AN ASSESSMENT OF THE USE OF GEOGRIDS IN UNPAVED ROADS AND UNPAVED AREAS

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INTRODUCTION

Scope of this paper

This paper presents an assessment of the use of geogrids in unpaved roads and unpaved areas. Unpaved areas comprise working platforms, storage areas, parking lots, log yards, etc. The phrase "unpaved roads and trafficked areas", sometimes used, is not used herein because it may be confusing (as it may imply that the areas are trafficked and the roads are not, and that the areas are not unpaved). The term "stabilisation structures" will be used to encompass these two types of structures; and the term "subgrade stabilisation" will refer to this application in general.

This paper includes two main parts. In the first part, a technical analysis is presented where the relevant properties of geogrids in unpaved roads and unpaved areas are discussed. In the second part, the state of practice is reviewed and factors that have an impact on the use of geogrids in unpaved roads and unpaved areas are discussed, such as: the cost of geosynthetics and aggregate, competition with geotextiles, and experience of decision-makers. The paper ends with a discussion of challenges for the future, including research needs.

This paper is written for readers who have a good knowledge of geotechnical engineering and geosynthetics and their applications. In particular, the readers are assumed to be knowledgeable about unpaved roads and unpaved areas, and to be familiar with the related terminology. Intentionally, the paper does not include any illustration in order to focus the attention of the readers on the analyses and discussions. The purpose of this paper is not to explain how to design and construct unpaved roads and unpaved areas, but to assess the use of geogrids in these structures.

Definition of the structures considered

A stabilisation structure consists of a layer of unbound aggregate (referred to as "aggregate layer" or "aggregate base") resting on the subgrade soil and subjected to traffic by vehicles on wheels. Today, in many of these structures, a geosynthetic (typically a geotextile or a geogrid) is used between the aggregate layer and the subgrade soil to improve the performance. Other locations of the geosynthetic could be considered (which could be a research topic), but, in this paper, only geosynthetics located between the aggregate layer and the subgrade soil are considered.

In most of the cases where a geosynthetic is needed, the subgrade soil is essentially a low-permeability material that contains a high percentage of fine particles ("fines") and has a high water content. In contrast, the aggregate is a high-permeability material that consists of coarse particles.

The subgrade soil is typically characterized by its undrained cohesion, c_u, or by its CBR. Several methods of conversion between undrained cohesion and CBR have been proposed. Typically, an undrained cohesion of 100 kPa is considered approximately equivalent to a CBR of 3 or 4%. It should be noted that the CBR is often referred to as a number rather than a percentage, e.g. 3 rather than 3%.

Aggregate is generally expensive. Therefore, it is often important to minimize the aggregate layer thickness for a given service life. This can be achieved by incorporating a geosynthetic in the stabilisation structure between the aggregate layer and the subgrade soil. Alternatively, incorporating a geosynthetic in a stabilisation structure can increase the service life for a given aggregate layer thickness. Therefore, parameters considered in a stabilisation structure are: service life, thickness of aggregate layer, and type and properties of the geosynthetic, if any.

Overview of geosynthetics used in stabilisation structures

The geosynthetics used in stabilisation structures (i.e. unpaved roads and unpaved areas) comprise essentially geotextiles and geogrids. Geocells are also used, but to a limited extent.

The geotextiles comprise woven geotextiles and nonwoven geotextiles. Geotextiles typically used to provide reinforcement to stabilisation structures are sometimes referred to as "stabilisation geotextiles". The geocells (also called geowebs) are honeycomb structures that are deployed at the site and filled with granular material. Compared with geotextiles and geogrids (which are both a few millimeters thick) the geocells are relatively thick (typically 100 to 200 mm).

A variety of geogrid types are used nowadays. They include: (i) woven geogrids, i.e. geogrids that consist of two sets of perpendicular woven ribs or yarns (often made of stretched polyester fibers) coated with a protective polymer (e.g. PVC or based on PVC); (ii) welded geogrids, i.e. geogrids that consist of two sets of perpendicular straps (also called "flat bars"), typically made of stretched polyester, welded at their junctions; and (iii) extruded geogrids which are monolithic structures that consist of two sets of perpendicular ribs typically made of drawn polyethylene or polypropylene. The term "extruded" is shorthand for extruded-punched-drawn, as these geogrids are, in fact, produced by extrusion, punching and drawing. Some of the extruded geogrids are multilayered. The wide variety of geogrids results in a wide variety of properties and modes of interaction with soil or aggregate.

Ever since they appeared in the early 1980s, geogrids used in stabilisation structures have been essentially biaxial geogrids, i.e. geogrids that consist of two sets of perpendicular elements (ribs, yarns, straps, bars). However, recently, one type of triaxial extruded geogrid has become available, and it can be expected that other types of triaxial geogrids

and new geogrid geometries will become available. First tests on stabilisation structures incorporating triaxial geogrids raise fundamental questions regarding the mode of interaction between geogrids and adjacent materials, in particular questions regarding the impact of geogrid geometry on geogrid interaction with adjacent materials. These fundamental questions open up important avenues for research; and it can be expected that this research will benefit all types of geogrids. Therefore, it is important that the fundamental questions raised by this new type of geogrid be thoroughly addressed in this paper

It seems that, in the past three decades, more effort has been devoted to perfecting the manufacturing processes of geogrids than optimizing their structure and properties to improve their interaction with soil. The author of this paper believes that, in the future, emphasis should be put on research work aimed at optimizing the structure and properties of geogrids to improve their interaction with soil. Accordingly, suggestions for research will be presented herein.

Applications and service life

There is a major difference between unpaved roads and unpaved areas. In the case of unpaved roads, the traffic is channelized, or at least is assumed to be channelized (even though, in wide unpaved roads, the traffic may wander to some degree). In contrast, the traffic is not channelized in the case of unpaved areas. However, the traffic may be channelized in some parts of an unpaved area, such as the entrance to a working platform.

Service life is typically expressed in terms of number of vehicle or axle passes in the case of unpaved roads. In the case of unpaved areas, a number of passes cannot be easily defined and there is no practical way to express the service life. Some judgment is needed from the part of a design engineer who uses for an unpaved area a design method where the number of passes is a parameter. Research is needed to clarify this matter.

In some of the discussions presented in this paper, it is important to distinguish between, on one hand, unpaved roads that are only used as unpaved roads (i.e. during their entire service life) and, on the other hand, unpaved roads that are, in fact, the aggregate bases of paved roads under construction and are used as unpaved roads only during construction of the roads.

TECHNICAL ANALYSIS OF UNPAVED ROADS AND UNPAVED AREAS

Role of the aggregate layer

The role of the aggregate layer is to distribute the load so the stresses applied to the surface of the subgrade soil are below the stress level that causes excessive deformation of the subgrade soil. (The mechanisms of distress of stabilisation structures are discussed in the next section.) The total load on the subgrade soil is the same as the total load applied by the vehicle (plus the weight of the aggregate layer), but it is applied over a much greater area than the contact area between the wheels and the aggregate layer surface.

A simple analysis can be done in the hypothetical case where a vehicle does not move, i.e. a static case where there is no traffic (i.e. no dynamic load, no repeated loading). For this simple analysis, it can be considered that the stresses that cause excessive deformation of the subgrade soil are stresses that exceed the bearing capacity of the subgrade soil. A simple bearing capacity calculation shows that, if the undrained cohesion, c_u, of the subgrade soil is greater than approximately 100 kPa, the subgrade soil can support the static load applied directly on its surface by the wheels of a typical truck. This shows that, if the subgrade soil has an undrained cohesion of the order of 100 kPa or less, an aggregate layer is needed to provide load distribution in the case where the load is static. In case of traffic loading, an aggregate layer would be needed for an even higher value of the undrained cohesion of the subgrade soil.

The effectiveness of load distribution depends on the aggregate layer thickness and stiffness. The effectiveness of load distribution can be improved by geosynthetic reinforcement, as discussed in a subsequent section.

Mechanisms of distress of a stabilisation structure

To understand the benefits of geosynthetics (and, in particular, geogrids) in stabilisation structures, it is necessary to understand the mechanisms of distress of these structures.

Description of distress of a stabilisation structure

If there is no aggregate layer, distress of a soil subjected to traffic manifests itself by excessive rutting due to excessive deformation of the soil, which results from: accumulation of soil deformation due to repeated traffic loading and/or bearing capacity failure of the soil.

As a result of excessive rutting, traffic becomes impossible or difficult to the point where the conditions are considered unacceptable. If there is an aggregate layer, distress also manifests itself by excessive rutting. However, due to the presence of two materials, the aggregate and the subgrade soil, the mechanism of rutting is more complex than for the case where there is no aggregate layer.

If there is an aggregate layer, excessive rutting, as observed at the surface of the aggregate layer, is essentially due to excessive deformation of the subgrade soil. In addition, there may be some decrease in aggregate layer thickness at the location of the ruts. Decrease in thickness of the aggregate layer not only contributes to the amount of rutting observed at the aggregate layer surface, but also (more importantly) decreases the ability of the aggregate layer to distribute the load on the subgrade soil, thereby increasing the deformation of the subgrade soil.

Clearly, deterioration of the aggregate layer plays a key role in the distress of a stabilisation structure. In other words, the integrity of the aggregate layer is essential to the performance of a stabilisation structure. This is discussed in more detail below.

Mechanisms of aggregate layer deterioration

There are essentially two mechanisms of aggregate layer deterioration: interpenetration (mixing) of aggregate and subgrade soil; and displacement of aggregate within the aggregate layer.

Interpenetration of aggregate layer and subgrade soil results from repeated loading. It manifests itself in two ways: downward movement of aggregate (i.e. loss of aggregate into the subgrade), and upward movement of fine particles from the subgrade soil (i.e. intrusion of fine subgrade soil particles into the aggregate). The loss of aggregate into the subgrade decreases the thickness of the aggregate layer, which decreases its ability to distribute the traffic loads. The intrusion of fine subgrade soil particles into the aggregate alters the mechanical properties of the aggregate, which makes the aggregate layer more likely to deform and less able to distribute traffic loads. It should be noted that a small amount of fine soil particles is sufficient to significantly alter the aggregate mechanical properties.

Displacement of aggregate within the aggregate layer may result from several mechanisms: deformation of aggregate layer as a whole, lateral spreading of aggregate, and bearing capacity failure of the aggregate layer. Deformation of the aggregate layer as a whole, as if the aggregate layer were a continuum (i.e. compression, distortion, bending, etc.), is generally insignificant; bearing capacity failure of the aggregate layer is rare. Lateral spreading of aggregate, moving essentially as discrete particles, is the dominant mechanism of aggregate layer deterioration, along with the interpenetration mechanism discussed above. The final result of the displacement of aggregate within the aggregate layer is a decrease in thickness (and possibly density) of the aggregate layer.

As a result of its decrease in thickness (and possibly density) and the alteration of its mechanical properties, the aggregate layer becomes progressively less able to distribute the traffic loads.

Summary of distress mechanisms

The mechanisms of distress of a stabilisation structure can be summarized as follows:

- deformation-deterioration of the aggregate layer either intrinsic to the aggregate layer (deformation of aggregate layer as a whole, lateral spreading of aggregate under repeated traffic loading, and/or bearing capacity failure of the aggregate layer) or resulting from aggregate layer /subgrade soil interpenetration (loss of aggregate into the subgrade, and/or intrusion of fine subgrade particles into the aggregate, which makes the aggregate layer more likely to deform); and
- deformation of the subgrade soil (accumulation of subgrade soil deformation due to repeated traffic loading, and/or bearing capacity failure of the subgrade soil, possibly due to improper load distribution resulting from aggregate layer deformation-deterioration).

Performance enhancement using geosynthetic

Purpose of performance enhancement using geosynthetic

Based on the discussions in the preceding sections, it is clear that, essentially, the aggregate layer must distribute the load during the service life (typically expressed in number of vehicle or axle passes in the case of unpaved roads). Therefore, the inclusion of a geosynthetic in a stabilisation structure will be beneficial if it: (i) increases the ability of the aggregate layer to distribute the load; and/or (ii) maintains the ability of the aggregate layer to distribute the load during the service life of the stabilisation structure. Two geosynthetic functions are involved: separation and reinforcement. These functions are discussed below with emphasis on reinforcement.

Separation

A geosynthetic performs the function of separation when it prevents interpenetration of two materials that tend to mix when they are squeezed together by applied loads. In the case of stabilisation structures, separation of the aggregate and the subgrade soil prevents the loss of aggregate into the subgrade and prevents intrusion of fine subgrade soil particles into the aggregate. This is important because, as noted previously in this paper, it only takes a small amount of fines to significantly reduce the mechanical strength of aggregate.

Geotextiles are typically used to perform the separation function. Indeed, a geotextile with adequate puncture and tear strength prevents the loss of aggregate into the subgrade and, with adequate opening size, prevents intrusion of fine particles from the subgrade soil into the aggregate layer.

However, a geogrid can also provide some degree of separation through individual action of each aperture and global action resulting from its continuity:

- A geogrid with adequate aperture size prevents the loss of individual aggregate particles into the subgrade.
- A geogrid that keeps the aggregate layer together reduces the opportunities for intrusion of the aggregate by fine particles from the subgrade soil.

However, if fine particles from the subgrade soil intrude into the aggregate, the effectiveness of the geogrid-aggregate interaction is likely to be reduced, which can be very detrimental to the performance because geogrid-aggregate interaction is the main mechanism of improvement of a stabilisation structure, as discussed in this paper. Even though geogrids can provide some degree of separation, geogrids used in stabilisation structures are essentially

expected to provide reinforcement. In fact, in some cases, a geotextile and a geogrid are used together: the geotextile to provide separation, and the geogrid (overlying the geotextile) to provide reinforcement.

Reinforcement

Geosynthetic reinforcement of unpaved roads and unpaved areas consists in improving load distribution and improving the subgrade bearing capacity.

The geosynthetic improves load distribution through two mechanisms:
- it improves the ability of the aggregate layer to distribute loads; and
- it carries out load transfer through the "tensioned membrane effect".

The geosynthetic improves the subgrade bearing capacity by confining the subgrade soil. (The terminology "confinement of the subgrade soil" should be used with caution. It is macro-confinement, i.e. confinement on a large scale. In contrast, confinement provided to aggregate within the geogrid apertures is micro-confinement, i.e. confinement at the scale of the geogrid apertures.)

The three reinforcement mechanisms (load distribution, tensioned membrane effect, and subgrade soil confinement) are discussed in the next section.

Reinforcement mechanisms

Improvement of load distribution by the aggregate layer

A geosynthetic improves load distribution through two mechanisms: (i) by minimizing deterioration of the aggregate layer; and (ii) by increasing the ability of the aggregate layer to distribute loads. These two effects are discussed below.

Geosynthetic reinforcement minimizes deterioration of the aggregate layer by preventing shear failure of the aggregate layer and lateral spreading of aggregate. Shear failure (or bearing capacity failure) of the aggregate layer is rare. Therefore, the main mechanism through which a geosynthetic prevents deterioration of the aggregate layer is by preventing or reducing lateral spreading of aggregate. This is achieved by interlocking between geogrid and aggregate. This mechanism does not exist with geotextiles.

As mentioned previously in this paper, load distribution is provided by the aggregate layer. From a mechanical standpoint, the aggregate layer and the subgrade soil form a two-layer system. It is known from the theory of elasticity that, in a two-layer system, the stress distribution on the lower layer depends on the modulus of the upper layer. There is a significant stress distribution difference between a two-layer system and a uniform soil. An aggregate layer with a high modulus reduces drastically the maximum stress on the subgrade under the wheel. It is also known from the theory of elasticity that there are tensile stresses at the bottom of the upper layer, which weakens the upper layer and reduces the stress distribution effectiveness. Therefore, the stress distribution effectiveness of the upper layer can be increased by adding tensile stiffness at the bottom of the upper layer, hence the use of geosynthetic reinforcement at the bottom of the upper layer (i.e. the aggregate layer).

It is important to note that just adding geosynthetic reinforcement at the bottom of the aggregate layer is not sufficient (especially with repeated loading). It is essential to impart tensile stiffness to the aggregate. To impart tensile stiffness to the aggregate at the bottom of the aggregate layer, there are two mechanisms: interface friction and interlocking. Interface friction exists between geotextile and aggregate and between some geogrids and aggregate. Interlocking is an interaction mechanism that is specific to geogrids. Due to its importance for geogrid-reinforced stabilisation structures, interlocking will be further discussed in a subsequent section.

Load transfer by the tensioned membrane effect

In addition to load distribution, geosynthetic reinforcement can contribute to load support through a mechanism called the "tensioned membrane effect". The tensioned membrane effect has been extensively discussed because, in early attempts at explaining the behavior of unpaved roads, it was thought that the tensioned membrane effect was the main mechanism governing the performance of unpaved roads. It is known now that this is not the case.

The tensioned membrane effect consists in decreasing the load induced in the subgrade soil under the wheels, by transferring part of this load to lateral zones (i.e. away from the wheels). The mechanism is the following. Due to the traffic loads, the geosynthetic is deformed and is, therefore, under tension. Under the wheels, due to rutting, the geosynthetic has a concave shape. The resultants (which are oriented upward) of the geosynthetic tensions on each side of the concave shape contribute to wheel support. These resultants are balanced by downward resultants associated with the convex shape of the geosynthetic away from the wheels.

From this analysis, it is clear that the tensioned membrane effect requires rutting (in fact, deep rutting) and calculations show that, for typical rut depths, the tensioned membrane effect is negligible. Also, the tensioned membrane effect works only with channelized traffic (i.e. if traffic keeps deepening the same ruts). Traffic is not channelized in the case of unpaved areas and traffic may not be channelized in some wide unpaved roads.

Thus, the tensioned membrane effect is not the main mechanism governing the behavior of unpaved roads and unpaved areas. The tensioned membrane effect is always negligible in geogrid-reinforced unpaved roads and unpaved areas, and it may carry only 10% of the load in geotextile-reinforced unpaved roads and unpaved areas that exhibit very deep ruts (Giroud et al. 1984).

Subgrade soil confinement

Due to the presence of a geosynthetic on top of the subgrade, the deformations of the subgrade soil are limited. In other words, the geosynthetic provides subgrade confinement. (It should be remembered that, as pointed out previously in this paper, the terminology "subgrade confinement" should be used with caution. It is macro-confinement, i.e. confinement on a large scale. In contrast, confinement provided to aggregate within the geogrid apertures is micro-confinement.) As a result, the soil can be loaded near its ultimate bearing capacity. In contrast, without subgrade confinement, a load equal to the ultimate bearing capacity would cause immediate failure. In other words, an unpaved road with no subgrade confinement by geosynthetic would fail at the first axle pass if the load at the subgrade soil level is equal to the ultimate bearing capacity.

Therefore, unpaved roads without geosynthetic must be designed to avoid loads equal to the ultimate bearing capacity. As a result, they must be designed for loads equal to the elastic limit. Accordingly, as shown by Giroud & Noiray (1981) with further refinements by Giroud & Han (2004), the allowable pressure on the subgrade soil is 3.14 c_u (c_u being the undrained cohesion of the subgrade soil) without geosynthetic, 5.14 c_u with a geotextile and 5.71 c_u with a geogrid. The difference between the geotextile case and the geogrid case is due to the difference in stress orientation which results from the difference between geotextile-aggregate interface friction and geogrid-aggregate interlocking (Giroud & Han 2004).

Reinforcement and displacement

It is always beneficial to keep the stabilisation structure deformations as small as possible:

- In the case of permanent unpaved roads and unpaved areas, small deformations mean less rutting and, therefore, better trafficability.
- If an aggregate layer, that is temporarily used as an unpaved road, is eventually incorporated in the structure of a paved road, it is important to minimize deformations to preserve the integrity of the aggregate layer to ensure long-term performance of the paved road.

If there is efficient interlocking between a geogrid and aggregate, the relative displacement required to mobilize interlocking can be expected to be small and to be less than the relative displacement required to mobilize interface friction. Therefore, geogrid-reinforced aggregate layers can be expected to deform less than geotextile-reinforced aggregate layers. Also, it may be assumed that geogrids that rely on interlocking with aggregate could result in less deformation of the aggregate layer than geogrids that rely on friction. However, this is only an assumption that must be evaluated through research.

Regarding displacements associated with geogrid reinforcement, there is another consideration which is perhaps more important than the stabilisation structure deformation discussed above, and certainly more fundamental. It is very important to mobilize interlocking with a displacement as small as possible so that the aggregate is subjected to minimum disturbance. In particular, if the aggregate has been placed and compacted to its maximum density, it is important that it remains at its maximum density.

Discussion of interlocking

Importance of geogrid-aggregate interlocking.

Discussions in the preceding sections show that interlocking between geogrid and aggregate plays a key role in the performance of geogrid-reinforced stabilisation structures. It should be noted that it is possible that geogrids of various types and/or characteristics do not provide the same level of interlocking with aggregate. This is discussed below.

Factors governing geogrid-aggregate interlocking.

The factors that govern geogrid-aggregate interlocking include the following:

- geogrid aperture size relative to aggregate size and grading,
- geogrid aperture shape,
- shape and stiffness of ribs, and
- stiffness (more than strength) of junction between ribs

These factors are discussed in subsequent sections. It should be noted that "inter" in "interlocking" clearly indicates that the two materials, the aggregate and the geogrid, play a role. Therefore, it is important to consider relative geogrid/aggregate properties rather than only geogrid properties. Accordingly, in the discussions presented in subsequent sections, the geogrid properties are presented in relation with the aggregate properties.

It is sometimes said that, thanks to interlocking, a geogrid "confines" the aggregate. This is correct, and, more precisely, it is "micro-confinement" at the scale of geogrid apertures. However, herein, the confinement terminology is avoided in the discussion of interlocking in order to prevent confusion with the macro-confinement of the subgrade provided by a geotextile or a geogrid at a large scale, as discussed previously in this paper.

In subsequent discussions, it is considered that efficient interlocking occurs when there is minimum displacement between the geogrid and the aggregate (i.e. "small-displacement mobilization") and minimum disturbance of the aggregate by the geogrid. In other words, it is considered that the geogrid should provide properties that the aggregate does not have and should not alter properties that the aggregate does have. Furthermore, there should be such an intimate match between the geogrid and the aggregate that a geogrid-aggregate "composite layer" is created. If there is perfect match between the geogrid and the aggregate, this composite layer has optimum properties.

Discussion of the size of geogrid apertures with respect to interlocking

The ability that a geogrid has to interlock with a given aggregate depends, among other factors, on the size of the geogrid apertures and the size and grading of aggregate particles. It has been known since the first uses of biaxial geogrids that there should be an appropriate match between the size of the geogrid apertures and the size of the aggregate particles (Jewell et al. 1984). As a simple rule, the geogrid aperture size is often selected as a certain fraction of the aggregate maximum particle size.

The phrase "aperture size" implies that a geogrid aperture can be characterized by one dimension, i.e. it is square or equivalent. More attention should be paid to the definition of the aperture size for apertures other than square such as: rectangular apertures; triangular apertures; and, more generally, apertures of future geogrids with innovative geometry. Also, research work should be undertaken to develop more sophisticated rules, e.g. rules that involve not only one aggregate particle size, but several characteristics of the particle size distribution curve of the aggregate.

Discussion of the shape of geogrid apertures with respect to interlocking

The ability that a geogrid has to interlock with a given aggregate depends, among other factors, on the relative geometry of the geogrid and the aggregate, i.e. the relationship between the shape of the geogrid apertures and the arrangement of aggregate particles. Describing aggregate arrangement is difficult. Traditionally, in soil mechanics, arrangements of identical spheres are used as a tool to understand arrangements of particles. Aggregate performs better if it is denser. The densest arrangement of identical spheres is the hexagonal arrangement and the least dense arrangement of identical spheres that are in contact together is the cubic arrangement. It may be speculated that a biaxial geogrid may tend to cause the aggregate to adopt locally a cubic arrangement in the vicinity of the geogrid, which is a loose arrangement for the aggregate, thereby limiting the benefit of interlocking. Then, at a certain distance from the geogrid, the aggregate may recover an arrangement that is more or less hexagonal (assuming that the aggregate has been placed in a dense state, i.e. has been well compacted). However, the transition in structure and density, from the cubic arrangement in the vicinity of the geogrid to the hexagonal arrangement away from the geogrid, is probably not favorable to optimum mechanical behavior of the aggregate. In contrast, a geogrid that interlocks with a dense aggregate without disturbing the arrangement of the aggregate is likely to be most beneficial to an aggregate that has been well compacted. (Incidentally, research on the impact of compaction on interlocking would be useful.) The discussion based on arrangement of spheres only provides an approximate description of the interlocking mechanism between aggregate and geogrid. Therefore, rather than "without disturbing the arrangement", it is preferable to say "with minimum disturbance of the arrangement".

The above discussion seems to lead to the conclusion that a geogrid should have a hexagonal structure in order to interlock with a dense aggregate (i.e. a well compacted aggregate having an approximately hexagonal arrangement) with minimum disturbance of its arrangement. In fact, there are two planar structures that may meet the condition of interacting with a dense aggregate while causing minimum disturbance of its approximately hexagonal arrangement: a geogrid with hexagonal apertures and a geogrid with apertures having the shape of equilateral triangles.

Both a geogrid with hexagonal apertures and a geogrid with apertures having the shape of equilateral triangles may interlock with a dense aggregate while causing minimum disturbance of its arrangement. However, there is a major difference between a geogrid with hexagonal apertures and a geogrid with apertures having the shape of equilateral triangles. In a geogrid with apertures having the shape of equilateral triangles, the ribs are aligned, whereas, in a geogrid with hexagonal apertures, the ribs are not aligned. If the ribs are aligned, the tensile characteristics of the geogrid are higher. Furthermore, if the ribs are aligned, it is possible to manufacture a geogrid with stretched ("drawn") ribs, which provides tensile characteristics that cannot be achieved without drawing.

It should be noted that the above discussion is only speculative and qualitative. The only purpose of this discussion is to suggest topics for research work aimed at providing a quantitative analysis of interlocking. Also, the above discussion is limited to the aggregate arrangement. It is likely that the shape of the aggregate particles has an impact on interlocking with geogrids. This is also a suggested subject for future research.

Discussion of the shape and stiffness of ribs with respect to interlocking

The shape and stiffness of ribs can be expected to play a key role in the development of interlocking between a geogrid and aggregate. Since interlocking is likely to play a key role in the behavior of unpaved roads and unpaved areas, it can be said that the shape and stiffness of ribs are likely to play a key role in the behavior of unpaved roads and unpaved areas.

As pointed out previously in this paper, efficient geogrid-aggregate interlocking requires that the relative displacement between the geogrid and aggregate be small. It may be assumed that a geogrid should be stiff to act with small displacement. However, if a geogrid is too stiff, it may disturb the aggregate structure during aggregate placement or it may lack strain compatibility with the aggregate, thereby disturbing the aggregate during the first application of a load. As a result, a geogrid that is too stiff could be detrimental or its benefits could be limited.

Regarding the shape of the geogrid ribs, two considerations are the height and the thickness of the ribs. For example, in the case of extruded geogrids (geogrids that rely essentially on interlocking with aggregate) it is thought that ribs should be: (i) thin (at least as thin as compatible with the required stiffness) in order to cause minimum disturbance to the aggregate; and (ii) tall (in the direction perpendicular to the plane of the geogrid) to maximize

interlocking but not too tall, which could hamper aggregate strike-through and, therefore, be detrimental to interlocking. Research is needed to quantify these qualitative considerations.

There may be a link between the geogrid/aggregate geometric match and the required stiffness of a geogrid. It is possible that the better the geometric match, the stiffer the geogrid can be without significantly disturbing the aggregate. This is another potential research subject.

Discussion of the stiffness of junctions between ribs with respect to interlocking

The mechanical behavior of junctions between ribs has been discussed by a number of researchers. Some think that this is an important consideration, while others do not. The terminology "junction strength" is generally used, but it seems more appropriate to use the terminology "junction stiffness" since only small strains are involved.

In the case of extruded biaxial geogrids, it seems logical to require high junction stiffness between the transverse ribs that provide interlocking and the longitudinal ribs that carry loads. At least, this is the simple view of load transfer between the two sets of ribs in a two-dimensional loading situation. In more realistic loading situations, where the direction of principal stresses is not perfectly defined, the distinction between transverse ribs and longitudinal ribs is not relevant, but the justification for junction stiffness may still exist. The aperture stability modulus, a property that combines the torsion stiffness of a geogrid and the junction stiffness, is used for biaxial extruded geogrids because a correlation appears to exist between this property and the performance of stabilisation structures incorporating biaxial extruded geogrids.

In contrast, field observations and other research do not appear to show a correlation between the aperture stability modulus and the performance of stabilisation structures incorporating triaxial extruded geogrids. It thus appears that the required geogrid properties may not be the same in the case of triaxial extruded geogrids and biaxial extruded geogrids. Clearly, more research is needed on the topic of the behavior of junctions between ribs.

In the case of geogrids that interact with aggregate in great part through interface friction, junction strength and aperture stability modulus do not appear to be important properties (as they are in the case of extruded geogrids, which interact with aggregate mostly through interlocking). Perhaps, in the case of geogrids that interact with aggregate mostly through interface friction, a minimum junction strength to ensure that the geogrid survives construction without damage is sufficient.

Conclusion on geogrid properties for interlocking

Based on the above discussions, it can be tentatively concluded that interlocking requires a geogrid with: adequate aperture size relative to the size and grading of the aggregate particles; aperture shape that best interacts with the densest arrangement of the considered aggregate; and optimized stiffness to provide reinforcement at very low deformations of the stabilisation structure while having strain compatibility with the aggregate.

These tentative conclusions may apply to all types of geogrids. However, they apply essentially to extruded geogrids, because other geogrid types may rely less on interlocking than the extruded geogrids. In fact, with geogrids other than extruded geogrids, the main mode of interaction may be other than interlocking, such as interface friction.

Specifically for the case of extruded geogrids, it can be added that ribs that are thin (to minimize disturbance of the aggregate) and tall (but not too tall, which could hamper aggregate strike-through) may be considered to enhance interlocking.

Finally, it is clear that the above discussion on the geogrid properties required for interlocking leads to a number of research subjects.

Discussion of tensile characteristics of geogrids

It appears, from the discussions in preceding sections, that interlocking is likely to be the dominant mechanism, at least for extruded geogrids. However, tensile strength is often mentioned in publications and specifications on geogrids. The use of tensile strength to characterize geogrids used in unpaved roads and unpaved areas is tempting because tensile strength is the simplest and most readily recognized (if not understood) mechanical property of a geosynthetic. Simplicity and recognition are not a justification for using a property. The property must be relevant.

Based on discussions in preceding sections, it is possible that tensile characteristics (essentially the tensile stiffness) are more relevant to the geogrids that rely less on interlocking and more on frictional interaction than to geogrids that rely essentially on interlocking (such as extruded geogrids).

It should be noted that, even when a geosynthetic is subjected to tensile forces in a stabilisation structure, the relevant property is not tensile strength but tensile stiffness ("tensile modulus"). This is because the strains involved are generally not sufficient to mobilize the ultimate strength. For example, tests by Watts et al. (2004) interpreted by Giroud & Han (2006) show that geogrid strains under dual wheels are still very small (i.e. between 0.1 and 1.2%) after full development of ruts at the end of the test.

It is important to note that the main reason tensile strength, i.e. ultimate strength (as opposed to tensile stiffness), is irrelevant (or negligible) is not because rutting is generally not sufficient to mobilize tensile strength. In fact, the main reason is that tensile strength is not relevant to geogrid-aggregate interaction (whether it is through interlocking or interface friction). As indicated in the preceding section, geogrid-aggregate interaction should be mobilized with very small displacement. Therefore, the geogrid ultimate tensile strength plays no role until the stabilisation structure undergoes deep rutting associated with large deformation of the aggregate layer and the subgrade soil. Then, the geosynthetic provides the tensioned membrane effect.

Survivability of geogrids

Resistance to construction damage is outside the scope of this paper, but it is important to mention it. Like any geosynthetic used in any application, a geogrid must be sufficiently robust to withstand the rigors of transportation, handling, installation, placement of materials in contact, and other construction activities. Also, the geogrid must be capable of maintaining the integrity of its structure and properties throughout its service life. The geogrid material must also not be degradable in any way in a soil environment.

REVIEW OF THE STATE OF PRACTICE

Scope of the review

The review of the state of practice presented herein is based on both facts and beliefs. While it is essential to know facts (e.g. percentages of uses per category), it is also important to know how geogrids are perceived by users.

Types of applications

As mentioned in preceding sections, the two main types of applications where an unpaved aggregate layer is subjected to traffic are unpaved roads and unpaved areas. However, when discussing the state of practice, it is important to distinguish between, on one hand, unpaved roads that are only used as unpaved roads and, on the other hand, unpaved roads that are, in fact, the aggregate bases of paved roads under construction and are used as unpaved roads only during construction of the roads.

Uses of geosynthetics in unpaved roads and unpaved areas

Geotextiles were first used in subgrade stabilisation thanks to pioneering work in the late 1960s by McGown in the UK and Leflaive in France. During the 1970s, geotextiles became extensively used in subgrade stabilisation applications (unpaved roads and unpaved areas), first in Europe, then worldwide. Geogrids, developed by Mercer in the 1970s, appeared in subgrade stabilisation applications in the early 1980s. Since then, they have been extensively used worldwide in subgrade stabilisation applications. Geocells (geosynthetic honeycomb structures) have been used to confine aggregate since the 1970s in some military applications; since the 1990s, they have been used in a relatively small number of civil engineering unpaved roads and unpaved areas.

From limited sources, it is estimated that, in the first decade of the 21st century, geotextiles are still used more than geogrids in subgrade stabilisation applications. In comparison, the use of geocells in these applications is very small.

From the same sources, it is estimated that, in the first decade of the 21st century, the use of geosynthetics in subgrade stabilisation applications is distributed as follows:

- approximately 25% in real unpaved roads (i.e. unpaved roads that remain unpaved);
- approximately 50% under aggregate layers that are used to carry some traffic while unpaved, but will eventually become the aggregate bases of paved roads; and
- approximately 25% in unpaved areas.

From the same sources, it appears that, in real unpaved roads, geotextiles are used more than geogrids because separation is the main consideration in many cases. In these cases, there is generally no design (i.e. no use of a design method). When no design is involved, the aggregate layer thickness and the geotextile are selected on the basis of preceding projects using the same geotextile. More generally, it seems that geotextiles are used more than geogrids in cases where there is no design, whereas geogrids are used more than geotextiles in cases where there is a design.

From the same sources, it appears that, in unpaved roads that are the first phase of construction of paved roads, geotextiles are used if the main concern is separation, whereas geogrids are used more than geotextiles when reinforcement is required, in particular when it is considered important to keep deformations of the aggregate layer as small as possible, which is a legitimate goal since the aggregate layer that is used as a temporary access road should retain its integrity (thickness, mechanical properties) prior to being incorporated in the paved road structure, in order to ensure long-term performance.

Finally, from the same sources, it can be said that, in the case of unpaved roads that are the first phase of construction of paved roads, the market is more or less equally split between geotextiles and geogrids.

Typical considerations involved in comparing geotextiles and geogrids

The main considerations involved in comparing geotextiles and geogrids for stabilisation structures include: the cost of the geosynthetic, the cost of aggregate, the benefit from improved performance, the separation function, experience of the decision-maker, and the maximum allowable deformation.

Geosynthetic cost

The cost of the geosynthetic is an important factor in the selection by the user of a geotextile or a geogrid. It varies significantly from one location to another. In the United States, the cost per square yard (a unit used in the United States, but unknown in other countries, and equal to approximately 0.8 m^2) is approximately \$2.4 to 4.8 for installed geogrids and \$1.2 to 2.4 for installed stabilisation geotextiles. As a result of the significant difference in cost, geotextiles are often preferred to geogrids. Furthermore, the cost of separation geotextiles is very low (\$0.5 to 1 per

installed square yard), which creates a strong incentive for using these geotextiles in stabilisation structures where separation is perceived to be the main issue (stabilisation structures for which no design is typically performed).

The above data on costs of installed geosynthetics can be tentatively generalized as follows: The ratio between the geogrid and stabilisation geotextile costs is approximately 2; and the ratio between the stabilisation and separation geotextile costs is approximately 2 to 3.

Aggregate cost

The cost of aggregate varies tremendously from one location to another. A high aggregate cost favors the use of geogrids since geogrids can save more aggregate than geotextiles. Comparing a wide (but not complete) range of costs of aggregate and geosynthetics in the United States, the author of this paper has concluded that:

- the cost of a typical biaxial geogrid is approximately equivalent to the cost of 50 to 200 mm of aggregate (and most generally 100 to 150 mm); and
- the cost of a typical stabilisation geotextile is approximately equivalent to the cost of 25 to 100 mm of aggregate (and most generally 50 to 75 mm).

Therefore, to justify the use of a geogrid rather than a geotextile from an economical standpoint, it is necessary to demonstrate that a geogrid can save significantly more aggregate than a stabilisation geotextile. In fact, there are many cases where the use of a geogrid saves more than 150 mm of aggregate. To that end, adequate design methods are needed. Design methods are discussed in a subsequent section.

Additional aggregate savings result from a reduction in undercutting when geogrid reinforcement is used. Undercutting consists of additional excavation of the subgrade soil to eliminate soft spots. In case of undercutting, more aggregate is generally needed to bring the surface of the aggregate layer to the design elevation. Undercutting is unwelcome because the associated costs (excavation and additional aggregate) are unpredictable. Geogrid reinforcement can bridge soft spots, thereby reducing the need for undercutting.

In addition to the basic economical benefits discussed above, there are significant environmental benefits associated with aggregate savings: less transportation of aggregate by trucks, hence less air pollution (dust, gasoline vapors), less noise, less carbon emission, less energy consumption, etc.

It should be noted that the geosynthetic and aggregate costs used above are for the United States, and that all markets have their own characteristics (including different patent protections and commercial practices). For example, in regions such as Canada and parts of Latin America, geogrid prices are significantly lower than in the United States.

Improved performance

Even when the geogrid is not completely paid for by the aggregate savings, it may be cost-effective due to improved performance. The geogrid will not only improve short-term performance, such as trafficability during construction, but it will also improve long-term performance as follows:

- in the case of an unpaved road, trafficability will be improved in the long-term due to less deformation; and
- in the case of a paved road, the fact that the aggregate layer has been kept in good condition during construction will be beneficial in the long term (and this effect is likely to be more marked in the case of geogrid than in the case of geotextile, because, as indicated previously in this paper, geogrid-reinforced aggregate layers undergo less deformation than geotextile-reinforced aggregate layers).

Separation

Geotextiles are preferred to geogrids when separation is needed between the aggregate and the subgrade soil. This is the case when the subgrade soil is very soft and open aggregate is used. However it should be noted that a geogrid can provide some degree of separation as explained previously in this paper and repeated below:

- a geogrid with adequate aperture size prevents the loss of aggregate into the subgrade; and
- a geogrid that keeps the aggregate together reduces the opportunities for intrusion of the aggregate by fine particles from the subgrade soil.

Sometimes, the functions of separation and reinforcement are performed by two different geosynthetics: a geotextile performing the separation function; and a geogrid (placed on top of the geotextile) performing the reinforcement function.

Experience of the decision-maker

There are still a number of decision-makers who tend to think that "all geosynthetics are good enough". They are not inclined to pay a premium for improved performance. As a result, they generally do not make a design effort; therefore, they miss an opportunity to evaluate the improved performance that would result from using a geogrid.

As many stabilisation structures are not designed, past experience plays an important role in the decision-making process. This is to the advantage of geotextiles because many decision-makers (design engineers, owners, contractors) tend to have more experience with geotextiles than with geogrids. This is particularly true with the least sophisticated of the decision-makers.

Sophisticated decision-makers are more likely to have experience with geogrids, or to have heard of geogrids at conferences or seminars, than non-sophisticated decision-makers. More importantly, sophisticated decision-makers (in particular design engineers) are likely to be interested in design methods, research and documentation of performance. Since design methods, research and documentation of performance often show that more savings can be made by

using geogrids, it can be inferred that the more sophisticated the decision-maker, the more likely geogrids are to be selected. Therefore, education of decision makers is likely to benefit geogrids.

Maximum allowable deformation

There are subgrade stabilisation applications where the deformations of the stabilisation structure should be below strict limits. The most typical example is that of an aggregate layer used as unpaved road during the construction of a paved road and incorporated in the paved-road structure in the last phase of construction. For the long-term performance of the paved road, it is important to minimize the deformation of the aggregate layer during the first phase of construction, i.e. when the aggregate layer is used as unpaved road. (Indeed, the two beneficial effects of limiting deformations of the aggregate layer during the construction phase are: to maintain the thickness of the aggregate layer; and to maintain the mechanical properties of the aggregate.) In such cases, design generally plays a significant role, and generally leads to the recognition of the fact that a geogrid with efficient interlocking with aggregate provides reinforcement to an unpaved road with significantly less deformation than a geotextile. As a result, in these applications, geogrids tend to be used more than geotextiles.

Conclusion regarding the comparison of geotextiles and geogrids

Based on the above discussions, it may be concluded that:

- Geotextiles are often preferred to geogrids when separation is needed between the aggregate and the subgrade soil, and in simple non-designed applications.
- Geogrids are often preferred in sophisticated applications, especially when limited deformations are required, in particular when the geogrid-reinforced aggregate layer will eventually be incorporated in a paved road.
- In other cases, a design effort would be needed to determine which geosynthetic is the most cost effective. However, such a design effort is rarely undertaken.
- Sophisticated decision-makers are more likely than others to have experience with (or knowledge of) geogrids and more likely to use design methods (which are likely to demonstrate that geogrids are cost-effective).

In conclusion, education of decision-makers and development of design methods are likely to benefit geogrids.

Typical arguments used in comparing various types of geogrids

As discussed previously in this paper, it is difficult to objectively compare geogrids of different types, because their modes of interaction with aggregate are significantly different: some geogrids interact with aggregate primarily by friction; whereas other geogrids interact with aggregate primarily by interlocking.

Before the advent of triaxial geogrids, only biaxial geogrids were considered for subgrade stabilisation applications. The situation was then simple. While some suppliers of geogrids promoted the use of tensile strength to compare geogrids, others promoted the use of properties linked to the junctions between the two sets of ribs, such as junction strength and aperture stability modulus. In fact, there is no contradiction between these two positions since tensile strength (or rather stiffness) is possibly the most relevant property for some geogrids, and load transfer between the two sets of ribs is essential in the case of other geogrids. It is also possible that, for some geogrids that rely essentially on friction for interaction with aggregate, junction strength may not be an important property for performance. Perhaps, in the case of purely frictional geogrids, a minimum junction strength to survive construction without significant damage is sufficient.

There is also some evidence that there may be points of diminishing return with some geogrid properties. As an example, tests performed with various geometries of triaxial geogrids (and therefore various junction strengths and aperture stability moduli) have shown that performance tends to decrease beyond a certain geogrid thickness and mass per unit area and, therefore, a certain junction strength and a certain aperture stability modulus. A tentative explanation is the following: a thicker and stronger triaxial geogrid is too stiff (and its ribs may be too thick). As a result, it may cause more disturbance of the soil than a more flexible type of triaxial geogrid of the same manufacture. Essentially, it appears that, for the type of triaxial geogrid tested, there is an optimum stiffness to better comply with the soil, i.e. better interact with the soil. This important observation may apply to other geogrid properties (and possibly to other geogrids) and needs to be better understood through research.

Also, tests have shown that unpaved roads with triaxial geogrids may perform better than similar unpaved roads with biaxial geogrids of similar manufacture, even though the junction strength and aperture stability modulus are lower for the triaxial geogrid than for the biaxial geogrid. This is consistent with the above comments on the optimum stiffness of triaxial geogrids. A tentative explanation is that junction strength and aperture stability modulus are less important in triaxial geogrids than in biaxial geogrids because there is less need for load transfer between ribs of different directions in a triaxial geogrid than in a biaxial geogrid. Also, it is possible that triaxial geogrids cause less distortion to the aggregate structure if they are more isotropic than biaxial geogrids, which can be a research subject.

The above discussions lead to the following tentative conclusion regarding the comparison between various types of geogrids:

- Frictional geogrids (i.e. geogrids that rely essentially on interface friction) and geogrids that rely essentially on interlocking cannot be objectively compared using the same property tests.
- Tensile strength (or, better, tensile stiffness) may be more appropriate for characterizing frictional geogrids.
- Junction strength and aperture stability modulus may be more appropriate for characterizing biaxial extruded geogrids.

- More needs to be learned on the relationship between properties of geogrids and their performance, and new measurement of properties should probably be developed.

Impact of design methods on selection of geogrids for subgrade stabilisation applications

The available design methods and the way they are used have an impact on the selection of geogrids in subgrade stabilisation applications. This is an important question because some unpaved roads and unpaved areas are designed, while some are not, as indicated in preceding sections.

Brief review of design methods

The Steward et al. (1977) method, which is extensively used in the United States, considers two cases: "with" and "without" geotextile. It does not take into account the properties of the geotextile. In other words, in the Steward et al. method, all geotextiles are considered to be equal.

The Giroud & Noiray (1981) method was developed for geotextiles. First, the method makes it possible to calculate the required thickness of aggregate without a geotextile. Then, the method makes it possible to calculate the aggregate savings resulting from the use of a geotextile. The only geotextile characteristic used in the Giroud & Noiray method is the tensile modulus ("tensile stiffness"), which is used to quantify the tensioned membrane effect. (In fact, to the best of the author's knowledge, it is the only method that quantifies the tensioned membrane effect.) In Europe and other parts of the world, the Giroud & Noiray method is sometimes used for geogrid-reinforced stabilisation structures as follows: first it is used for calculating the required thickness of an unreinforced aggregate layer on the considered subgrade soil; then an empirically based "stabilisation factor" is used to reduce the aggregate layer thickness. This "stabilisation factor" has been developed based on various trafficking trials performed over the years to quantify the benefit provided by using a geogrid.

The Giroud & Han (2004) method provides a mathematical framework that makes it possible to quantify the benefits of all types of geosynthetics. The method requires calibration in the case of geogrids, whereas no calibration is needed in the case of geotextiles. It is important to note that, for valid use and to ensure reliable results, the Giroud & Han method requires calibration for each specific type of geogrid under consideration. So far, to the best knowledge of the author of this paper, it has been calibrated only for extruded biaxial geogrids from one manufacturer, using the aperture stability modulus as the characteristic property of the geogrids. Other properties, or group of properties, can be used to calibrate the method for all types of geogrids. Testing is underway to calibrate the method for a certain type of triaxial geogrid. In the past several years, hundreds of unpaved roads and areas in the United States, Canada and Latin America have been designed in a consistent manner using the Giroud & Han method; and, to the best knowledge of the author of this paper, there have been no performance problems on projects designed using this method. The Giroud & Han method has recently been added to the FHWA (US Federal Highway Administration) Geosynthetics Training Manual as a recommended design method. (Regrettably though, the manual does not stress that the method requires calibration and validation for every geogrid material.)

This brief review shows that the Giroud & Han method is different from other methods, as it makes it possible to quantify the influence of geogrid properties. In contrast, other methods give the same results regardless of geosynthetic properties. For example, the Stewart et al. method shows no difference between reinforcement products; and the Giroud & Noiray method shows a difference only for very large deformations, i.e. when the tensioned membrane effect is effective.

Use of design methods

When geogrids are used to provide reinforcement in stabilisation structures, the use of a design method is recommended to demonstrate the benefits provided by the geogrids. However, it is difficult to convince some users that design should be performed for stabilisation structures, which are perceived as simple structures. As design methods are progressively improved through calibration with field performance, the benefits provided by geogrids will be better quantified, which should increase the credibility and, therefore, the use of design methods for unpaved roads and unpaved areas. Clearly, improvement of design methods should be a research priority.

Design of unpaved roads seems to be provided more by geogrid suppliers than by design firms. However, design engineers are becoming more sophisticated: they used to do no design (and they specified the same geotextile as in a previous project); now they perform a geotechnical investigation and cooperate with a geogrid supplier to do the design. Design engineers become more interested in the design of unpaved roads and areas because they increasingly realize that, thanks to design, they can: (i) save money by decreasing aggregate thickness; and (ii) better control costs by making more accurate predictions of performance.

CHALLENGES FOR THE FUTURE

The nature of the challenges

Prior to discussing specific challenges, it is important to identify the nature of the challenges associated with unpaved roads and unpaved areas.

Better understanding and quantification of relevant phenomena and mechanisms

As always in technical disciplines, phenomena must be better understood and quantified. This is obviously the case in unpaved roads and unpaved areas since phenomena are very complex. The fundamental reason for the complexity is that loads are applied in one direction (vertical) while the geosynthetic is perpendicular to that direction. As a result of this complexity, "subtle mechanisms" are involved as pointed out by Giroud (2008) in a review of challenges facing the geosynthetics discipline: "In the past three decades, many design methods have been developed by extending to geosynthetics engineering traditional methods used in geotechnical engineering. This approach has been very productive. However, the simplest methods from geotechnical engineering were the first to be adapted to geosynthetics engineering. As a result, subtle mechanisms potentially of importance to the performance of structures incorporating geosynthetics have been overlooked."

Three of the five examples of "subtle mechanisms", mentioned by Giroud (2008) for the geosynthetics discipline in general, are relevant to unpaved roads and unpaved areas: "small deformations and repeated loading; quantification of interface mechanisms between adjacent materials; quantification of the performance of reinforced soil treated as a composite material rather than a juxtaposition of two components". And Giroud (2008) concludes that "researchers will need to develop design methods for subtle mechanisms that have been neglected in the past."

Impact of materials on challenges

The geosynthetics discipline is focused on the geosynthetic materials. Therefore, the challenges for the future are linked to the geosynthetic materials that can be expected to be used in the future. Based on discussions in this paper, it can be expected that the use of triaxial geogrids will grow in the future and that other types of geogrids will be developed with innovative configurations. Therefore, one of the challenges will be to develop testing and design methods that are relevant to geogrids with configurations different from the traditional biaxial configuration. It should be expected (and accepted) that different types of geogrids be characterized by different properties.

Education

It is known that education is a permanent challenge for the geosynthetics discipline. This is due to the fact that "geosynthetics have been the most important innovation in geotechnical engineering in the second half of the 20th century", in particular because "geosynthetics have pervaded most branches of geotechnical engineering" and also because the variety of geosynthetics is more complex than the variety of soils, as shown by Giroud (2008) based on a review of innovations in geotechnical engineering. As a result, there is a lot to teach about geosynthetics to geotechnical engineers who are known for conservatism and are often reluctant to learn about innovative solutions.

The education challenge is even greater regarding the use of geogrids in road applications because the mechanisms involved are complex (and even "subtle", as mentioned above) and some of them are still not well understood. Education will not be discussed further herein, but the mechanisms that need to be understood first, and then addressed in the education effort, are discussed below.

Discussion of technical challenges

Design and testing methods relevant to new geogrids

As mentioned in preceding sections, it can be expected that triaxial geogrids and other new forms of geogrids will be used increasingly. Therefore, design methods able to quantify the benefits provided by triaxial geogrids and other new forms of geogrids should be developed. The design methods should be calibrated for different types of geogrids (which are likely to be characterized by different properties).

Current design methods for unpaved roads often assume a two-dimensional situation, which may be the case when the traffic is perfectly channelized, especially after deep ruts have developed. Before the development of deep ruts, the stress field induced by a single or a dual wheel may be closer to axisymmetrical than to two-dimensional. Axisymmetrical design methods will be particularly useful in the case of unpaved areas because, in that case, the traffic is not channelized. To use axisymmetrical design methods, testing of geogrids will have to be done in multiple directions. Currently, geogrid properties are generally measured in only one or two directions, which may not be sufficient for axisymmetrical design methods. Research should be undertaken to determine which types of geogrids are isotropic (in particular for small strains), and to evaluate the benefits of geogrid isotropy.

Quantification of interaction between geogrid and aggregate

Interaction between geogrid and aggregate is clearly a "subtle mechanism", using the expression that was mentioned above, and perhaps the ultimate subtle mechanism. An important challenge is to better understand the geogrid-aggregate interaction mechanisms for the various types of geogrids.

As mentioned previously in this paper, the interaction mechanisms are different for the various types of geogrids. A better understanding of the mechanisms should lead to an appropriate selection of the relevant properties of the different geogrids. These properties could then be used to calibrate a design method, such as the Giroud & Han method, in a way that is appropriate for any specific type of geogrid.

As noted previously in this paper, a triaxial geogrid with lower tensile strength and aperture stability modulus than a biaxial geogrid of similar manufacture may perform better in the field. As suggested previously in this paper, this

may be due to superior interlocking resulting from the triangular shape of the apertures and higher ribs. This important observation needs to be investigated. Furthermore, it can inspire research that may benefit all types of geogrids.

As also noted previously in this paper, based on field observations on the performance of aggregate layers reinforced with triaxial geogrids, there seems to be optimum properties for triaxial geogrids, e.g. a better performance seems to be achieved with triaxial geogrids having such optimum properties than with triaxial geogrids that are thinner-weaker or thicker-stronger. These observations suggest the concept of mechanical compatibility between geogrid and aggregate. This seems consistent with the fact that the main mode of performance improvement is interaction between geogrid and aggregate and not addition of strength to the structure. Investigating this mechanism is an important challenge for researchers and should benefit all types of geogrids.

Finally, it may be appropriate to also study the impact on interlocking of aggregate geometry (overall shape, angularity, surface condition) and even aggregate strength. The same way some geogrids interlock better than others with aggregate, there must be aggregates that interlock better than others with geogrids. Even further, it may be possible to imagine aggregate that interlock very well with a certain geogrid, but does not interlock very well with itself. In other words, there may be cases where forces are transferred very well between geogrid and aggregate, but poorly between the layer of aggregate that is adjacent to the geogrid and the next layer of aggregate. In conclusion, not only aggregate-geogrid interlocking should be studied, but also what could be called "internal interlocking" of the aggregate. As an ultimate development regarding aggregate, one may imagine a research program leading to an ideal shape for aggregate particles, such as a mini tetrapod (a shape adopted after extensive testing for large concrete blocks used for coastal protection). Then, synthetic or mineral aggregate molded to ideal shapes could be envisioned (provided such aggregate could be produced at an acceptable cost).

Researchers investigating interlocking should develop compatibility rules between geogrid apertures and aggregate particle size distribution curve to replace the crude rules currently used, as mentioned previously in this paper. This leads to the next challenge, the analysis of a soil-geogrid composite material.

Composite reinforced-material approach

As discussed above, a better understanding of geogrid-aggregate interaction is the key to progress in stabilisation structure design. It is tempting to go one step beyond and to treat the aggregate and geogrid together as one composite material. This concept seems more appropriate for large masses of soil reinforced with multiple layers of closely spaced geogrids. At a scale significantly greater than the geogrid spacing, it is possible to define a continuum with average properties. From a mathematical standpoint, there is no special difficulty, but laboratory testing on very large specimens would be required to directly measure the properties of the composite material, rather than deriving the properties of the composite material from the properties of the geogrid in isolation and the aggregate properties.

It may be difficult to apply this composite-material concept to unpaved roads and unpaved areas. Interlocking between the geogrid and aggregate does create a composite material. However, at a certain distance from the geogrid, the aggregate is not interlocked with the geogrid. Therefore, the transition between the interlocked-aggregate composite material and the "free" aggregate must be analyzed, which is likely to be difficult. This may be linked to a research on the optimum locations for the geogrid.

Whether it can be used for unpaved roads and unpaved areas, or it can only be used for multilayer reinforced soil masses, the composite material approach should be investigated in the future. This may lead to the use of more layers of medium-strength geogrids, with emphasis on interlocking rather than on tensile characteristics. This would be "intimate reinforcement" or "material reinforcement" rather than "structure reinforcement".

Quantification of the effects of repeated loading

The quantification of the effects of repeated loading would be very difficult using traditional geotechnical methods. This can be only achieved through full scale testing or advanced mathematical modeling. Also, work should be done on the quantification of the repeated loading itself. The use of the number of vehicle or axle passes is appropriate only if the traffic is perfectly channelized. In other cases, clarification is needed.

Tentative list of research needs

This tentative list (based on preceding discussions) is not complete. It is only intended to foster discussions.

Fundamentals of geogrid-aggregate interaction
- Better understanding of the geogrid-aggregate interaction mechanisms for the various types of geogrids using testing and mathematical models
- Determination of optimum mechanical compatibility between geogrid and aggregate under conditions of small displacement and repeated loading
- Evaluation of potential benefits of geogrid isotropy on geogrid-aggregate interaction

Study of the parameters of geogrid-aggregate interaction
- Influence of size and shape of apertures on interlocking (and, more generally, interaction) with aggregate
- Influence of size, shape and stiffness of ribs on interlocking (and, more generally, interaction) with aggregate
- Influence of junctions between ribs on interlocking (and, more generally, interaction) with aggregate
- Impact of aggregate characteristics (shape, grading, strength) and compaction on interaction with geogrids

Study of the intrusion of fine particles from the subgrade soil into the aggregate
- Evaluation of the ability of geogrids to provide separation
- Evaluation of the impact of intrusion of fine subgrade soil particles on interlocking between aggregate and geogrids

Geogrid properties
- Evaluation of properties of geogrids as a function of direction and evaluation of the isotropy or anisotropy of the various types of geogrids
- Determination of the relevant properties of the different types of geogrids for correlation with field performance

Design methods
- Calibration of design methods with field performance for various types of geogrids using the identified relevant properties
- Development of design methods for axisymmetrical situations and situations where traffic is not channelized
- Quantification of repeated loading for cases where the traffic is not channelized

Alternative approaches
- Evaluation of a "composite material" approach where the geogrid plays the role of material reinforcement rather than structure reinforcement
- Optimum location(s) of geogrid(s) in the aggregate layer

CONCLUSION

Qualitative analyses and field observations show that geogrids are adequate materials for aggregate reinforcement in stabilisation structures (i.e. unpaved roads and unpaved areas). Some quantitative analyses and design methods provide an evaluation of the benefits of geogrid reinforcement for stabilisation structures. However, the currently available methods are too dependent on properties of geogrids measured "in isolation". The challenge for the future is to develop design methods that truly reflect the way geogrids improve the performance of stabilisation structures. The mechanism is "interaction with aggregate" rather than "addition of strength to the structure". In other words, it is "intimate reinforcement" rather than "structure reinforcement". When this technical challenge is met, then education of the decision-makers (designers, owners, contractors) will be possible.

Geogrids have been extremely successful in an application, which initially (in the 1970s) used geotextiles exclusively. However, there are still many challenges that must be met to ensure a bright future for geogrids. Challenges for the future have been identified. For geogrids, the future starts today.

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