions presently used to form geogrids. Thus single junction testing is not reported in this paper.

For overall Quality Control and Performance testing purposes, large representative-sized samples of the geogrids are essential. Such tests incorporate the influences of the type of ribs and junctions forming the geogrids. These are the most important tests and in this paper, three different types of biaxial geogrid have been tested in this manner, as detailed below.

4.2 Uniaxial CRS Testing

Uniaxial CRS testing according to ASTM D 4595-86 (1994), BS 6906 (1987) and ISO 10319 (1993) was undertaken on three different types of biaxial geogrids, Table 1. These Index tests were undertaken in the two orthogonal directions separately in order to determine the short-term tensile properties of the geogrids. This approach is extensively used for Quality Control purposes and to some degree for Performance testing purposes.

Table 1 Properties of the Biaxial Geogrids Tested

Property	Biaxial Geogrid		
	A	B	C
Mass Per Unit Area	580	370	560
Polymer Composition	PP	PP	PET
Molecular State	Varies from random to oriented (Amorph to Semi-Crystalline)	Highly oriented (Semi-Crystalline)	Highly oriented (Semi-Crystalline)
Junctions	Integral	Welded	Welded
Macro Structure	Biaxially stretched punched sheet	Welded pre-stretched monolithic flat bars	Welded pre-stretched monolithic flat bars
Short-term Nominal Strength*	40 / 40	60 / 60	60 / 60

* Manufacturer's specification

The test results are shown in Figs. 1 to 3 and-confirm the expected behaviour of the three geogrids. It should be noted that, the short-term strengths measured are in all cases significantly higher than the Nominal Strengths reported by the manufacturers of the geogrids.

4.3 Uniaxial Sustained Load Testing

Uniaxial sustained load (creep) testing according to BS 6906 (1987) was undertaken on the same three biaxial geogrids, to determine their long-term material properties. The isochronous load-strain curves obtained from these tests indicate that the geogrids exhibit time-dependent load-strain behaviours, Figs. 4 to 6.

Comparing these data to the data in Figs. 1 to 3, shows that the, stiffness at operational strains of about 2% determined on the basis of the Nominal Strength or short-term CRS testing will be quite different to those obtained from the sustained loading testing. Thus, it is suggested that there is not a single value of stiffness or strength, rather the short-term values will be very much different from the long-term values.

5. Biaxial Testing of a Range of Biaxial Geogrids

5.1 General

All of the above test methods were conducted under uniaxial loading conditions. Where biaxial loading or strain conditions apply, (e.g. in load transfer platforms, roads and some embankments), the material properties of biaxial geogrids, as determined by uniaxial testing, may not be applicable. Thus to identify whether or not this was the case, biaxial tensile testing was undertaken.

5.2 Test Specimen Shape and Size

Various forms of biaxial short and long-term testing of biaxial geogrids have been undertaken previously, Bush and Bőhment (1992), Nimmesgern (1994) and Saathof (1997). However, the test specimens were reported to have suffered severe distortion, forming into non-orthogonal shapes with non-uniform stressing developing, particularly at junctions. This resulted in premature rupture and/or problems with clamping. In contrast, in other disciplines, biaxial testing has been more successfully carried out and proven to be capable of establishing the biaxial properties of biaxial materials without the difficulties experienced in testing biaxial geogrids, Krause and Bartolotta (2001) and Bridgens and Gosling (2003).

The essential difference between the test methods was actually the shape of the test specimens employed. The other disciplines employed cruciform-shaped test specimens rather than square or rectangular specimens. Thus it was decided to employ cruciform-shaped test specimens to test biaxial grids.

The sizes of the biaxial geogrid test specimens chosen were chosen in order to be representative of the macro-structure of the geogrids. Similar considerations to those adopted for the choice of uniaxial test specimens were chosen. Thus for the geogrids tested, test specimens were prepared with 5 ribs in each direction and so 25 junctions within the central section of the test specimen. This resulted in overall cruciform test specimen dimensions of some 500 x 500 mm, with central areas of 100 to 220 mm square, as shown in Fig. 7.

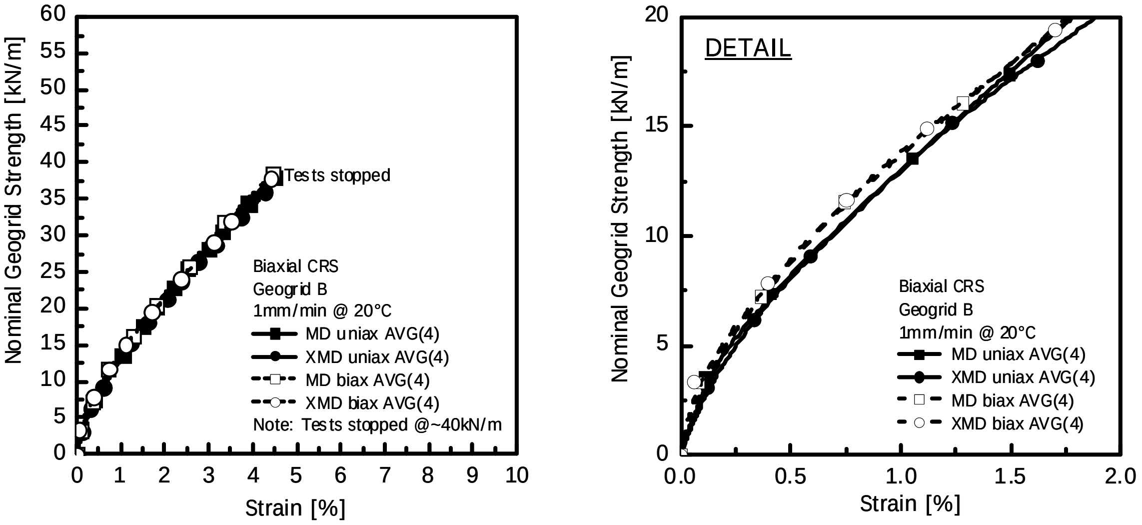


Figure 1 Uniaxial and Biaxial CRS tests – Geogrid A

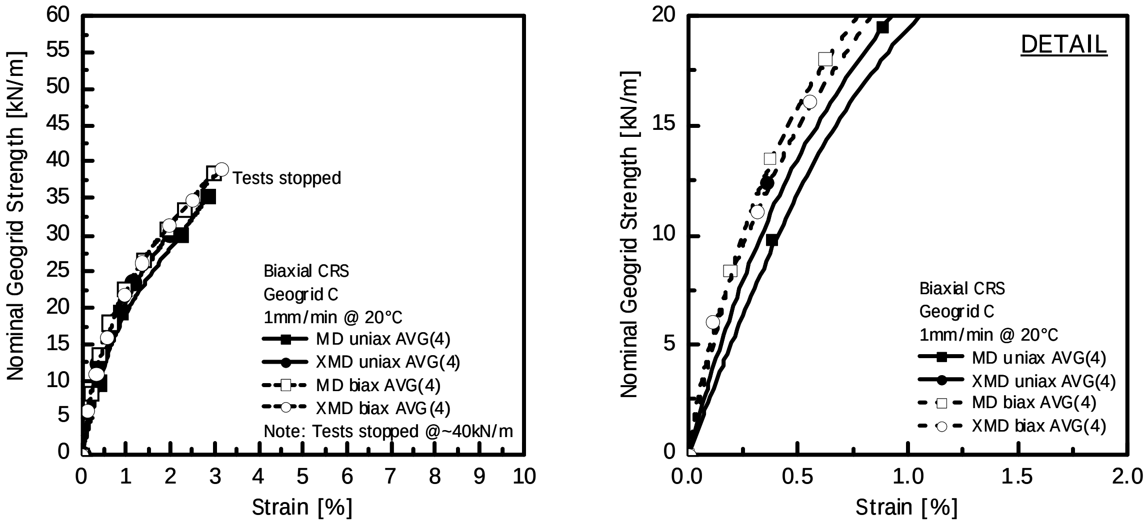


Figure 2 Uniaxial and Biaxial CRS tests – Geogrid B

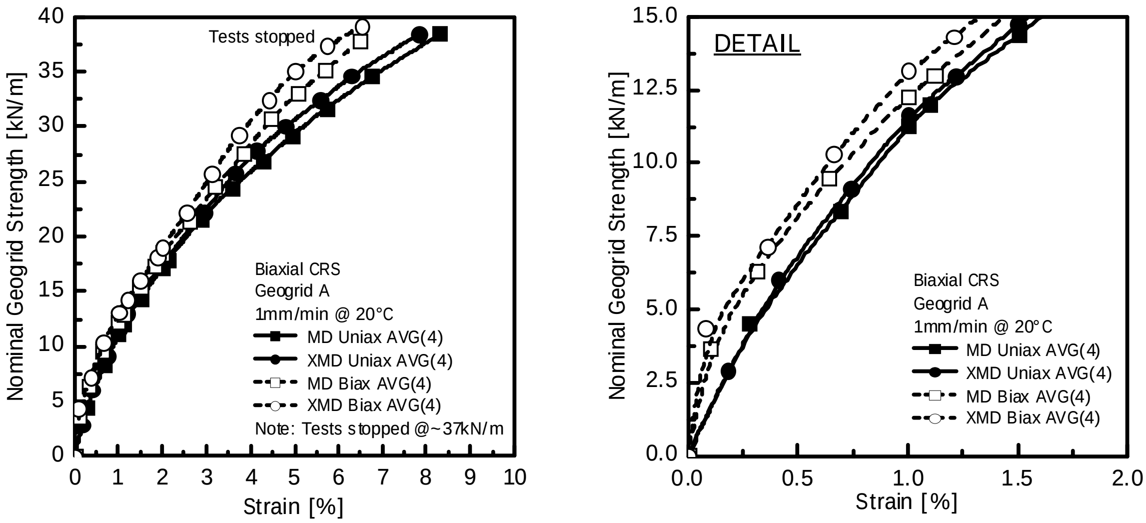


Figure 3 Uniaxial and Biaxial CRS tests – Geogrid C

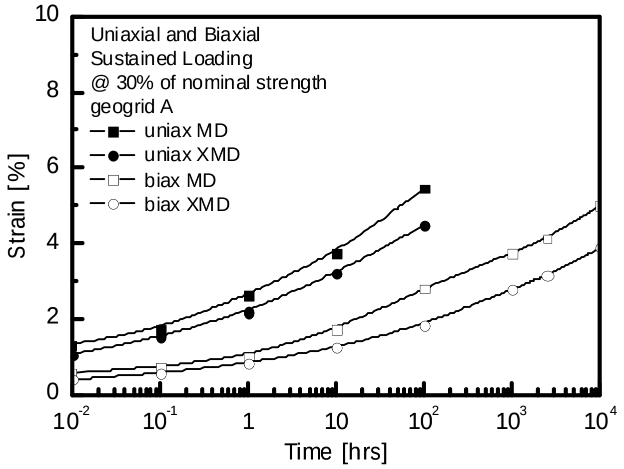


Figure 4 Uniaxial and Biaxial Sustained Loading Tests – Geogrid A

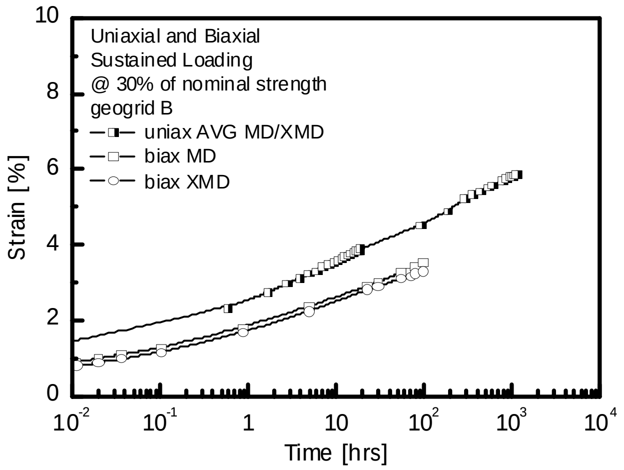


Figure 5 Uniaxial and Biaxial Sustained Loading Tests – Geogrid B

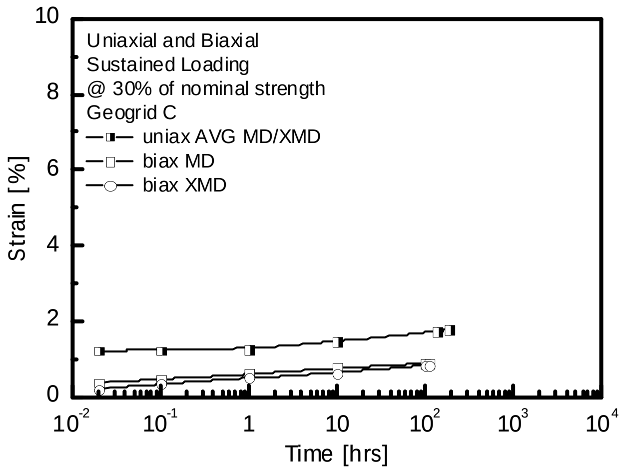
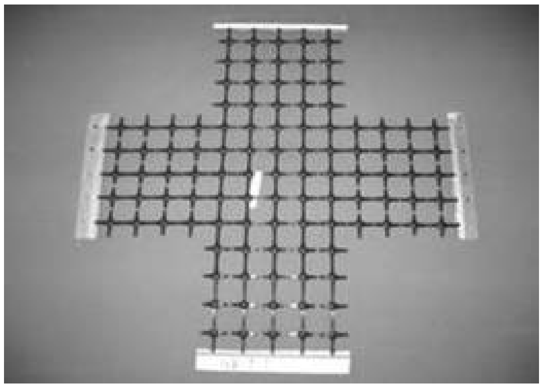
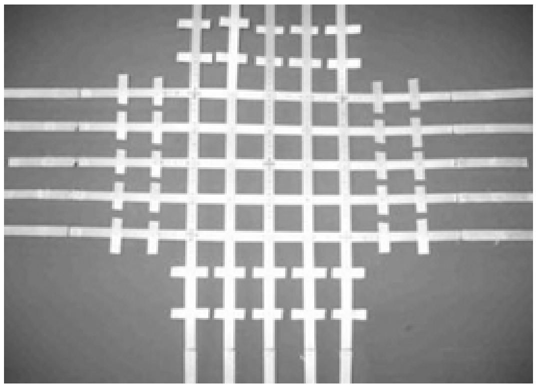


Figure 6 Uniaxial and Biaxial Sustained Loading Tests – Geogrid C



(a) Geogrid with integral junctions



(b) Geogrid with welded junctions

Figure 7 Typical Criciform Biaxial Test Specimens for Biaxial Geogrids

5.3 The Methodology Adopted for Biaxial CRS Testing

The test methodology employed for the biaxial testing was generally in accordance with BS6906, Part 1 (1987), but using the cruciform-shaped specimens. The test specimens were held in suitable clamps, which prevented slippage and specimen damage during testing, Fig. 8. The tests were carried out under a controlled environment of 20±2°C and 65 per cent relative humidity. The loads were applied to the test specimens under isotropic rate of deformation conditions of 1 mm/min, although it is possible to apply any combination in the apparatus. The loads were measured by two 4-bridge resistance load cells, calibrated to an accuracy of ±0.5N. The deformation rate applied. Deformations were measured at the clamps by means of Linear Vertical Displacement Transducers [LVDTs] and at various positions on the test specimens using digital photogrammetry. This was achieved using a 4 Mpixel digital camera mounted above the test specimen. The LVDTs achieved a resolution of ±10 μm, whereas the digital photogrammetry achieved at post-processing a resolution of ±50 μm.

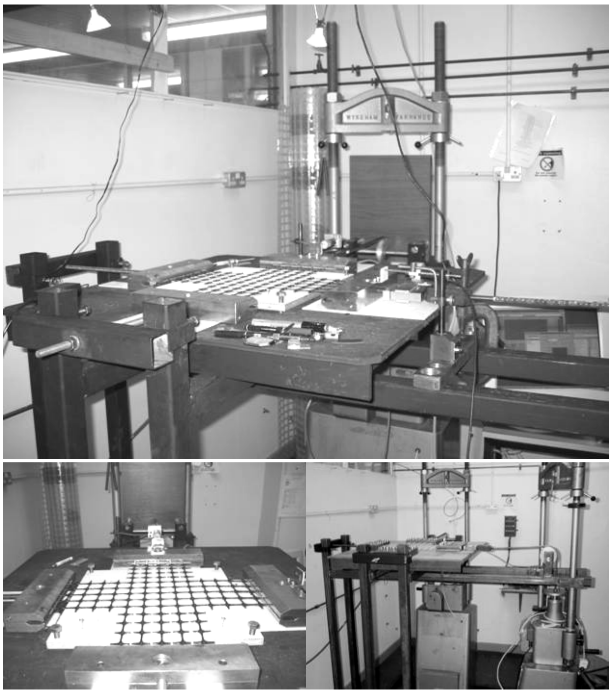


Figure 8 Biaxial CRS Test Apparatus

Figure 9 Biaxial Sustained Loading Test Apparatus

5.4 The Methodology Adopted for Biaxial Sustained Load Testing

The test methodology employed for the biaxial sustained load testing adopted the same clamping arrangements as those used for the biaxial CRS testing, Fig.9. The sustained loads were applied in an isotropic manner, ie the MD and XMD were the same and were rapidly applied and removed at the same time. The applied load levels ranged from 10 to 50 per cent of the Nominal Short-term loads provided by the manufacturers. Three tests were conducted at 30 per cent loading to check on reproducibility. All loads were applied in less than 5 secs., for 100 hours then unloaded in less than 5 secs., with recovery of the test specimen measured over a further 100 hours. The tests were again conducted in a controlled environment of 20±2°C and 65 per cent relative humidity. Deformation measurements on the test specimen were conducted using the photogrammetic technique employed for biaxial CRS testing.

5.5 Test Results

The test results obtained from biaxial CRS testing of the three biaxial geogrids shown in Table 1 are shown in Figures 1 to 3. These data indicate somewhat higher stiffnesses than obtained from the uniaxial CRS test data.

The test results obtained from biaxial sustained load test of the same three biaxial geogrids are shown in Figs. 4 to 6. These data indicate very much higher stiffnesses than obtained from the uniaxial sustained loading test data.

6. Discussion

Polymeric geogrids exhibit elasto-visco-plastic load strain behaviours, McGown (2000). The relationship between the various elastic, viscous and plastic components of their behaviour and their micro- and macro-structure, is complex. The presence of junctions in biaxial geogrids is of particular significance as they can modify their overall behaviour.

When subject to uniaxial loading/straining, the junctions require to strain in one direction only. When subject to biaxial loading/straining, the junctions require to strain simultaneously in two directions. Thus under biaxial load/strain conditions the junctions of biaxial geogrids will appear stiffer than under uniaxial load/strain conditions. This increased stiffness will be due to some increase in elastic stiffness but be predominantly due to increased visco-plastic stiffness.

The load-strain data obtained from the Uniaxial and Biaxial CRS Short-term tests are dominated by the elastic behaviour of the geogrids together with short-term visco-plastic behaviour. Thus as expected the differences between the measured uniaxial and biaxial behaviour of the geogrids is identifiable but not highly significant. In contrast, the change in load-strain behaviour identified from Uniaxial and Biaxial Sustained Load tests is highly significant. The difference in initial elastic strain under load is readily identifiable as is the difference in visco-plastic strains with time.

The overall effect of applying biaxial loading/straining to biaxial geogrids is thus a highly significant, time dependent phenomenon. The choice of design stiffness and strength will thus be time dependent and be influenced by the nature of the biaxial load/strain conditions applied. Thus the use of design data based on uniaxial testing may be problematic if the applied loads/strains in the soil reinforcement application are biaxial in nature and if the biaxial geogrids used have numerous and initially highly amorphous junctions. For this reason, the differences in uniaxial and biaxial behaviours of biaxial geogrids are likely to be highly product specific.

7. Conclusions

1. The various types of biaxial geogrids now available for use in ground engineering works, have been described and shown to represent a diverse range of polymers with many different micro- and macro-structures.
2. Three different types of biaxial geogrid have been tested under a range of different test conditions.
3. The Uniaxial CRS and Sustained Load tests were undertaken in conformity with existing standard test methods and provided test data which confirmed previously published stiffness and strength data for the geogrids. As expected, these differed from the Nominal Stiffness and Strength data provided by the manufacturers.
4. New Biaxial CRS and Sustained Load test apparatus and testing methods were described. Data obtained from these were shown to be significantly different from Uniaxial test data, particularly the Sustained Load test data.
5. It has been suggested that the use of design data based on Uniaxial testing may be problematic in situations where Biaxial loads/strains exist in applications.
6. It is suggested that the differences between the Uniaxial and Biaxial load-strain behaviour of biaxial geogrids will be highly product specific.

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