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The importance of the performance modulus Ep in the design of civil engineering structures

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ABSTRACT: In any Civil Engineering Earthworks application, where the physical strength of a geosynthetic material is being utilised, both a knowledge and understanding of the fabric's performance modulus is critically essential. In this paper, the Authors describe the internal fabric structure details that affect the performance modulus (Ep), which differs in fundamental respects from the stiffness modulus (E) of the constituent polymer alone. The paper also describes the design implications of different Performance Moduli on reinforced soil and embankment support under total and effective stress conditions. The implications and significance of variations in Ep on the application of safety factors and polymer creep are also discussed.

1 PERFORMANCE MODULUS - Ep

The Performance Modulus (Ep) of a geotextile or geogrid differs materially from the modulus of its constituent polymers prior to the fabric manufacturing process. The modulus of a material, such as polypropylene or polyester is generally similar in all directions within a given block of the polymer. It is defined as the stress level that would be necessary to induce a strain deformation of 100% in the material. The first thing to recognise is that the native polymer will not strain beyond 8%-15% without rupture. Secondly, at strains even as low as 2%-5%, polymers will experience creep. If these critical strains are not exceeded, then polymers will usually stabilise and further creep ceases.

The material modulus E, is therefore a theoretical figure which can not be directly measured for geosynthetics. The "100%" strain must be extrapolated, for example, by multiplying the 10% strain by 10, or the 5% strain by 20 , etcetera. This is valid in the case of a highly elastic material having a linear stress/strain response, but in the case of materials with non-linear responses - especially fabricated structures such as geosynthetics, the native polymer modulus can never be obtained and must be abandoned in favour of an effective modulus. Since, the engineer is interested in the utilisable forces conferred by the effective modulus, it can be called the Performance Modulus - Ep.

Nearly all fabricated geosynthetics exhibit a non-linear Performance Modulus, which describes the variation in strain of the fabricated product to increasing stress. This is usually plotted on a simple graph labelled stress-v-strain as shown in Fig.1.

There are two interesting factors to be noted in connection with this commonly-used graph type. Firstly, graphs are usually constructed with the variable input factor along the x-axis and the resulting respondent factor on the y-axis. In the case of this diagram, the stress (as applied to the specimen by a machine) is shown on the y-axis and the specimen's responding strain (as measured) is shown on the x-axis. Despite this inversion, it is convenient to leave the graph in this form because of the ultimate use to which it will be put by the design engineer. Secondly, in the case of geosynthetic testing, the stress is rarely (if ever) measured in the true sense of force/unit area, and so is not true stress. If a study of the pure polymer was being made, then the cross-sectional area of the test specimen would have to be measured to calculate the stress (force/unit area). However, in the case of geosynthetics, the engineer's interest is more pragmatic. There is the need to compare one geosynthetic with another in the form in which they are produced. So the graph is adjusted to have a vertical y-axis labelled as force/metre width - usually kN/M, which we can call the 'width stress' or σ_w. This is the second reason why 'E' should be substituted by the meaningful and more scientifically accurate term "Performance Modulus" - Ep.

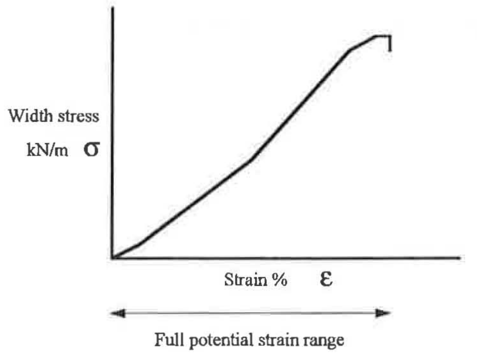

Fig.1 Typical non-linear tensile stress/strain curve for textile.

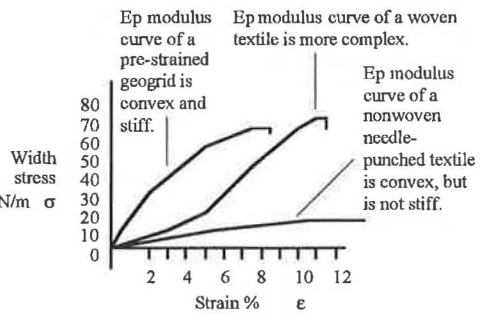

Fig.2. Explanation of different shapes of Ep curve for the three main types of geosynthetic.

2 COMPONENTS OF THE PERFORMANCE MODULUS CURVE

The curve components of a typical woven textile, a pre-stretched geogrid and a needlepunched nonwoven can be generalised as shown in Fig.2. The modulus curve of a typical reinforcing grid is usually convex as shown, since the polymer has been pre-strained in the manufacturing process. As soon as stress is applied, therefore, the grid (which has no loose fibres to deform) picks up the stress in the polymer and describes a stiff curve in the first instance. When strain levels increase, the effect of the original pre-straining becomes less marked and the curve tends to flatten. In the case of a nonwoven needlepunched, hardly any of the stress is carried in the polymer directly, since the fibre mat consistently yields, disentangling and thus producing a very flat stress/strain curve. In practice, the ultimate level of strain of these fabrics is commonly between 40 and 100%. The Ep modulus curve of the woven fabric is a combination of the previous two. At first fibre re-orientation provides a flat modulus, but rapidly the woven fabric straightens out and the stress is imposed on the polymer, leading to a rapidly steepening curve.

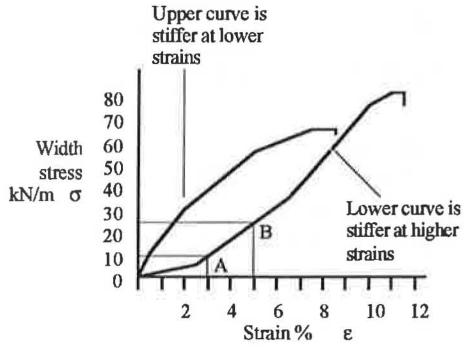

Fig.3. Illustration of different Ep moduli derivable from a typical curve - both at relatively small strain levels.

Two consideration are of importance in preparing any given design. Can the earthworks structure be designed so as to use the full range of available strain or must imposed stresses on the geosynthetic be kept sufficiently low as to keep the fabric within it creep-stable range (a factor dependent upon the polymer type)? Secondly, since the graph is non-linear, how can one define Ep for design purposes? The apparent Performance Modulus varies continuously depending upon the amount of width stress (σ_w) being applied and the consequent varying strain being developed.

Fig.3. shows two 'apparent' values of Ep taken at random along the curve.

If, on the lower curve, point A were taken to calculate the fabric's Ep then 10kN /m produces 3% strain, so linear extrapolation would give a Performance Modulus (Ep) of 10 x 33 = 330kN/m. Taking point B would give Ep = 24 x 20 = 480 kN/m. This product is 'less stiff' at low strain levels. It is intrinsically safe since unexpected increases in imposed stress result in increasing modulus being generated. However, conservatism in the design assumptions leads to a substantially increased cost, since a relatively low Ep modulus will have to be used to generate desirable low strains in the structure. In simple terms, the assumptions will tend to be safe but expensive.

The implications on design, of the upper curve, on the other hand are a) the given product is 'stiffer' i.e. has a higher Ep at low strain levels, and b) the given fabric will absorb more stress only at the expense of increasingly great induced strain. So, utilising the fabric at higher stress levels means that errors (unexpected variations) in imposed stress will have larger strain consequences than at lower strain levels. This must be considered when specifying partial safety factors. For example, if a safety factor of 1.1 (partial factor 0.1) is applied to the factors leading to imposed stress, then the effect of utilising that partial S.F. will be different at different width stress levels. This leads to the concept of the width stress-related partial safety factor SF^{str} where 'str' can mean stress or strain. In practical terms, this means that when stress-related partial safety factors are applied, they should only be specified at a given stress level for a given geosynthetic fabric. This must be stated at the time of specification into the design and must be re-examined in the event of a change of geosynthetic being proposed.

It is common for geosynthetic commercial literature to state only the ultimate Width Stress failure and Ultimate Strain levels of products. Even from the elementary considerations above it is apparent that this information is insufficient for responsible design purposes, Further, since no-one is going to design for a failure condition, why supply the fabric's failure information so emphatically?

3. TYPES OF Ep CURVE FOUND IN PRACTICE.

Fig.4 shows a typical multi-phase stress-v-strain curve produced by woven geotextiles. It can be seen that at the start, the curve is flat, with a large strain for a small stress increase. Subsequently, the curve steepens.

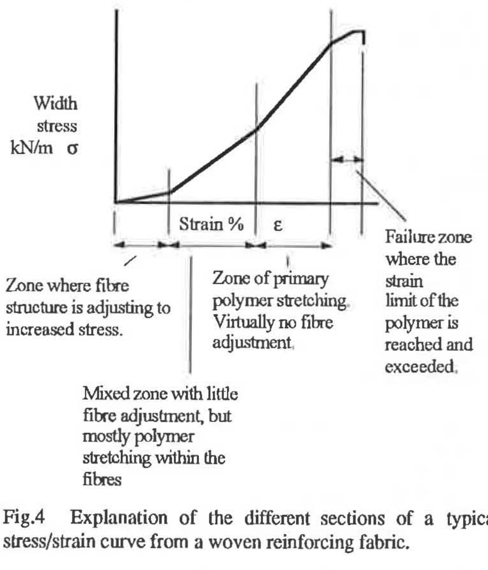

Fig.4 Explanation of the different sections of a typical stress/strain curve from a woven reinforcing fabric.

As increasing tensile force is applied to a test specimen of geotextile, there are two elements which can lead to the production of the early flat curve. Firstly, movement of the textile in the grips of the machine. This is only apparent if strain is being measured by measuring the clamp separation. It is removed as an anomaly if strain measurements are taken optically directly onto the fabric being tested. However, having removed this element of distortion, there is a second cause of initial high strain. This is the re-orientation and straightening of the constituent fibres as the early stress is applied. In the case of woven fabrics or grids, where fibres are already parallel with the imposed stress, this re-orientation quickly ceases and stress is passed into the polymer fibres which start to stretch. Therefore, as in the lower curve of Fig.3, the slope steepens and the stress/strain performance reflects more that of the textile polymer. In the case of nonwoven fabrics such as needlepunched and heat bonded textiles, the re-orientation process continuously dominates the deformation of the test specimen, so that induced strains are very high and a smaller proportion of the stress is carried in the polymer. So ultimately, it is harder for a nonwoven to reach the same ultimate stress levels as a woven or grid of the same polymer weight. Further, with a nonwoven, it is difficult to define a true strain failure point as the fibres just keep separating and re-orientating and a clean test break is hard to produce.

The first consequence of this to engineering design is that the width stress/strain curve is rarely linear and therefore a linear interpolation of the ultimate failure figure back to the origin would be dangerous since it would give an over-optimistic expectation of the resistive force available from the textile. The second consequence is that design engineers should attempt to minimise the initial stretching of geosynthetics in reinforcement applications by stretching the fabric prior to covering wherever possible. Even light hand tensioning is better than nothing in this regard. To understand the behaviour of any given textile in this context, it is necessary to have the full stress/strain curve available for study. Design engineers who design without this curve available are not designing at all - they are likely to be optimistically guessing. Design engineers should therefore not design using any fabric whose full stress/strain curve is not available.

This statement is all the more important in the case of the frequently available composite fabrics where two separate stress/strain curves are superimposed and where consequently two failure peaks result, as shown in Fig.5. This shows a typical curve from the tensile testing of a composite nonwoven felt with a woven scrim needled on.

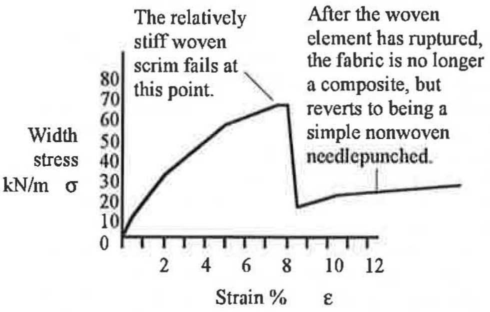

Fig.5. Ep Performance Modulus curve of a composite woven/nonwoven geotextile.

This type of product can certainly not be specified by its 'failure point', since it has two. The design implication of this is that only the performance figure of the woven scrim can be used unless the structure is to pass through a traumatic stress path. The strain path shown in the figure is that derived from a test machine, which permits the stress level to fall away to a balance point with the underlying nonwoven, after the woven element has failed. However, in reality, if the stress level does not fall away, as might well be the case in a real soil structure, then the consequence of rupture of the woven element would be instantaneous failure - if stress absorption was being used as part of the design criteria. The high strain capacity of the nonwoven element cannot be utilised in a design without passing through the high-stress rupture of the woven element.

4. PERFORMANCE MODULUS IN RELATION TO TEMPORARY ACCESS ROADS.

It can easily be overlooked that the performance modulus being utilised in the design and functioning of temporary access roads is that in the weft (or cross-machine) direction of a geotextile or grid. Often, the performance characteristics in the weft direction are decidedly inferior to those in the warp direction. The prime consequence of this is that engineers should remember to specify the weft performance as the required design parameters and secondly, the full weft direction stress-v-strain curve should be available before design is executed. Using this curve, the designer can assess the true working modulus of the weft fibres at the required strain levels of say, 4% or 8%. Excessively high strains can lead to the very rapid onset of creep failure in the textile polymer.

Although the use of the modulus of the fabric is fundamental to the calculation of the performance of the geosynthetic, a simple parametric study can show that for any given textile, variation from a linearly interpolated assumption as to the value of the Performance Modulus has little effect on the outcome. A typical calculation showed that for a 12 tonne laden vehicle making 1000 standard axle passes over a 10 kN/m shear strength soil, variations of +-2kN/m (20%) in the modulus point, generated less than 3mm difference in road thickness.

The outcome of this is that whilst optimum economy of design will be obtained from the use of the actual stress strain test curve, nonetheless, the use of a linearly interpolated value from the ultimate stress/strain failure point would be a realistic method to adopt.

5. DRAINAGE APPLICATIONS AND PERFORMANCE MODULUS.

In drainage applications, the strength of the fabric per se is not being utilised. However, the stress/strain behaviour is. In particular, the ability of a geosynthetic filter fabric to extend is often one of its most valuable features. It is rare that calculations are conducted on this matter and the behavioural shape of the stress/strain curve is not of any consequence in general applications. It is valid to use the ultimate stress/strain failure point as an indication of the overall extensibility of the fabric.

6. IMPLICATIONS OF THE SHAPE OF THE Ep CURVE ON REINFORCED SOIL SYSTEMS.

It is in this aspect of design that the knowledge of the shape of the stress/strain curve is most important, because it is in this application that long term forces are imposed on the geosynthetic. Any errors in the assumption of the shape of the Ep curve will be multiplied through a series of demanding partial safety factors to lead to significant detrimental economic impact on the project. A typical calculation can demonstrate this.

Reinforcement Fabric ... woven geotextile
Ultimate failure stress ... 100 kN/m width.
Ultimate failure strain ... 10%
Constituent polymer ... polyester
Creep Factor 2.00
Structural fill ... angular gravel
Density of fill ... 20 kN/m3 ... +2%
Factor 1.02
Peak angle of friction (phi) ... 40 degrees
Percentage damage expected ... 20%
Factor 1.25
Grip efficiency of textile ... 80%
Environmental degradation ... 2%
Factor 1.02
Required life ... 60 yrs Degradation 50%
Factor 2.00

These parameters are fairly simple for the purpose, and so may suitably serve for this illustration. Take, within this structure, a textile at a depth of 5 metres below the surface. The vertical stress on the textile will be 100 kN/m2. Say that the outward force is 0.4 of the vertical (40 kN/m2), then if the textile spacing is every 0.5m, there will be a need for a textile with a working strength of 20 kN/m width.

In the case of the textile above, assuming that the required working strain is 2.5%, then the assumed working load, on a linear interpolation basis, will be 25 kN/m. As illustrated in the Figs. above, it would take only a small tail effect caused by the re-orientation of the fibres to modify the 'straight line assumption' and produce an actual performance stress level of much less. For example 15 kN/m.

The various partial safety multipliers must now be applied, for site damage, for friction loss between textile and gravel, for environmental deterioration and for ageing over the life of the structure. The partial safety factors that affect the calculation of working stress in the first instance are:-

a) the deterioration with time, which in this case assumes that the geosynthetic will have lost half its original strength over 60 years through polymer degradation
b) possible slight local increase in fill density
c) percentage of damage expected during placement
d) environmentally induced deterioration, which in this case is assumed to be nominal.

To allow for these factors, the nominal strength of 20 kN/m will have to be multiplied by 1.02 x 1.25 x 1.02 x 2.00 to produce a required working strength of 52.02 kN/m. If the curve is non-linear and (as is commonly the case in reinforcing geotextiles) it is below a linear interpolation, then the real available working stress may only be 15 kN/m. When multiplied by the partial factors, this comes to only 39.01 kN/m. The 5 kN/m assumption error is multiplied into a 13 kN/m specification deficit.

As a result, strain would be increased by over one third to something in the order of 3.75%. A design requirement of 2.5% would be translated into 3.75% as a result of the assumption of a linear interpolation of the Ep curve. In practice, the linearly interpolated design would underestimate the required amount of geosynthetic by 39:52 i.e. 25%.

Given a more critical scenario, where the required strain level was apparently easier at say 4%, the overestimation of the modulus curve could result in the textile being stressed above its creep resistant level, thus leading to premature failure of the structure.

For example, if the required strain level had been 4.5%, then the experienced strain could have exceeded 5.5% and probably led to premature failure after several years. It is more dangerous that this miscalculation will be unlikely to lead to immediate or rapid failure of the structure. The further implication of these observations is that design strain levels in reinforced soil elements should be kept to substantially below the percentage level at which creep is induced for each type of polymer, if the test curve is unavailable. Far better to have available the actual test curve and make an accurate design. On a reliable curve, strain will have been measured directly on the fabric, not between the jaws of the testing machine.

7. IMPLICATIONS OF THE SHAPE OF THE Ep CURVE ON EMBANKMENT SUPPORT DESIGNS.

It is most common for embankment support designs to stress fabric for a relatively short period of time. Calculations are usually based upon total stress analysis for the temporary support of the embankment, whilst the long term unsupported stability is assessed from effective analysis. If embankments are to be supported in the long term, then the comments made in Section 6 apply. For short term analysis, most of the comments apply in the same way. Factoring for age is not usually as severe on an embankment design, but since this is not one of the immediate partial factors used in the considerations, it has no direct effect on the underestimation likely to arise from the lack of a test curve. It is a commonly observed feature that the slope of stress-strain curves are unaffected by ageing; rather their ultimate failure point reduces down the existing curve slope. Therefore age will not cause an interpolation error.

In the case of basal reinforcement of embankments, there are other design implications than for reinforced soil walls. In particular, when an embankment is to be constructed over a soft subsoil, the stiffness of the geotextile reinforcing layer is of critical consequence to the outcome of the success of the design. One of the main objectives of the textile is to reduce shear stresses in the underlying soft soil, thus keeping the bearing capacity as high as possible. If induced strains are underestimated by 25%, then the outcome can be a substantial reduction in the actual global safety factor of the structure. It is possible that this could lead to failure through foundation movement or creep of the geosynthetic. In the first case, foundation failure can result if the bearing capacity is exceeded. In the second case, for total stress analysis, imposed stresses and strains can be very high on embankment support textiles. This is permitted in the design for short periods whilst the pore water pressures in the foundation soil dissipate. It is well known that small increases in stress above the creep onset point result in disproportionately quickening failure. Polyester will fail over years at 60%, months at 70%, weeks at 80% and hours at 90% of ultimate load. This is intended to illustrate the increased danger of induced creep failure in the case of embankments, owing to the higher level of proportional stress that is accepted in total stress design.

8. IMPLICATIONS OF THE SHAPE OF THE Ep CURVE ON BONDED COMPOSITE PRODUCTS.

In the case of bi-component bonded products, the stiffer of the two will clearly carry the majority of the stress under tensile loading conditions in a test machine. However, it is interesting to consider in more detail the mechanisms whereby stress can be imposed onto a composite fabric under real site conditions.

Where a two-component bonded product is subject to stress, it can be subject to shear forces either from the lower modulus or the upper modulus side of the product. Similarly, there may or may not be resistance to that shear on the other surface. Two examples are given below in Fig.6.

Take Case A in Fig.6. This is typical of a composite product laid on a slope with an overlying layer of granular material. In this instance, if the upper layer is the lower modulus, as shown, then this layer will deform extensively trying to impart shear forces to the stiffer layer below. (Gravity loading is discounted since it is assumed that the overlying stress is considerably greater than self-weight induced stresses). As the stress increases on it, the upper surface will try to extend, but the lower interface will be held back by the higher modulus lower material. At this interface, high differential shear stresses will be generated which mean that the shear strength of the upper layer will be the limiting factor in the ability of the composite to absorb stress. The lower layer will never be stressed in shear to its ultimate capacity and the design will be built around the properties of the upper lower-modulus layer.

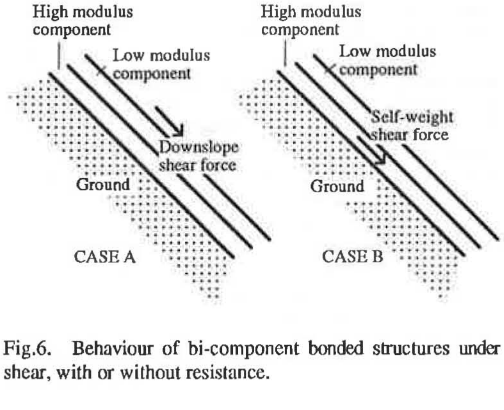

Fig.6. Behaviour of bi-component bonded structures under shear, with or without resistance.

If the scenario in Case A is reversed and the higher modulus material is above, the stress limitation is the same, insomuch as the stiffer material will transfer the applied load downwards into the softer material below, which will attempt to deform, but be restrained at the material interface. In effect, the lower modulus material again dominates the design considerations.

The ability of the composite pair to reach peak shear levels will depend upon the lower layer's friction angle with the underlying soil. Usually, this will be considerable lower than the inter-layer cohesion, so the product will tend to slide before failure occurs at the bonded interface or else the lower layer will be disrupted by shear.

Case B, on the other hand represents a different case. This is the situation where a composite membrane is laid on a sloping surface and is left exposed, so its shear force is generated by gravity loading from its own weight. This is more complex and there is a difference here. The material above, if of a lower modulus will only exert its own internal weight stress onto the underlying fabric. The underlying material is stiffer and is generating its own body weight. Clearly, in this case, the overlying fabric is highly unlikely to cause its own self rupture, since each square unit will be able to transmit its own weight downwards into the stiffer layer below. Shear deformation will be limited to slightly above that of the underlying material.

The underlying material will now act as a single component unit with a small imposed downwards shear load. The modulus of this material is the dominating factor in the design requirement in terms of its own internal stability against its own plus the imposed dead-weight. Its angle of friction with the ground is also a factor which will be taken into account in consideration of the ultimate force which can be imposed on itself. At a certain angle, the material will either slip or be damaged, thus limiting the force capable of being generated internally to cause shear rupture.

9. IMPLICATIONS OF THE SHAPE OF THE Ep CURVE ON MULTI-LAYER CONTAINER DESIGNS WITH SLOPING EDGES.

Frequently, multi-layer non-bonded structures are constructed where, for example, geomembranes are both underlain and overlain by geotextiles for protection purposes. These scenarios are very similar to those discussed in Section 8, with the exception that there are often three or more layers and the inter-layer forces are not exerted by chemical bonding, but by friction.

In this case, shear forces are transmitted internally within the composite via inter-layer friction. So the first principle for consideration in the design considerations is the relative values of the coefficients of friction between the various layers. The weakest inter-layer friction value will provide the lower-bound limit on shear stresses which can be generated within each polymer layer. Total forces capable of being imparted downwards are limited by friction considerations.

10. IMPLICATIONS OF THE CONCEPT OF PERFORMANCE MODULUS ON DATA INPUT TO FINITE ELEMENT MESH AND SIMILAR COMPUTER PROGRAMS.

Bearing all of the above in mind, it is interesting to look at the method and validity of input data and methods used in the construction of FEM programs for design purposes.

The first thing necessary to say is that FEM program users should be particularly careful to avoid believing that they have accurately simulated the real site conditions. No matter how good the algorithms and the data, the output is just a simulation and must always be treated with caution. It is common to see FEM reports using definitive language. This tendency must be resisted.

For example, an FEM package will require the input of the Young's Modulus E into the mesh, when a geosynthetic is to be emulated. How can this be done? We actually produce a Performance Modulus Ep from our test procedures. So with a 2mm thick grid, for example, should we assume that the input layer is a 2 mm thick uniform layer of a reduced modulus as tested, or a very thin layer of an enhanced modulus which reflects the pure polymer's performance.

Perhaps a useful way is to calculate the actual cross sectional area of the grid per metre width and apply the Ep stress figure to that, to get a real Modulus. Then, reduce the thickness of the inserted layer to match the measured cross sectional area over the one metre width of the model.

The upper of the two curves in Fig.7 might be taken as representing a typical commercial 65 kN/m width rectilinear geogrid stress/strain plot. To calculate the grid's Ep (Performance Modulus) then 30kN /m produces 2% strain, so linear extrapolation would give a Performance Modulus (Ep) of 30 x 50 = 1500 kN/m width. But to assess a Young's Modulus, we need to know the cross sectional area over which the force of 1500 kN will be applied. We can either (A) assume a nominal 2 mm thickness, or (B) we can look at the actual cross sectional area of the polymer being stressed in the grid.

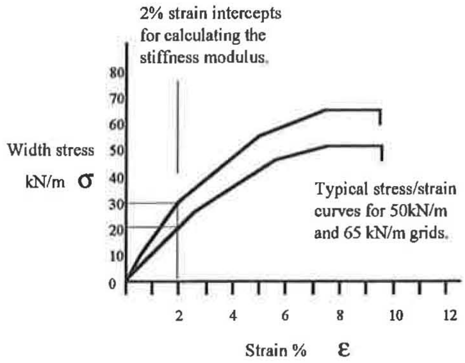

Fig.7. Typical WidthStress vs Strain curves for pre-stretched rectilinear geogrids with ultimate rupture levels of 50 - 65 kN/m width.

In the first instance, we would come up with a cross-sectional area of 1 metre x 0.002 metres = 0.002 m2, or else we can look at the cross section of the actual polymer being distorted, which is probably 20 grid tendons of cross section 10 mm2 along the 1 metre length, leading to a cross-sectional area of 200 mm2 = 0.0002m2.

(Note that it is not the rib junctions that do the work, it is the pre-stressed tendons at their thinnest point at the central point of the rectangle edge, not at the corners of the rectangle.)

So a force of 1500 kN is needed to create 100% extension over either a cross sectional area of 0.002m2 or 0.0002 m2

In case A, this is 1500/0.002 kN/m2 = 750,000 kN/m2
In case B, this is 1500/0.0002 kN/m2 = 7,500,000 kN/m2

Since 1 N/m2 = 1 Pa, 1kN/m2 = 1kPa and 1 MN/m2 = 1MPa.

Therefore, the Young's Modulus in case A would be 0.75MPa and in Case B 7.5MPa.

The Case B interpretation is possibly the most useful, and it is interesting to note that these calculations produce similar levels of modulus to those of typical soft soils. The reason why grids and textiles work is that they do provide a tensile element within what is essentially a non-tensile granular medium. They perform well because they have similar moduli to the soil and thus in many applications, permit the soil to mobilise its own internal shear strengths before relying upon (or at the same time as relying upon) the tensile strength of the synthetic geogrids or geotextiles within it.