MECHANICAL STABILIZATION OF UNBOUND LAYERS: EFFECT OF GEOGRIDS ON LOW STRAIN BEHAVIOUR OF GRANULAR MATERIALS AND ESSENTIAL CHARACTERISTICS FOR OPTIMUM PERFORMANCE IN PERMANENT ROADS

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ABSTRACT

The use of geogrids in mechanically stabilized earth (MSE) structures and for trafficked areas over soft soils is well known. The essential characteristics of geogrids for MSE have well established over many years and are incorporated into national and international codes and standards. However, the mechanisms by which geogrids function in permanent roads and therefore the essential characteristics of geogrids operating at low strains in this application have often been disputed. This paper will present results from several recent research projects that identify the stabilization mechanisms that operate and identifies essential characteristics for geogrids in this function. A comparison is made between the stabilization function of geogrids and tensioned membrane reinforcement function of geogrids and the significance of this functional difference in the selection of essential geogrid characteristics for specification purposes. Such an understanding is essential if specifications are to protect designs that utilise the benefits of mechanical stabilization to increase pavement life.

Keywords: *STABILIZATION, GEOGRID, PAVEMENT*

1 INTRODUCTION

Design methods for MSE structures incorporating geosynthetics are well established. The design usually comprises an external stability check plus an internal check on stability, examining various potential failure surfaces, checking for tensile failure of the reinforcement and pull out of the reinforcement. Various codes have been published and are in regular use around the world. Required performance characteristic for the reinforcing elements are straightforward. The pull out resistance for various fill types is needed and a long-term design strength. The design strength is usually obtained by applying reduction factors to the short-term strength to take account of durability, installation damage, creep reduction factors, etc. Determination of short term tensile strength and long term creep performance is well understood and well documented. When it comes to road pavement applications the situation is a little different. There are no national or international design codes incorporating the effect of geogrids. Most commonly used road design methods are based upon empirical performance data. There are no geogrid characteristics that have been proven to directly relate to performance in a road and no pavement design method that allows the incorporation of specific geogrid characteristics to improve structural performance.

Most engineers are familiar with the use of geogrids in dealing with soft ground problems. In this application the geogrid facilitates the placement and compaction of a granular layer and provides additional load capacity to support construction traffic and provide a foundation to the upper layers of a pavement. However, there are also very real economic benefits to be gained from taking advantage of the effect of geogrid stabilization on the performance of the full pavement in permanent roads. The stabilization of a granular layer with an efficient geogrid can provide enhanced layer stiffness at low strain and reduce permanent deformation. These improvements to the behavior of a granular layer can contribute to the trafficking capacity of the pavement and increase the pavement life.

If the characteristics of the stabilized layer are proven and understood, the geogrid effect can be incorporated into standard pavement designs. The most commonly used design methods globally are based on empirical principles. Improvement factors obtained from monitored trials and research may be used to modify these empirical methods to incorporate the geogrid effect. The design method described by the American Association of State Highway Authorities (AASHTO, 1993) are used by most US States and in a number of countries globally. AASHTO have recognized the potential benefits from geogrid inclusion by publishing specific guidance on their use in permanent roads in the form of R50-09 (AASHTO, 2010) setting out standard practice for geosynthetic 'reinforcement' of aggregate base course layers in flexible pavement structures. The R50-09 document recognizes the potential for improved pavement life as well as reduced layer thicknesses. There is recognition that different geosynthetics perform differently and that benefits associated with the design carried out for one geosynthetic product cannot necessarily be translated to another product. R50-09 states that benefits cannot be derived theoretically based on specific geosynthetic characteristics and requires that 'field verification' is conducted for designers to validate their design approach. Accelerated Pavement Testing (APT) at full scale has been used to develop product specific performance data and validate empirical design method

2 HOW GEOGRIDS WORK IN PERMANENT ROADS

When a geogrid is incorporated into a granular material the particles interlock with the geogrid and are confined within the geogrid apertures. The degree of confinement depends upon the aperture size in relation to the particle size, the stiffness of the geogrid, the geometry of the geogrid and the efficiency of the junctions (Giroud, 2009). The requirement to maintain small deformations in the surfacing means that the geogrid will be working at low strains, typically less than 0.5% (Jas, Stahl, te Kamp, Konietzky, & Oliver, 2015). Hence geogrid tensile stiffness at low strain is a key performance characteristic.

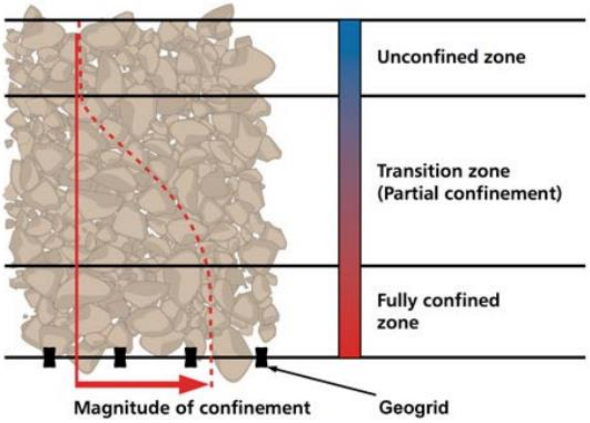

Figure 1 Zones of confinement

By confining granular particles within the apertures of a stiff geogrid, the particles are restrained from moving laterally. A granular material is strain-dependent; lateral restraint provided by the geogrid reduces strain and thereby increases the stiffness of the granular layer. Evidence of lateral restraint has been provided by an increase of horizontal stress measured in a base incorporating a geogrid (Wayne, Fraser, Reall, & Kwon, 2013). Granular particles immediately adjacent to the interlocked particles are themselves restrained by particle to particle interlock. Thus the influence of the geogrid inclusion extends beyond the geogrid particle interface. It is however reasonable to assume that the influence of the geogrid on the stiffness of a granular layer will decrease in relation to the distance from the geogrid. An illustrative representation of this variation in geogrid influence is shown in Figure 1. The magnitude of the confinement effect – and hence the magnitude of enhanced stiffness is divided into three zones of confinement..

Figure 2: Multi-layer shear box to investigate stabilization effect at various levels above geogrid

Evidence for this zone of confinement is provided by innovative use of a multi-level shear box at Universitas-Gyor. (Horvat, Szabolcs, & Zoltan, 2013) (Cook & Horvat, 2014). The 1m by 1m shear box is shown in Figure 2. Shear resistance is increased by the inclusion of a geogrid. Several different forms of geogrid were tested as well as the non-stabilized condition. Both compacted and uncompacted conditions were tested for each case. The effect is evident in varying degrees for a range of geogrid types.

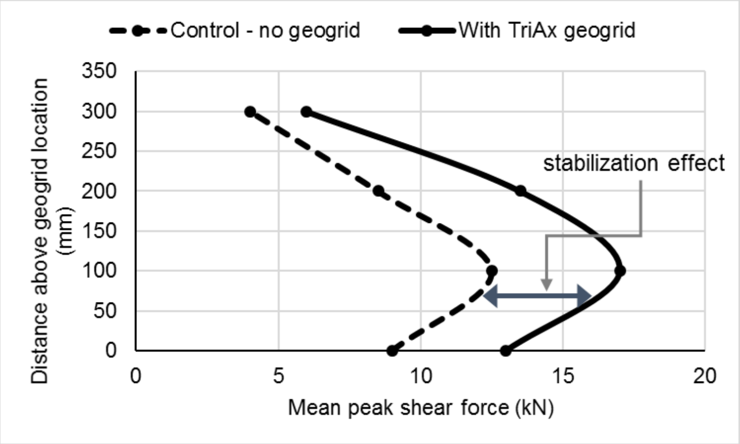

Figure 3: Shear force at various distances above the geogrid location showing effect of stabilization geogrid

Figure 3 shows the average shear force at various distances above a multi-axial type geogrid layer. The effect extends up to a distance of 30cm from the geogrid, with the effect reducing with distance from the geogrid.

Further evidence for the stabilization effect and the existence of a zone of confinement comes from Discrete Element Modelling (DEM) of a geogrid below a granular material. (Jas, Stahl, te Kamp, Konietzky, & Oliver). Figure 4 shows the model construction comprising a 120mm layer of granular material above the geogrid with a soft clay subgrade layer beneath the geogrid. Figure 5 illustrates the location of each of the layers for which the stress condition is examined. The plate load is applied for five cycles. The stresses in the granular material directly below the ram for each load application (BL1 to BL5) are shown in Figure 6. The dotted lines are for the non-stabilized condition the continuous lines (with BX suffix) are stabilized with geogrid. The geogrid-stabilized model takes a higher horizontal stress. This effect is shown in a zone of influence extending 8 – 10 cm above the geogrid. Other DEM studies have further demonstrated that "enhanced" properties exist in a mechanically stabilized layer within a "zone of influence" that is in close proximity to the geogrid and extends away from the geogrid for a distance that will vary depending on aggregate type, geogrid type, and construction (Konietzky, te Kamp, Gröge, & Jenner, 2004) (McDowell, Harireche, Konietzky, & Brown, 2006).

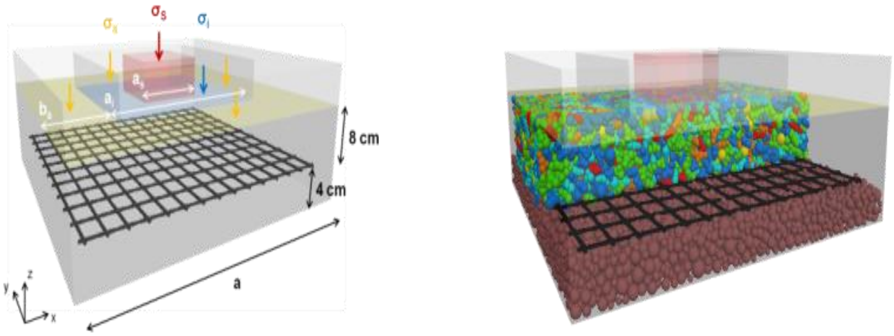

Figure 4 DEM model of plate load test with geogrid between aggregate and clay subgrade layer with surcharge applied

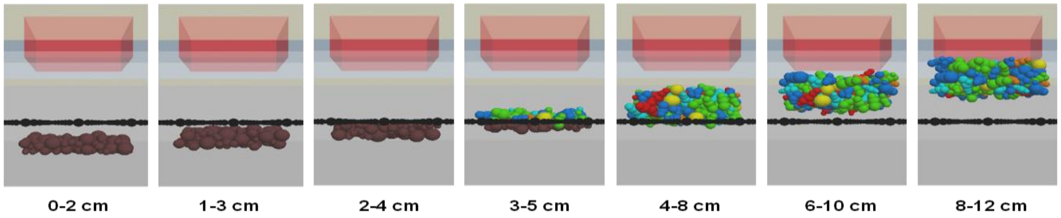

Figure 5 The stress condition is examined within seven separate layers

Discrete Element Modelling DEM has also been used to investigate the geogrid aggregate interatction in a mechnically stabilised layer below a moving wheel. In this study (Jas, Stahl, te Kamp, Konietzky, & Oliver, 2015) modelled soils and geogrids with fully calibrated micromechanical properties were set up shown in Figure 7. The sugrade was modelled as a soft layer to intensify the effective mechanisms.

Two forms of geogrid were modelled and their behaviour compard in the model. Both were integral geogrids; a biaxial geogrid and a multi-axial geogrid of similar apperture size and weight.

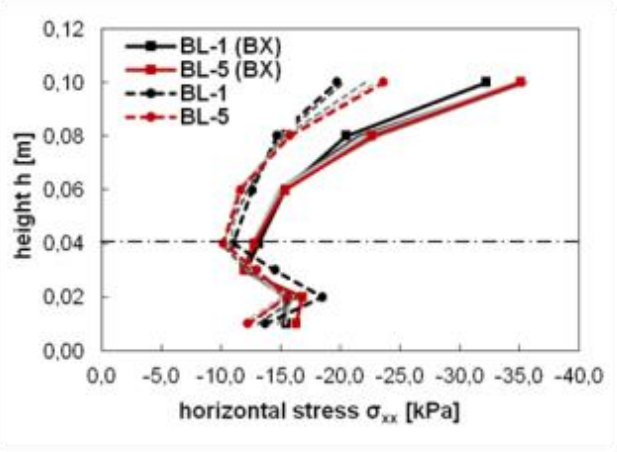

Figure 6: Horizontal stresses in the mechanically stabilized layer at seven levels for five load cycles under load

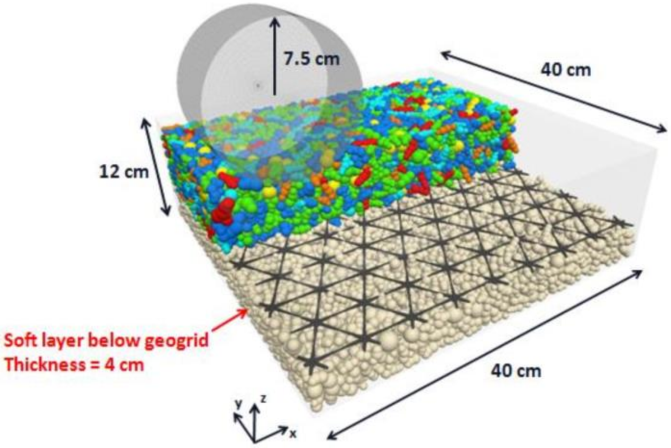

Figure 7: DEM Wheel trafficking simulation set up

Figure 8 shows snapshots of a cross-section showing the individual particles and indicating with colors the magnitude of their displacements. The displacements of the granular particles in line with the wheel path show a clear reduction of the subgrade deformation when stabilized with a geogrid. Obviously, the maximum displacements are directly under the wheel, and reduce downwards. The stabilizing geogrids show a clear borderline of the displacement, protecting the weaker clay efficiently. There is some difference between a biaxial geogrid and multi-axial (TX) grid, with the multi-axial geogrid showing a reduced degree of particle displacement

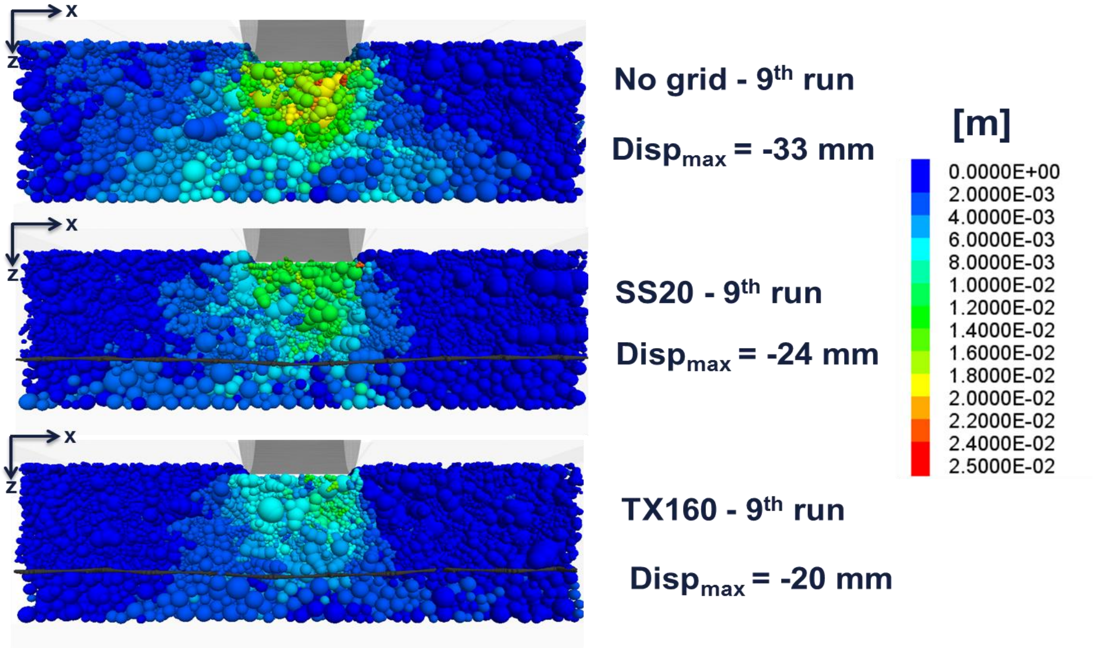

Figure 8: Particle movement in the XZ direction under rolling wheel load, comparing non-stabilized sections (top), biaxial geogrid stabilized (middle) and multi-axial stabilized (bottom)

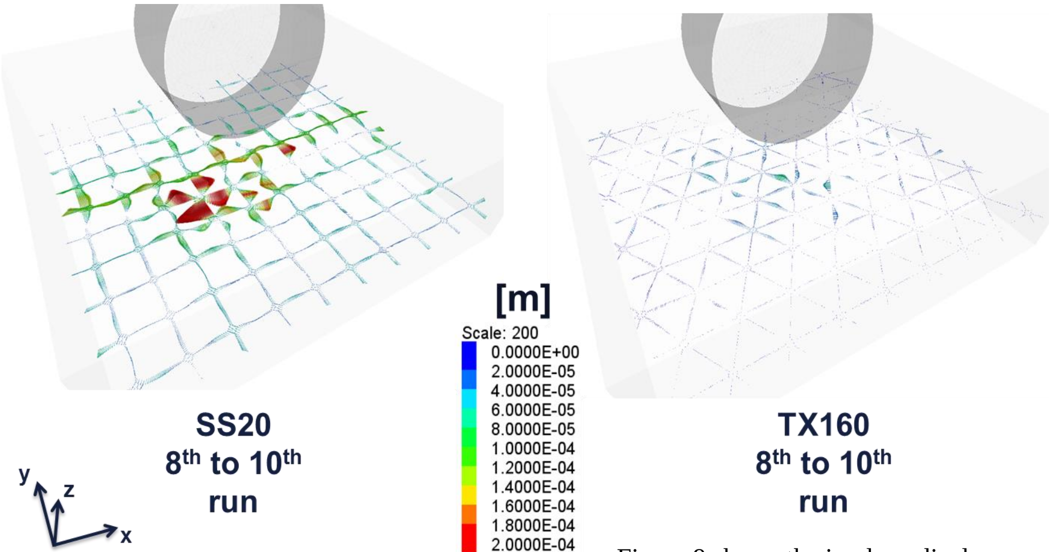

Figure 9: In-plane geogrid displacement under rolling wheel load between 8th and 10th pass, comparing biaxial geogrid stabilized (left) and multi-axial stabilized (right)

Figure 9 shows the in plane displacements in the geogrid between wheel run 8 and 10. The displacements are very small for both geogrid types and concentrated close to the centre of load application. The biaxial geogrid rotates around the node. The forces exerted by the aggregate particles of the sub-base on the ribs of the grid bend the ribs and are transferred to the adjacent ribs through the node. Clearly the stiffness and strength of the node will have some influence on performance

In order to provide a visualisation of the tensile behaviour of the geogrid, In Figure 10 the stresses between the spheres have been transformed into forces, to eliminate the efect of changing rib cross-sectional area.

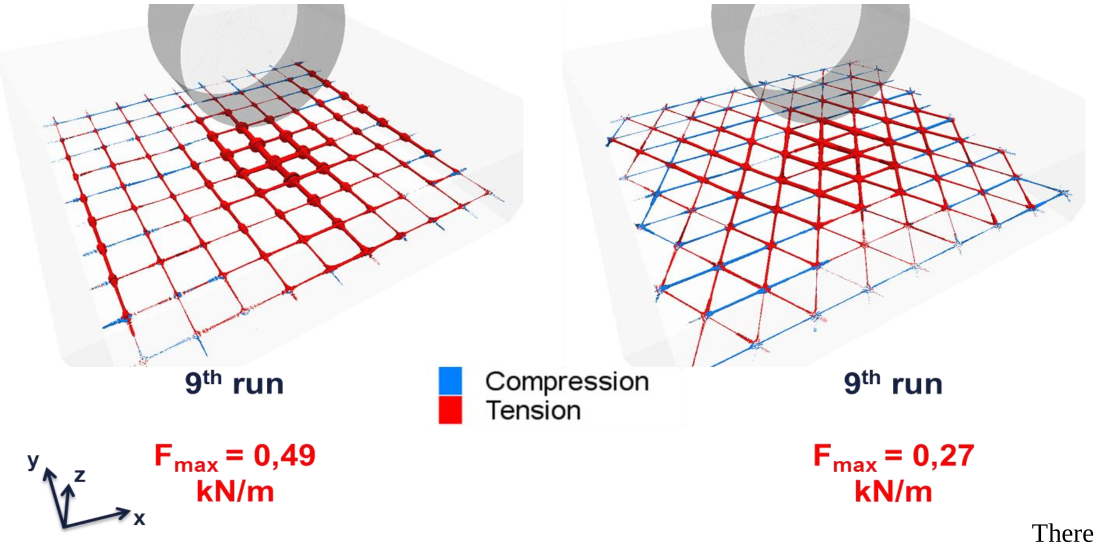

Figure 10: Forces in geogrid ribs under rolling wheel load between, comparing biaxial geogrid stabilized (left) and multi-axial stabilized (right)

There are four points that need to be noted:

1. In both geogrid cases the ribs are seen to be not only under tension: but also under compression away from the centre of load. This is quite logical, but probably never well understood.
2. The magnitude of the forces and strains in the grids (both in tension and in compression) are very small. They are less than 0.7 kN/m' for the biaxial geogrid and less than 0.3 kN/m'. for the multi-axial (TX) geogrid The strains are on the order of 0.5% This is a very small proportion of the total tensile capacity of the geogrids and it confirms that ultimate tensile strength is not relevant for stabilization applications.
3. The forces in the grids in Figure 10 show that the biaxial grids have a higher tensile force in the ribs immediately below the load, indicating high confinement in this region, but there are also tensile forces extending some distance from the load in the ribs in the transverse direction that transfer the load across the wheel path, anchoring into the adjacent areas that are not loaded. There is compressive load in the line of the wheel path. These areas of tensile load transfer are not very wide and the loads are relatively small. But the mechanism is one of tension in the ribs and confinement in the aggregate.
4. The multi-axial (TX) grids appear to transfer the forces from the granular particles via a different mechanism. There is tension in concentric hexagons centred below the load (See Figure 10). When these hexagons are in tension they confine the granular particles due to a tension-ring effect (that we know as an essential component in dome structures). Observations of video of the rolling wheel model created from the wheel passing from one end to the other shows that the active 'tension rings' transfer along the geogrid always centred under the load, in a sequential overlapping tension ring effect.

3 INCREASED MODULUS AND DEFORMATION RESISTANCE OF A MECHANICALLY STABILIZED LAYER

There are standard test protocols that can be utilised to investigate the stabilization effect of geogrids on a given granular material. In one such study the researchers (Kwon, Wayne, Norwood, & Tingle, 2012) utilized a triaxial cell test set up (Figure 11) to derive the resilient modulus of a poorly graded silty gravel (crushed limestone) aggregate material following the AASHTO T307 procedure (Determining the Resilient Modulus of Soils and of Aggregates) and NCHRP 598 (Repeated Load Permanent Deformation). Both stabilized and non-stabilized samples were tested. The geogrid used was a hexagonal multi-axial punched and drawn geogrid (similar to the study above) placed in the mid-point of the samples. The results were used by the researchers to fit a constitutive model where resilient modulus can be predicted for any level of stress. A comparison of the predictive modulus values between stabilized and non-stabilized materials showed that stabilized specimens exhibited a stiffness benefit ranging from 5% to 20% depending on the stress regime used for comparison (Figure 12). The researchers point out that while the differences in calculated modulus can be small, these differences can have a significant effect on pavement performance.

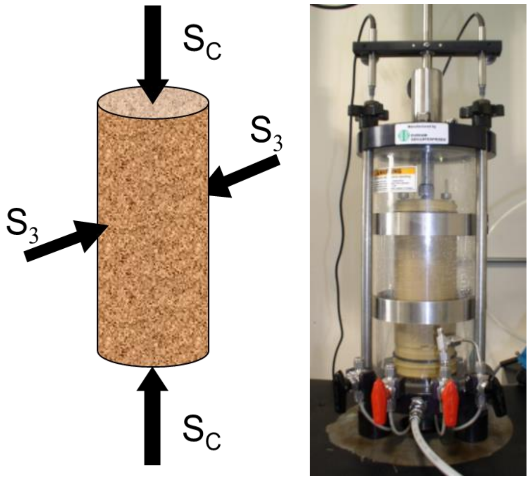

Figure 11: Triaxial test set up with cyclic stress (Sc) and confining stress (S3)

The permanent deformation tests conducted in accordance with NCHRP 598 protocol gave a deformation response as shown in Figure 12. Testing is normally terminated after 10,000 cycles under this protocol as shake down is readily achieved and if continued, plastic strain leads to failure of the specimen. The non-stabilized sample was able to withstand the 10,000 cycles as prescribed by the NCHRP 598 test and showed axial strain of only 4.5%. This same specimen was able to withstand an additional 6,690 cycles at 180psi axial stress before reaching the 10% strain criteria.

The stabilized sample did not exceed the shakedown limit even after an 8% axial strain deformation level and was able to withstand the 10,000 cycles at a strain of only 3.9%. This same specimen was able to withstand an additional 10,000 cycles at 180psi axial stress and only reached 6.5% strain, indicating a greater resistance to permanent deformation compared to the same material without stabilization.

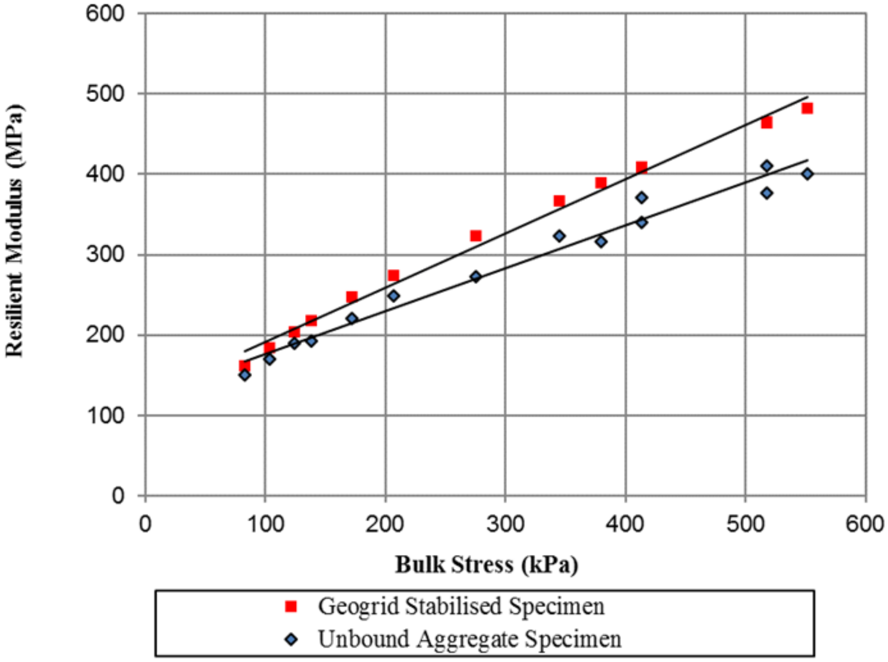

Figure 12: Repeated load, permanent deformation (following NCHRP 598 protocol)

4 FULL-SCALE ACCELERATED PAVEMENT TESTING

Kwon et al (2012) have identified a useful process to quantify the effectiveness of geogrid stabilized pavement structures based upon the framework adopted by the Caltrans Accelerated Pavement Testing Program (Harvey, Roesler, Coetzee, & Monismith, 2000). The CAL/APT process is summarized in Figure 13. A hypothesis is put forward – the solution concept. This must then be investigated and quantified in laboratory tests. Analysis is then carried out to predict the in-situ results. If the concept is valid, then a programme of full scale assessment follows. APT facilities can by usefully employed for this stage. The full-scale testing should validate the concept and enable benefits to be quantified. If successfully validated the concept can be accepted and implemented.

The concept of utilising a mechanically stabilized layer to improve the performance of flexible pavements has been shown to be feasible in the laboratory. By enhancing base layer stiffness and reducing permanent deformations the potential exists to increase the life of pavement structures by the incorporation of a suitable geogrid. Thus proof of concept has been achieved. Validation for specific geogrid products at full-scale is then needed to prove the solution viability. This is aligned with the recommendations of AASHTO R50-09 which confirms that benefits for specific geogrids cannot be derived theoretically and that a design carried out for one product cannot easily translate to the same benefit for another product. Test sections are required for a specific product followed by field verification to affirm the design approach.

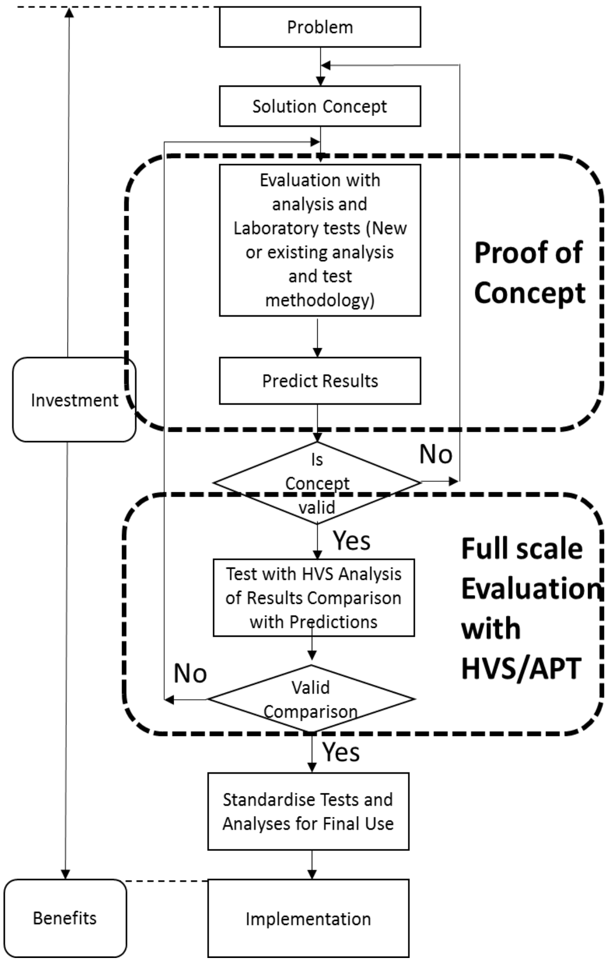

Figure 13: The CAL/APT framework for validating stabilized pavements (after Harvey et al, 2000)

The APT facility at the US Army Engineering Research and Development Centre has been utilized for two major test programs to investigate the performance benefit of hexagonal multi-axial geogrids. The Phase 1 testing evaluated the performance of a mechanically stabilized base in a thin, flexible pavement. Three test sections, one with a mechanically stabilized base and two non-stabilized test sections were constructed under controlled conditions (Figure 14). The stabilized section was paved with 50mm of asphalt and the two control sections with 50mm and 75mm of asphalt respectively.

The granular base was 200mm for all sections and subgrade was designed to have a CBR of 3%. The geogrid was placed at the subgrade/base interface. Results from Phase 1 have been reported elsewhere. (Jersey, Tingle, Norwood, Kwon, & Wayne, 2012). Permanent surface deformation was measured periodically throughout trafficking (Figure 15). The results indicated that the onset of rutting occurred more rapidly in the non-stabilized sections than in the geogrid-stabilized section.

FWD readings were taken periodically throughout the trafficking. The modulus calculated from this data shows that the inclusion of the stabilization geogrid in section A increased modulus compared to the other two non-stabilized sections. The data obtained were also used to investigate centerline deflection and calculate Base Damage Index (BDI). The reduced deflection values of the stabilized section A indicated improved retention of pavement strength compared to the non-stabilized sections, B and C. The BDI was used to identify strength and stiffness of the base layer. Pavement stiffness was seen to be increased due to the inclusion of the geogrid

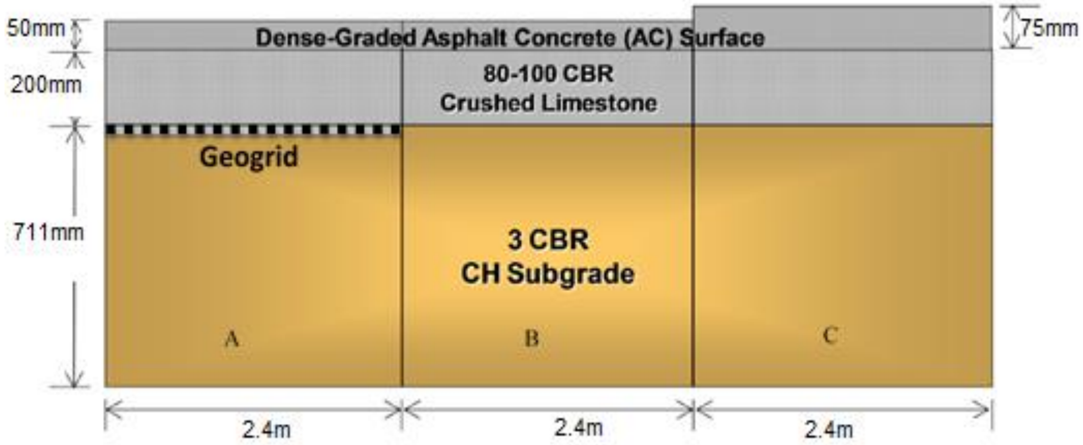

Figure 14: USCOE Phase 1, All three sections with 200mm base.
Section A stabilized with a geogrid, Sections B & C are non-stabilized

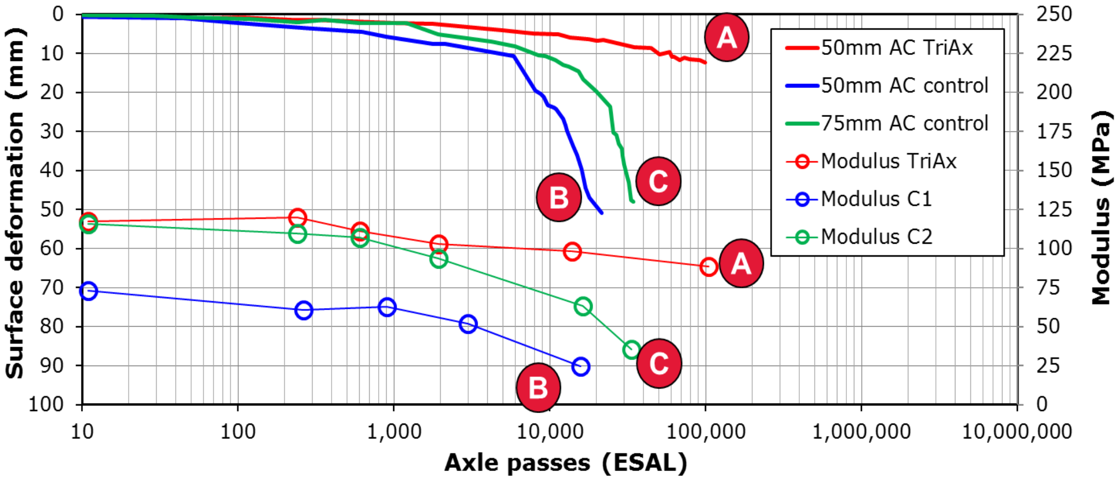

Figure 15 Surface deformation indicating increased service life and increased modulus of the stabilized pavement section

6 FIELD VALIDATION

A large number of pavement structures have now been constructed utilizing hexagonal multi-axial geogrid in a mechanically stabilized base layer. Many of these have been monitored and a significant number have been subjected to APLT and FWD testing to verify on-site performance. In one recent project the New Hampshire Department of Transportation (NHDOT) reconstructed a 3.5km section of road in Rochester. Three distinct stabilization conditions were constructed, two of these included a hexagonal multi-axial stabilization geogrid. The base layer and asphalt layer thickness was consistent throughout. The stabilization conditions were:

- Geogrid within the granular base layer, no geotextile
- Geotextile at subgrade/base interface and no geogrid
- Geotextile at subgrade/base interface plus geogrid within the base layer

The NHDOT commissioned CRREL to conduct an in-situ investigation of performance (Affleck , et al., 2015). FWD testing was carried out on all pavement sections. Based on the seasonal back-calculated moduli for 2014 and 2015 the mechanically stabilized pavement section provided higher moduli than the other sections. The report goes further and states that aggregate layer thickness can be reduced to 33%-42% if the base course is stabilized with the specific geogrid in this project. The authors’ conclusions state, “This higher stiffness should allow the pavement to withstand many more traffic repetitions before fatigue cracking develops; and the geogrid should minimize the influence on thermal cracking.”

In-situ testing at the La Media road project, part of improvements to Highway 906, located in the City of San Diego, California, demonstrated an improvement in modulus from incorporation of a stabilization geogrid (Nelson, Fountain, & Wayne, 2012). A mechanically stabilized pavement section consisting of 100mm of asphalt concrete, 100mm of Class 2 Aggregate base and 275mm of Class 4 aggregate subbase over a clayey sand subgrade. Two layers of multi-axial stabilization geogrid were incorporated one below the subbase and the second below the aggregate base. A significantly thicker control section comprised 180mm of asphalt concrete over 735mm of class 2 aggregate base. A series of plate load tests were performed on both sections at the top of the aggregate base layer and modulus of subgrade reaction calculated using the IAN 73/06 revision 1 published by the UK Highways Agency. The modulus of the stabilized section was reported to be 52% higher than the thicker non-stabilized section.

7 CONCLUSION ON PERFORMANCE RELATED CHARACTERISTICS

Geogrids stabilize a granular material by providing confinement of aggregate particles, limiting particle movement and controlling deformation. A stabilization geogrid enables development of a composite; the mechanically stabilized layer. The behavior of the aggregate is altered within the stabilized layer. The influence of the geogrid extends some distance above and below the geogrid.

In order to stabilize a geogrid must have apertures that are compatible with the aggregate size to enable full interlocking to to occur. The geogrid ribs need to be of a shape and thickness to facilitate confinement of the aggregate within the apertures. The degree of confinement will be influenced by the stiffness of the geogrid at low strains and by the efficiency of the nodes connecting the ribs.

The geometry of the geogrid structure can influence the mechanism of confinement and the degree of stabilization. Multi-axial geogrids and biaxial geogrids can both stabilize, but the mechanism is different. For hexagonal structure geogrids the evidence suggests the confinement is influenced by the hexagonal 'tension ring' and for this tension ring to be stable the in-plane stiffness of the geogrid needs to be near-isotropic or uniform in all directions. A measure of this uniformity is the ratio of maximum to minimum stiffness measured radially in multiple directions as defined in the European Organisation for Technical Approvals Technical Report TR41 (EOTA, 2012).

Ultimate tensile strength and stiffness at higher strains have no significance when considering the stabilization mechanism. Tensile strength only becomes an important factor at high geogrid strains caused by large deformations with surface rutting. But a road will have failed in terms of serviceability requirement after only relatively small deformations have occurred. Hence only the stabilization function is relevant for roadways (Giroud & Han, 2016).

Despite strong evidence to support the existence and quantify the beneficial effect of stabilization, plus evidence supporting the significance of the above characteristics, there is no evidence that confirms a direct correlation between in-situ performance and any single geogrid characteristic or product related identifier. Hence the need for full scale accelerated pavement testing for the determination of design parameters and development of design methodologies followed by site validation.

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