

MECHANISTIC EMPIRICAL DESIGN OF GEOGRID REINFORCED PAVED FLEXIBLE PAVEMENTS

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INTRODUCTION

Pavement design has progressed significantly since the early 1900's. This continual need to move toward more sophisticated and complex prediction models has come from a rather poor correlation between observed and predicted performance. There are a large number of variables that affect performance and therefore these models are really only "best estimates" of what can be expected. A further complication is that performance models based on empirical performance data in one region might need to be validated and calibrated for another region and therefore a single performance model cannot typically be applied universally - without modification. Further design or prediction tools should be applied with a thorough understanding of the local pavement materials and not be used in isolation. Geogrids are increasingly thought of as pavement materials and are now widely used in pavement structures to improve performance or reduce component thicknesses. Although the pavement material types and local conditions might be extremely variable, a geogrid can be installed and provide uniform performance anywhere within a pavement section, over the length of roadway or in any region around the world. This paper provides the universally accepted principles and mechanisms of geogrids and in what way they can positively influence their pavement materials and pavement performance and provides ways in which these benefits can be measured.

The geogrid influences both the mechanistic and the empirical components of the Mechanistic Empirical (M-E) design method. There have been many attempts to capture the benefits of geogrids in M-E design methods, but they have failed to keep it simple. The geogrid mechanisms are simple and often the developer of models create sophisticated geogrid models to overcome a lack of performance testing data. The short term and long term improvements introduced by the geogrid need to be measured using existing field and laboratory equipment. Validating the geogrid mechanistic and empirical contribution has highlighted some limitations with some but not all of the existing validation test methods.

This paper explores some of the basic testing methods, but concludes that if the geogrid industry wishes to use the M-E design platform, then it will have to comply with the practice of field or accelerated testing studies.

GEOGRIDS IN PAVEMENTS

A flexible pavement structure comprises a number of layers of unbound aggregates, stabilized aggregates and asphalt. These layers are combined to form a pavement structure that aims to protect the subgrade and provide a level of serviceability for the each of the layers.

There are two types of flexible paved pavement structures, and they are thin and thick asphalt structures. It is important to recognize the difference between these two structure types as the pavement structure failure mechanisms are different. Both pavement structures fail in a combination of rutting and fatigue. The source of the rutting is primarily in the aggregate and subgrade in the thin asphalt structure and primarily in the asphalt in thick asphalt structure. Both pavement structures will ultimately experience fatigue failure, which will signal the end of the structural life.

Both base reinforcement and asphalt reinforcement geogrids can be used within a flexible pavement structure to improve it's performance, however this paper will be restricted to base reinforcement. Base reinforcement geogrids can be incorporated into these pavement structures to delay both the rutting and fatigue.

Geogrid benefit

Geogrids are by definition "a geosynthetic material consisting of connected parallel sets of tensile ribs with apertures of sufficient size to allow strike-through of surrounding soil, stone, or other geotechnical material", Koerner, (1998).

The most common uses of geogrids in pavement applications are for "Subgrade Improvement" and "Base Reinforcement". The scope of this paper will be limited to the use of geogrids for Base Reinforcement which can be designed using the Mechanistic Empirical design methods.

Installing a single layer or multiple layers of geogrid beneath or within the aggregate base or subbase courses of a flexible pavement structure will improve the stiffness of the aggregate material in close proximity to the Geogrids, Cavanaugh et. al. (2008). The goal is to reduce the amount of aggregate materials required (initial cost saving), to increase the life of the pavement (life-cycle cost saving), or a combination of the two.

Geogrid location

The most common position for a geogrid in a flexible pavement is at the interface of the subgrade and the unbound subbase or unbound base course. However, this should not be considered the default location and therefore the geogrid position should always be determined by estimating where the maximum deformation will occur, or where the benefit of increased stiffness can most benefit the performance of a critical or the weakest pavement layer.

Where the thickness of an unbound aggregate layer is less than 300mm, then the geogrid will only be able to be located at the bottom of the layer. If the unbound aggregate layer thickness is greater than 300mm then the geogrid can either be installed at the bottom of the layer or in the middle of the layer. The thinnest unbound aggregate layer that can be reinforced is a 150mm layer.

The geogrids should not be installed beneath asphalt layers, under or within treated or stabilized aggregate layers.

PAVEMENT DESIGN METHODS

The evolution of road design can be captured by the image in Fig. 1. Road design from the Roman era through to the 1930's was based on engineering judgment or past experience. The idea of providing a harder and stiffer surface material with less stiff materials providing support was conceived by the Romans and forms the basis of design today. This philosophy forms the basis for our current need to protect the subgrade and ensure serviceability of the pavement structure layers. In the 1930's following the Great Depression and a proliferation in new technologies, the cover based design approach was developed, but still required a significant amount of engineering judgment. It was only in the 1960's that the \$20million (1960's) AASHO road test was performed and led the way for the launch of the AASHTO series of design methods. With these new more sophisticated cover based design methods came a greater number of design inputs. In the mid 1970's the South African's released an innovative linear elastic mechanistic empirical design method, which again increased the required inputs for design, Theyse, et. al. (1996). However, with this increased level of design sophistication, came the need for improved methods of field and laboratory testing as well as techniques of material characterization.

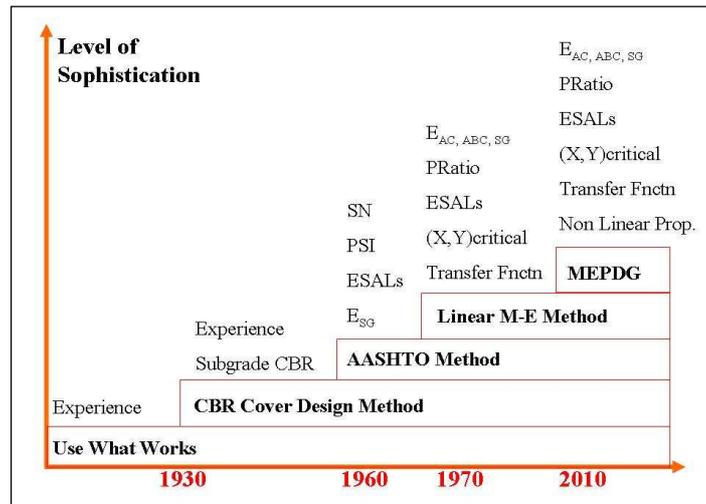


Figure 1 : Evolution of Design Methods

Since the 1990's there has been a proliferation of design methods that vary between purely empirical methods to very sophisticated finite element - non linear - mechanistic empirical (M-E) design methods (e.g. MEPDG). It is now possible to design using information as detailed as the asphalt mix recipe for example. This continual development of design methods has been driven by road asset owners' and designers' need to more accurately predict performance, better accommodate new material types and account for rapidly changing traffic patterns. However, it should be noted that there are many road asset owners that adopt less sophisticated empirical design methods with great success and are extremely successful in managing their roads. Therefore, it should be noted that a successful design approach can therefore not solely rely on sophisticated design tools alone, but needs to be combined with a thorough understanding of the performance of local materials and local environmental conditions.

To fully capture the benefit of a geogrid in a design method, the linear elastic M-E design approach best accommodates and can capture the unique contribution of the geogrid that influences the construction, the application of a single load and the accumulation of deformation, Al Qadi et. al. (2008). The M-E design approach is also better suited to including a geogrid's benefits, because the required inputs force the user to better define their local materials and provide a means by which the geogrid contribution can be validated post construction, during and after the structural design life. The next section defines the M-E design method in greater detail and addresses how the geogrid benefit can be captured within both the mechanistic and empirical components of M-E design.

THE MECHANISTIC EMPIRICAL DESIGN APPROACH

The M-E design method is a road performance prediction method. The M-E design method name implies that there are two key design components namely a Mechanistic component and an Empirical component. Like most other design methods, this design approach requires that the designer needs to define the design input such as the pavement layers, traffic and environmental considerations. These two design components are essentially interdependent calculation models that both require input and generate output. The Empirical component output is then measured against the original design hypothesis, and if it fails, then by means of an iterative process, the design is modified and re-evaluated. The mechanistic and empirical components are discussed in greater detail below.

The Mechanistic Component

The Mechanistic component of the Mechanistic Design Method can be likened to a giant complex calculation engine. The user defines input that includes the pavement structure's geometry, the pavement material properties, and the load. The input is sent to a calculation engine that can extract stresses and strains anywhere within the pavement structure. The critical stresses and strains are the output from the mechanistic component or this calculation module. The calculated critical stresses and strains are commonly referred to as mechanistic responses and can be validated in research projects using instrumentation and in the field using tools such as the Falling Weight Deflectometer (FWD). The introduction of new materials such as geosynthetics or other complex pavement materials always require mechanistic response validation.

The performance benefits of geogrids have been defined in empirical design methods with relative ease, but less so in the Mechanistic Empirical design method. In the Mechanistic model, the contribution of a thin geogrid material to a pavement structure is much more complex to define and model, Perkins et. al. (2009). Even though a geogrid increases the effective load footprint and thereby reduces the vertical compressive stresses beneath the geogrid, this benefit is not able to be measured or validated using conventional field testing equipment. The geogrid also confines and thereby stiffens the aggregate, effectively mechanically stabilizing the aggregate, Kwon et. al. (2007). The stiffness increase is attributed to aggregate interlock or aggregate confinement during construction and trafficking. The increased stiffness is also retained over the life of the pavement, which accounts for the delay in the onset of fatigue cracking in the overlying asphalt.

The Empirical Component

The Empirical component of the Mechanistic Design Model can be likened to the current empirical design methods such as the AASHTO 93 design method (AASHTO, 1993). A single performance prediction equation is used to estimate the life of the pavement. However in the Mechanistic Empirical design approach, a number of equations are used within an analysis and are applied to the individual components of the pavement structure. The M-E pavement design method is therefore more sophisticated than the previous empirical approach in that the design addresses component serviceability as opposed to the surface serviceability only.

The way in which the pavement layers fail is represented by a "Transfer Function", or otherwise called a "Damage Model". The Transfer Function is an equation that calculates the predicted life of a layer and is dependent on a critical parameter which is a key output of the mechanistic model. It appears obvious to simply assume that the full contribution of a geogrid could be incorporated by a Transfer Function, however this is not possible in most cases.

If a geogrid is included in a specific aggregate layer of a thin asphalt flexible pavement the Transfer Function of that layer needs to be able to relate to the measured surface performance from a pavement study. Clearly, the source of and types of distress that occur in various pavement structure types and will influence which Transfer Functions can be used to account for the presence of geogrids.

In a thin asphalt flexible pavement for example, the aggregate layer and subgrade rutting accounts for a large percentage of the total surface rutting. Typically, the total surface rutting in a thin asphalt flexible pavement is accounted for by a Subgrade Transfer Function. Therefore, it can be assumed that in order for the geogrid to influence the Surface Rutting Transfer Function the geogrid should be included in an aggregate layer within the pavement structure. If the rutting will primarily occur in the aggregate layers, then the Subgrade Transfer Function can still be used to predict the life of the pavement. However, it would be better to locate the Geogrid in the area where the maximum rutting will occur, which is not always in the subgrade, and could be higher up in the pavement structure.

In a thick asphalt pavement, the principles for applying Transfer Functions still apply. The big difference between the thick and thin asphalt sections is that the rutting primarily occurs in the asphalt layer. The testing of the thick asphalt section also complicates the impact of the geogrid on the surface rutting as the first cycle of rutting will only occur in the asphalt. By trying to account for the geogrid benefit by using the subgrade rutting model will not work. Therefore for thick asphalt sections, the primary contribution of the geogrid will be to influence the onset of fatigue cracking. The additional and retained stiffness of the geogrid reinforced aggregate will reduce the tensile strain at the bottom of the asphalt layer and therefore increase the life of the layer, Al Qadi et. al. (2008). It is assumed that there will be a Geogrid Reinforced Aggregate Transfer Function that will demonstrate the stiffness retention and stiffness increase of the aggregate layer. This will have long term performance benefits for the overlying asphalt layers.

VALIDATION OF GEOGRID BENEFIT FOR MECHANISTIC EMPIRICAL DESIGN

As discussed earlier, the design of a pavement using this sophisticated design approach provides two dimensions by which the design can be checked. The first design check component that can be checked is the response of the pavement to load. The second design check component is the measurement of the traffic to achieve a limiting level of surface distress. These checks are applied to all pavements and therefore the response and damage contribution of the Geogrid should be able to be measured, and therefore validated. The process where the models are modified to account for a discrepancy between the predicted and measured results, is known as calibration. In the author's opinion, an empirical model can be successfully applied in both high traffic or low traffic conditions if continuously validated and calibrated. A poorly validated model, whether sophisticated or not, will not be successful.

There are many tools that are used to validate the response and damage for pavements. Some of the tools are better suited to showing the benefit of geogrids and are discussed in the following sections. Not all tools are suited to geogrids and these are also disclosed in the following sections.

During Construction

There are a number of tools available that can be used to determine the quality of construction of the subgrade or aggregate layers. These include, but are not limited to the Dynamic Cone Penetrometer (DCP), the Light Falling Weight Deflectometer (LFWD), the Plate Load Bearing Test, and the field CBR test. The geogrid has the ability to influence the stiffness with depth, and therefore the only testing equipment suited to evaluate the stiffness with depth is the DCP. Although the impact of non uniformity with depth can be measured with other devices at the surface, the depth of influence cannot be accurately determined.

The Dynamic Cone Penetrometer test can be used post construction, pre-trafficking and post-trafficking. This test also clearly demonstrates the benefit of a geogrid to increase the allowable modulus ratio between layers. Typically a modulus ratio of 5 is used to define the maximum allowable modulus ratio between aggregate layers. The addition of a geogrid can increase this value to between 7 and 9. The DCP can also be used to demonstrate the benefit that the geogrid can bring to stiffness retention during trafficking. The following example is taken from a research study and is reported on elsewhere, Tutumluer et. al. (2009), Fig. 2.

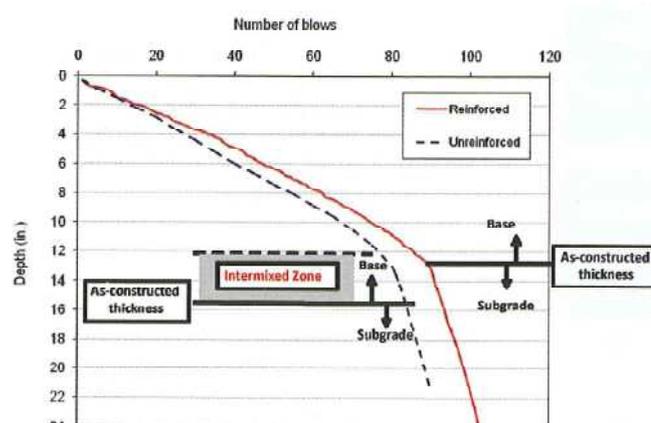


Figure 2 : DCP Test Data for University of Illinois Pavement Test Sections (unreinforced and Geogrid reinforced sections)

Plate Load testing is also a useful field testing method to measure the contribution of a geogrid. Although the results cannot be used directly in the M-E approach, the results clearly show the influence of the Geogrid on the permanent deformation characteristics of the pavement structure. This test is normally conducted on the aggregate layer following construction. The following field performance data taken from a section with a 400mm thick base over a subgrade with a CBR of 8% ~ 80MPa, Fig.3. This test was performed with a 200mm diameter circular plate and the load was applied statically.

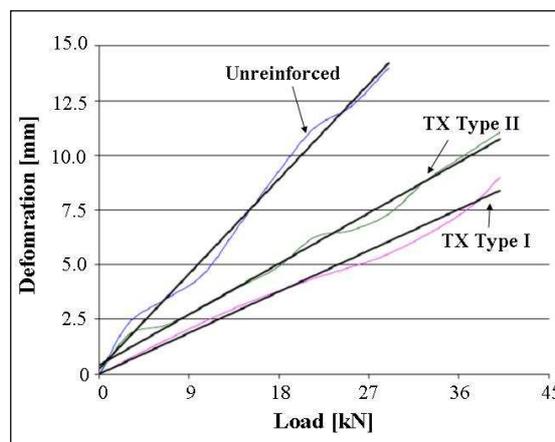


Figure 3 : Plate Load Test on Reinforced vs Unreinforced Field Sections - Carroll County CA June 2009

Field Performance

There are many methods of collecting performance data as shown in Fig. 4, Hugo et. al. (2004). However, the value of the data depends on the type of testing. The type of research needed to develop and validate a Transfer Function needs to be full scale. Full scale tests are limited to field studies and accelerated pavement performance studies. In both these cases, the high cost of testing typically results in a fairly limited test matrix or scope, and so it is customary to expand the test matrix by undertaking smaller scale laboratory studies or numerical modeling. When performance models are developed for M-E with limited full scale research data, the industry tends to develop more sophisticated models, Perkins et. al. (2009). The problem is that the validation of these models with performance data becomes more complicated. In the author's opinion, the level of variability of pavement materials and layer thicknesses together with the fairly low sophistication of data collection is way behind the level of design sophistication being proposed. The fact that many unsophisticated models that are being applied successfully in Germany, Jooste (2009), shows that you can keep it simple and still be successful.

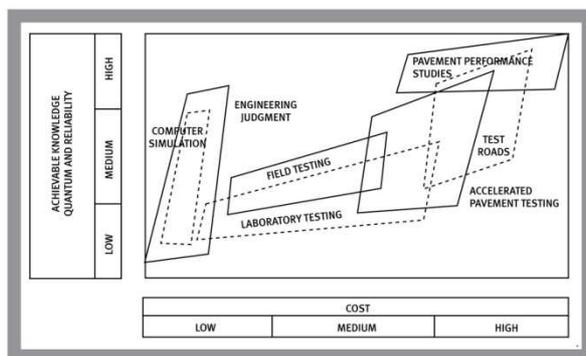


Figure 4 Interrelationship between pavement engineering facets that collectively and individually contribute to knowledge (Hugo et al. 1991)

Clearly, full scale pavement performance studies and accelerated pavement studies provide the best data with which to develop performance models for M-E.

Full scale pavement performance and accelerated pavement testing of thin and thick asphalt flexible pavements requires different approaches to be taken. For thin asphalt pavements, the traffic loading can be applied in a single phase, and structural failure will be achieved (both rutting and fatigue). For thick asphalt pavements, the traffic loading will only initiate a serviceability failure, (asphalt rutting), in the first phase. To achieve structural failure, the pavement test section would have to be rehabilitated and trafficked again - providing a second phase of traffic loading. Depending on the thickness of asphalt, this could require two or more phases. Typically, due to cost, this level of trafficking is not performed for accelerated pavement testing research programs. This limitation prevents the true empirical benefit of geogrids to be accounted for in thick asphalt pavements over its structural life. Furthermore, the stiffness response benefits of the geogrid have not had sufficient opportunity to influence the long term fatigue performance of the asphalt. Recent accelerated pavement studies, have found that testing a 125mm asphalt section using accelerated pavement testing devices have resulted in phase 1 distress only, Henry et. al. (2008). This means that no distinguishable structural distress could be observed, nor could the contribution of the geogrid be measured.

There are a number of field studies that have been undertaken to evaluate the benefit of geogrids in pavements, Aran (2006). Typically, the geogrid reinforced sections are thinner than the unreinforced sections. Therefore as long as the sections remain thin or thick, then at the end of the structural design period, the sections should perform the same with respect to rutting and fatigue. If the geogrid has been added to a thin asphalt unreinforced section then the geogrid reinforced section will exhibit delayed rutting and fatigue. If the geogrid is added to a thick asphalt unreinforced section, then the section will exhibit similar asphalt rutting serviceability performance, but the onset of structural fatigue will be delayed.

The Falling Weight Deflectometer (FWD) is often used to attempt to evaluate the response of the geogrid reinforced pavement structure. This response data is then used to establish the condition of the pavement layers. Although the FWD is used toward the end of the service life to understand or quantify the residual life in the pavement, it is often also used to confirm the structural capacity following construction. The geogrid has typically not been mobilized following construction, and therefore its contribution is not able to be observed by a standard 9-10Kip FWD load. If the intent is to validate or verify the contribution of the geogrid following construction, then the author recommends that a wide range of load levels are used - up to 18Kip, and each drop should be duplicated. A further use of the FWD to show the benefit of the geogrid is to periodically measure the pavement, and the Geogrid reinforced base will show a delayed stiffness loss with time. This benefit is unfortunately not considered in most Mechanistic Empirical design approaches, but is applied in Multiple Phase Pavement Analysis.

The FWD's ability to demonstrate the benefit of a geogrid will become more evident as the industry comes to terms with the way in which the geogrid mechanisms function. The use of artificial neural networks will help improve the level of understanding and the ability to predict performance with Geogrids.

CONCLUSIONS

- A geogrid provides different benefits in both thin and thick flexible pavements, and therefore requires different research approaches to quantifying the benefit.
- A geogrid's location should be based on the anticipated zone of maximum deformation or where the improved and retained stiffness will provide maximum benefit.
- Full scale pavement performance studies and accelerated pavement testing should be used to provide easily validated performance models for M-E.
- The level of sophistication of the design method should not be increased to offset a lack of pavement performance data or accelerated pavement testing data.
- Each geogrid type should be tested with full scale pavement studies to get their own performance models, as no two geogrids perform alike.
- A validated and calibrated empirical design method can be used as successfully as a validated and calibrated sophisticated design method.
- A geogrid offers mechanistic benefit through the M component in M-E by offering stiffness improvement and stiffness retention.
- A geogrid offers empirical benefit through the E component in M-E by delaying the onset of rutting and fatigue.
- The geogrid's contribution is best validated by a DCP or plate load test following construction of the section.
- The FWD can better capture the contribution of a geogrid in a pavement section by increasing the loads to mobilize the strains in the geogrid. The FWD can also be used to demonstrate the geogrid's ability to retain the aggregate stiffness over time.

FUTURE RESEARCH NEEDS

Geogrids can only be accounted for in both flexible and rigid pavement structures using either shift factors or very complicated numerical analysis. Given these two extreme approaches, the following should be considered as future research needs:

- Develop a Subgrade Transfer Function for each geogrid family using an acceptable accelerated pavement testing method for flexible pavements.
- Develop an empirical model that can account for the retained stiffness benefit for each geogrid family on the surrounding materials.
- Develop the current "load and response" field testing equipment (e.g. Falling Weight Deflectometer) by using multiple load levels and test locations (e.g. in and between the wheel paths) to enable the benefits of geogrid families to be captured.
- Develop an accelerated pavement testing program that will enable geogrid families to be compared with one another, and will allow transfer functions to be developed.
- Develop a long term pavement performance testing protocol which will enable the performance of geogrid families to be validated and will allow for the calibration of transfer functions.
- Develop an existing or new test method that can be used to compare geogrids within a family, but would not be used to measure the difference between geogrid families. Accelerated full scale testing should be used as the sole means of comparison between different geogrid families.

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