INTRODUCTION

In the early 1980's, the Author's research group at the University of Nottingham had the privilege of being a part of the pioneering research work that took place into the various civil engineering applications of the newly invented high strength polymer grid materials later to become known as 'geogrids'. The work took place at several universities, each looking into different aspects, and the work was guided by the inventor of the geogrid, the late Dr Brian Mercer with a Steering Group chaired by Sir Hugh Ford, which also included some consulting engineers. The Nottingham task was to investigate the potential for using geogrids in the reinforcement of asphalt for highways and other paved areas. This early work, over the period 1981 to 1986, proved very successful and provided the manufacturers with a practical basis for launching the product into the marketplace. Details are available in Brown et al (1984) and Brown et al (1985a). Further research has been carried out over the intervening 20 years, both at Nottingham (Caltabiano and Brunton, 1991 and Brown et al, 2001) and elsewhere (e.g. De Bondt, 1999). Recently, as a result of a Royal Society grant under the Mercer Senior Award for Innovation Scheme, the Nottingham group extended their research into the applications of geogrids for reinforcement of railway ballast (McDowell et al, 2006 and Brown et al, 2007b). Whereas, the asphalt research had been essentially of a practical experimental nature, the railway work, in addition to extensive experimental studies, also involved development of an improved theoretical understanding of the mechanics of reinforcement. In both cases, the laboratory research over the years has been closely linked to developments in the field to assess the practicalities of geogrid application on site.

This paper presents the highlights of the key findings from 28 years research at Nottingham and assesses the state of knowledge as a basis for sound design and application. Important areas for future research are then identified. While the paper focuses mainly on the use of polymeric geogrids, some reference is made to work carried out with steel and glass fibre products.

PHILOSOPHICAL APPROACH TO RESEARCH

Initially, the research had to identify potential applications of geogrids for the reinforcement of asphalt. This was done by identifying various possibilities in the context of the mechanical response of pavements to repeated loading from traffic and the failure mechanisms that develop, for which the use of a geogrid could possibly be beneficial. The approach was essentially a pragmatic one, though it was founded on a theoretical understanding of how pavements respond to wheel loading and, in particular, how critical stress conditions arise in asphalt layers, both for new pavements and for strengthening overlays applied to existing ones. Consequently, laboratory experiments were devised to simulate field conditions and, later, pilot scale wheel tracking tests were conducted to extend this work towards the field situation. The question of field installation was recognised early on as presenting a significant problem and contact was maintained between developments in this area and the laboratory research. It was also recognised from the start, that if the early research yielded promising results, then a major effort would need to be made on applying the results to design, in order to demonstrate the potential benefits of using geogrid reinforcement. This link between experiment, field application and design using relatively simple theoretical concepts has been a key feature of the Nottingham contribution over the years.

The other early research work on geogrid applications involved a major effort on the reinforcement of soil, of granular materials in haul roads and of concrete, in addition to the laboratory testing of geogrids to measure their key mechanical properties. It was recognised that, compared with soil reinforcement, the asphalt applications would involve much lower mobilised strain levels in the geogrid and would need to consider the effects of repeated loading and of elevated temperatures at the time of installation. While the asphalt, soil and granular materials applications flourished, concrete reinforcement was not pursued beyond the early 4 years research effort.

SUMMARY OF ASPHALT APPLICATIONS

Experimental facilities

In deciding on the most appropriate experiments to perform in order to simulate typical field conditions, it was important to understand the key failure mechanisms that can develop in asphalt pavements for which the presence of a reinforcing element could be potentially useful. These include fatigue cracking, wheel track rutting and reflection cracking in asphalt overlays over old pavements, usually those constructed of jointed concrete. While all of these mechanisms are caused by repeated transient wheel loading, the reflection cracking problem can also be strongly influenced by thermal effects caused by diurnal temperature changes.
Figure 1 shows photographs of these various failure mechanisms and illustrates how geogrids may be deployed to increase resistance to each.

**Figure 1. Applications of geogrids in asphalt pavements**

a) Rutting

b) Fatigue cracking

c) Reflection cracking
Figure 2 illustrates the various pieces of apparatus which were developed in order to simulate the above failure mechanisms. In addition, the pilot scale Nottingham Pavement Test Facility (Brown and Brodrick, 1981), shown in Fig. 3, was deployed to examine the behaviour of whole pavement structures under moving wheel loads both with respect to fatigue cracking and rutting.

In order to understand some aspects of the behaviour which were observed in these various experiments, it is important to first consider the key mechanical properties of the geogrids which were used and of the asphalt into which they were installed. The problem of exposing the polypropylene geogrid to asphalt paving temperatures up to 160°C was quickly solved by the manufacturers through the development of a ‘heat set’ version that has been successful in practice.

The geogrid property considered to be of most importance was its elastic stiffness at the low strains likely to be mobilised in an asphalt layer. Cyclic load tensile tests were conducted at 20°C, 1 to 8Hz and at cyclic strains up to 0.6%. These revealed that the elastic stiffness of the geogrid was about 1MN/m, which is approximately equivalent to a Young’s Modulus of 12GPa, when the effective cross sectional area is taken into account (Brown et al, 1985a). There was little or no dependence on frequency over the small range investigated. A typical asphalt mixture into which a geogrid may be installed has an elastic stiffness of about 4GPa at the same temperature and a frequency of 12Hz, representative of traffic moving at about 80km/hr. Cyclic load tension/compression tests on reinforced and unreinforced specimens of asphalt showed that the elastic stiffness was unaffected by the presence of the geogrid (Brown et al, 1984). This was because the stiffnesses of the two materials were of the same order of magnitude. This theme of reinforced asphalt, and also reinforced granular material, having the same response to transient loading as unreinforced material, emerged repeatedly from a range of experiments over the years. It was, therefore, apparent that the reinforcing effects of a geogrid are only mobilised at the higher strain levels associated with the development of failure mechanisms such as fatigue cracking, permanent deformation, which causes wheel track rutting, and thermal cracking.

The experimental arrangements illustrated in Fig. 2 were each developed to investigate a particular aspect of geogrid asphalt reinforcement. The sizes of the test specimens in each case are shown in brackets with the figure captions. These read: length x width x depth.

Figure 2(a) shows a beam on an elastic support made of synthetic rubber which was subjected to cyclic loading. The rate at which a fatigue crack propagated from a crack initiator cut into the centre of the beam underside was monitored both for reinforced and unreinforced beams in order to quantify any increase in the fatigue life of the asphalt when reinforced.

Figure 2(b) shows a similar arrangement but with a gap in the plywood support that was provided over the rubber. A stiffer rubber was used. This was to simulate the situation experienced by an asphalt overlay placed over on old jointed concrete pavement for which reflection cracking above the joint is a common practical problem in the field. Again comparative data were collected for reinforced and unreinforced asphalt beams.

Figures 2(e), (f) and (g) each illustrate more sophisticated tests that were developed later to study aspects of cracking in more detail. Figure 2(e) shows a beam with a support system consisting of a combination of rubber and steel which evolved through experimental trials to present a method that more closely representing field conditions for transient reflection cracking (Brown et al 2001). Crack propagation rates were measured as before.

The apparatus in Figure 2(f) presented an attempt to combine the slow strain application caused by thermal effects with the transient strains resulting from wheel loading (Caltabiano and Brunton, 1991). The thermal cracking problem was studied directly using the device shown in Fig. 2(g) in which the asphalt was bonded to a concrete slab with a gap representing a joint in an underlying concrete pavement. Strain measurements were taken on the upper surface of the asphalt as the two parts of the concrete slab were moved slowly apart to a particular value (up to 8mm) at -5°C over a period of several hours and then moved together again at the same rate.

The Slab Test Facility (STF) illustrated in Fig. 2(c) was developed to test a range of asphalt slabs both reinforced and unreinforced and included some incorporating non-standard geogrids with larger apertures that the production material shown in Figure 4(a), which was used for all the other early work. This was later modified by the manufacturers to the dimensions shown in Fig. 4(b). The objective of these wheel tracking tests was to determine the wheel track rut depths that developed in reinforced slabs compared with unreinforced ones. Earlier tests of this type were undertaken with the existing Pavement Test Facility (PTF) using a somewhat larger wheel load. A few tests relating to reflection cracking were also conducted using a modified support system for the slabs.

Later, the PTF was used to study a variety of asphalt pavement structures incorporating geogrids and including overlays to previously tested and damaged pavements. These experiments were helpful in understanding the effect of varying the location of the geogrid and how cracking and/or rutting developed in reinforced sections compared with unreinforced ones.
Figure 2. Experimental facilities used to test reinforced asphalt

a) Fatigue cracking (520x150x90mm)
b) Reflection cracking (525x150x100mm)
c) Rutting (1200x340x80-100mm)
d) Interface shear (320x320x150mm)
e) Crack propagation (400x200x90mm)
f) Combined thermal and transient loading (400x136x75-100mm)
g) Thermal cracking (2000x200x80mm)
Summary of main findings

Fatigue cracking

The apparatus shown in Fig. 2(a) was used to obtain some preliminary fatigue data for a typical asphalt concrete (Brown et al. 1985a). The geogrid was tried at two positions in the beam; 11 mm and 22 mm above the base. The crack initiator cut into the base was 5 mm long. Unreinforced beams were also tested. Failure was arbitrarily defined as when the crack reached 52 mm above the base. Figure 5 summarises the results in the form normally used for asphalt fatigue curves. It is apparent that there was an increase in life at any strain level for the reinforced cases but that best performance was achieved when the geogrid was in the lower position in the beam which was nearer to the point where the cracks initiated. The data indicated that an increase in fatigue life of ten times was possible when a geogrid was deployed in this lower position. This information was used in subsequent pavement design computations to demonstrate the effectiveness of the geogrid either in facilitating a thinner asphalt layer for the same life or for extending the pavement life relative to a structure with unreinforced asphalt (Brown et al. 1985a and b).

The data shown in Fig. 6 were obtained using the later apparatus, illustrated in Fig. 2(e), and show the crack growth for an unreinforced beam compared with beams incorporating various reinforcing materials (Brown et al. 2001). The data represent the mean values from a number of tests. Taking the curves for the control and ‘poly’ reinforced beam allows a comparison to be made with the earlier data in Fig. 5. The control beam failed when the crack had grown to a length of 40 mm after about 250,000 cycles. The poly reinforced beam lasted for 550,000 cycles before the same degree of damage had been done; an increase in life of 2.2 times. This is comparable with the case in Figure 5 when the geogrid was placed in the higher position. This was 17 mm above the tip of the crack initiator compared with 20 mm in the later experiments and so is clearly comparable.
In both these sets of experiments it was assumed that the number of cycles to crack initiation would be unaffected by the presence of the geogrid, as it had earlier been demonstrated that the elastic stiffness and, therefore, the induced tensile strain which controls crack initiation, would be the same for reinforced and unreinforced beams. Consequently, the experiments focused on measuring the propagation phase of the fatigue cracking by providing a clear crack initiator at the bottom of each test specimen.

**Reflection cracking.**

The initial experiments to study reflection cracking were conducted using the apparatus shown in Fig. 2(b). These generated extremely encouraging results when the geogrid was located at the bottom of the beam as illustrated by the photographs in Fig. 7, which illustrate a clear and significant benefit from use of the reinforcement.

![Figure 5](image_url)  
**Figure 5.** Fatigue relationships for reinforced and unreinforced asphaltic concrete

![Figure 6](image_url)  
**Figure 6.** Crack development for asphalt reinforced with different materials

(a) Reinforced beam after $1\times10^6$ cycles  
(b) Unreinforced beam after $4.3\times10^5$ cycles  

**Figure 7.** Comparison of test specimens after reflection crack testing
Figure 8 shows a summary of all the data from this set of experiments, indicating the effect of geogrid location. Although there was a significant increase in life for all the reinforced cases, placement at the bottom of the beam, nearest to the discontinuity, was by far the most effective.

![Figure 8. Summary of all reflection crack data](image)

All these experiments focussed on the effects of transient repeated load, whereas later tests, using the equipment shown in Fig. 2(f), combined an initial tensile strain applied by stretching the rubber support and then superimposing the transient repeated load. The most realistic of these experiments generated the comparative data shown in Fig. 9, which showed that the geogrid reinforcement could result in an increase in life by a factor of 10 compared with the unreinforced case (Caltabiano and Brunton, 1991). The data in Fig. 9 includes tests with unreinforced polymer modified bitumen as well as normal bitumen in the asphalt. It also shows the effect on an unreinforced beam of increasing the initial crack opening which simulated the thermal movement.

Reflection cracking resulting from thermal movements at low temperatures (-5°C) was studied using the apparatus shown in Fig. 2(g). A summary of the results is presented in Fig. 10. This shows that an unreinforced asphalt overlay could only withstand a crack opening of 1mm before failure at a strain of 0.6%. The polymer geogrid reinforced asphalt, by contrast, had not failed at a crack opening of 8mm and under a strain of nearly 1.2%.

![Figure 9. Summary of reflection crack tests incorporating thermal and transient loading](image)

![Figure 10. Summary of results from thermal cracking tests at -5°C comparing the performance of various reinforcement types](image)
A few reflection cracking tests were conducted on larger asphalt specimens using the STF (Fig. 2 c) modified as shown in Fig.11 to provide a discontinuity in the support beneath the slab. These tests were considered to be more realistic in terms of simulating field conditions. The slab thicknesses were nominally 55mm for one pair of tests and 100mm for the other. Each pair consisted of a reinforced and an unreinforced slab. All were 1.2m long and 0.85m wide with loading of 2.8kN for the thinner pair and 4kN for the thicker ones. The geogrid was located at the bottom of the slab.

Both of the control slabs had failed by cracking after 30,000 and 40,000 load cycles respectively for the thinner and thicker slabs. Neither of the reinforced slabs had shown any signs of cracking after 100,000 cycles.

Figure 11. Slab Test Facility arranged for reflection crack tests

Rutting

A number of asphalt slabs were tested under moving wheel loads in both the STF and the PTF. All tests were conducted at 30°C and continued for 50,000 cycles and some typical results and test specimens are shown in Fig. 12. Comparison of the final rut depths of reinforced and unreinforced slabs showed that reductions in rutting of between 20 and 60% were possible. In terms of the number of wheel load applications to a critical rut depth, an increase by a factor of three was indicated by the data for reinforced slabs.

The geogrids were located near the centre of the beams so that the ratio of geogrid depth to width of the wheel contact area was about 0.3. Later tests of pavement sections in the PTF with this ratio as 1, showed no reduction in rut depth. Clearly, the geogrid needs to be located in a position where it can be most effective in resisting the tendency of the asphalt to accumulate permanent strains that result in rutting.

Figure 12. Typical slab pairs after wheel track rutting tests and cross sectional profile after 50,000 cycles

Performance testing

The importance of geogrid location was well illustrated in some PTF experiments involving 80mm asphalt layers placed directly on a low stiffness foundation of granular material over soft soil. This was done to encourage both fatigue cracking and rutting to develop under repeated wheel loading. Three sections were constructed in series so that they were subjected to identical wheel loading. One was unreinforced, the second had a geogrid installed at mid-depth and the third had a geogrid placed at the bottom of the asphalt. Figure 13 shows photographs of cross sections cut from the pavements at the end of testing, which involved a wheel load of 9kN applied for 200,000 repetitions at 20°C. Clearly the unreinforced section failed comprehensively by cracking and the significant rut depth included a large contribution from the supporting layers. With the grid in the centre, there was still evidence of cracking but the rutting was here contributed only from the supporting structure. The asphalt layer thickness was maintained, indicating that the geogrid had been effective in limiting the permanent strains in this layer. By placing the geogrid at mid-depth, it was at 0.3 times the width of the loaded area, the same as in the earlier slab tests which demonstrated effective reduction in rutting. In the bottom photograph, there is no evidence of cracking. This confirms that placing the grid at the bottom of the asphalt layer is the correct location to counteract the tensile strains that cause cracking, which have a maximum value in this zone. The small amount of rutting developed almost entirely from permanent deformation within the asphalt layer as the geogrid was here at a depth of 0.6 times the loaded area width, where it was less effective at resisting rutting. However, by the prevention of cracking, the structural integrity of the layer was preserved, stresses transmitted to the supporting structure were reduced and the permanent deformation in the support was lower than in either of the other two cases.
Interface shear testing

It was recognised that positioning of a layer of geogrid between two layers of asphalt could provide a shear weakness through interfering with the interlayer bond required for structural continuity. To investigate this experimentally, several sets of experiments were conducted with various versions of the direct shear testing apparatus shown in Fig. 2(d). The most realistic of these, involving application of repeated shear, yielded comparative measurements of shear stiffness for the interface. For the geogrid principally discussed in this paper, the shear stiffness was significantly lower than for an interface with no inclusion and for the geogrid with a fabric backing, which is the preferred material for current applications, the stiffness was even lower. Since few measurements were taken and the matter is of great importance for design, it is an area for future research.

Theoretical modelling

Over the period of intense experimental work summarised above, relatively little effort was put into the development of theoretical models to predict the performance of reinforced asphalt. An exception to this was the work reported by Thom (2000) and by Brown et al (2001). This employed a simplified approach using crack propagation theory and assumed that a geogrid, when present, acts to hold the two sides of a developing crack together. The influence of the geogrid was taken into account as the crack approached the plane of the geogrid as well as when the crack arrived and continued beyond this level in the asphalt layer. This exercise revealed that some of the key parameters involved are:

- Bond strength between geogrid ribs and asphalt
- Geogrid stiffness
- Interface stiffness

Figure 14 (after Thom, 2000), shows some typical predictions for asphalt overlays above a jointed concrete pavement and a cracked asphalt pavement. Predictions for the reinforced and unreinforced cases are shown and crack propagation both from the top and from the bottom of the overlay was considered. For the concrete pavement, the geogrid was placed near the surface while for the asphalt case it was at the bottom of the overlay. The results are expressed in terms of the number of load cycles required for the crack to reach a particular level in the asphalt. It will be seen that the advantages of the reinforcement are apparent in both cases.

FIELD INSTALLATION

Early experiments were carried out in parallel with the laboratory studies in order to develop a reliable means of installing geogrids in asphalt. This led to the conclusion that it was vital to ensure that the geogrid was securely attached to the substrate before paving over it, otherwise the geogrid would be disrupted and cause serious damage to the asphalt layer. Initial techniques included the use of a chip seal (surface dressing) to stick the geogrid to the existing surface but in recent years this has been replaced by the use of geogrid which has a fabric backing bonded to it which can be effectively glued to a hot bitumen sprayed surface. Whichever technique is used, it is clear that the important potential benefits of geogrid reinforcement will not be achieved on site unless good workmanship is employed.
RAILWAY APPLICATIONS

Recent research by the Author and his colleagues has helped to focus on some of the fundamentals of reinforcing railway ballast with geogrids. The work has been presented in detail elsewhere by McDowell et al (2006), Brown et al (2007b) and summarised by Brown et al (2008).

Testing at full scale both in a simplified apparatus to assess geogrid performance in ballast (Brown et al 2007b) and in a new Railway Test Facility (RTF) (Brown et al, 2007a) demonstrated that important reductions in the rate at which railway track settlement develops can be achieved by use of the correct geogrid located near the bottom of the ballast layer as demonstrated by the results in Fig. 15 obtained from the RTF. Field trials on the West Coast Main Line also demonstrated the benefits of this form of reinforcement (Sharp et al 2006).

![Figure 14](image1.png)

(a)180mm overlay to jointed concrete
(b) 40mm overlay to cracked asphalt

Figure 14. Theoretical predictions of cracking in asphalt overlays

The main objective of this work was to determine the geogrid properties, both geometric and mechanical, which would result in optimum performance as reinforcement for railway ballast with a nominal particle size of 50mm and the following key points arose:

- The ratio of geogrid aperture size to particle size for best performance was 1.4.
- Influential parameters that affect reinforcement effectiveness included geogrid stiffness at low strains (high values best), geogrid cross sectional profile (sharp corners and thick ribs best), geogrid rib bending stiffness relative to overburden pressure and junction strength, which should be high.

An important aspect of this work, which still continues at Nottingham, was use of the Discrete Element Method (Cundall and Strack, 1979) to model reinforced ballast (McDowell et al 2006). The results were compared with some simple pull-out tests and revealed the same desirable aperture to particle size ratio of 1.4 for optimum performance as was determined from the experimental work.

![Figure 15](image2.png)

Figure 15. Settlement of sleepers for reinforced and unreinforced railway track tested in the RTF
CONCLUSIONS

1. The application of geogrids for the effective reinforcement of asphalt in pavements has been clearly demonstrated and applied in practice.
2. This reinforcement can reduce the incidence of cracking and rutting in pavements.
3. The reinforcement of railway ballast to reduce the rate of track settlement has been optimised and shown to be effective in practice.

FUTURE RESEARCH

As pointed out at the start of this paper, the large quantity of research on reinforced asphalt carried out over the years has been essentially pragmatic and experimental. This is less true for the more recent work on railway track applications. The following areas are proposed for future research activity:

- Improved theoretical understanding of the basic mechanisms involved in geogrid reinforcement of asphalt and granular materials for roads, railways and other paved areas. An example of this was provided by the optimisation of geogrid properties for effective reinforcement of ballast. This work needs to be extended to graded aggregates of the type used for road construction.

- Understanding the extent of the zone of influence that a geogrid has when installed in a particular situation. This was highlighted by the railway ballast research. The resistance offered to tensile strain by the geogrid, which is a maximum at the geogrid location, deteriorates with distance from that level. Careful experiments backed up by theoretical modelling are needed to tackle this issue.

- A design philosophy, which has been explored in a preliminary way, is that of regarding a reinforced pavement layer as a composite material with its properties modified to reflect the action of the geogrid it contains. This could be a helpful aid to design but fundamental research is needed to establish how the properties of the composite are determined. The extension of theoretical modelling using the Discrete Element Method can be helpful in exploring with the computer a series of "what if" scenarios once the basic models have been shown to provide reliable predictions. This was demonstrated in a limited way in the optimisation of aperture to particle size for railway ballast.

- Field installation techniques need to be improved and the important issue of recycling needs further research. There is little point in improved design methods unless they can be realised on site in the context of a modern approach to construction. Related to this is the matter of interface shear characteristics when a geogrid is present.

- Current work being carried out by the Author and his colleagues involves a new geogrid product which has triangular rather than square apertures. This is considered to be more appropriate for reinforcement of pavements where the loading beneath a wheel is essentially axisymmetric. Further work on this will be required.

- In the future, other novel products may appear either from manufacturers or they could emerge from research studies. In all cases, the need for a sound understanding of the basic mechanics of reinforcement will be needed if reliable design methods are to be developed.

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