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Geogrid for unsealed forest roads: installation considerations and bearing capacity testing in New Zealand

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ABSTRACT

This study established 10 field trials on corporate forest roads in New Zealand to demonstrate geogrid installation procedures and test for differences in bearing capacity, hereafter referred to as road strength, for road segments with and without geogrid reinforcement. The primary objective of this research was to determine if thinner aggregate surface layers could be used in conjunction with geogrid reinforcement without significant reductions in road strength. Each trial consisted of three 25-m long road segments randomly configured with the following pavement designs: (1) Control section that consisted of a single aggregate layer overlying a compacted subgrade soil; (2) Geogrid reinforcement that used the same aggregate thickness as the Control; and (3) Geogrid + Reduced Aggregate treatment that used a thinner aggregate layer. Road strength was measured with a Clegg Hammer for the prepared subgrade, finished road surface (i.e. before traffic), and after one winter of log truck traffic. Overall, there were no clear differences in road strength among treatments before or after trafficking. Several factors related to studying operational forest roads are thought to have contributed to this finding, including relatively low traffic volumes (285–1220 loaded trucks) and variability in aggregate thickness within and among sites. Geogrid-reinforced roads may perform better over time and with more traffic. In terms of cost, this finding supports the common practice of simply using thicker aggregate layers to achieve a desired strength as long as aggregate is cheap, local, and readily available.

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Forestry; unpaved road design; geosynthetics; road-bearing capacity; cost-benefit analysis

Introduction

Forest roads in New Zealand, as in many parts of the world, are privately built by forestry companies that are focused on providing fit-for-purpose roads of lowest possible cost (Sessions 2007; Fairbrother et al. 2009). Unsealed forest road construction standards typically deviate considerably from published design standards such as Austroads (1992), AASHTO (1993), or APRG (1997). With aggregate costs ranging from 40 to 80% of total road construction costs, savings are often achieved by using thinner aggregate layers comprised of lower quality, locally sourced materials (Kestler 2009). Depending on local geology, access to sufficient quantities of good quality granular material is a common challenge for many forestry companies. There is a need to find ways to reduce aggregate thickness while increasing road strength. Further issues can include inadequate preparation of the subgrade through compaction or soil property modification (Boston et al. 2008), or poor understanding of the physical and mechanical characteristics of the locally sourced aggregates (Fairbrother 2011a).

Forestry roads are also often constructed with very short lead times, being in use within weeks of construction. Other characteristics that differentiate forest roads from public roads include a relatively short duration of intensive use by heavy vehicles to accommodate timber harvesting. They may also be built with steep grades to minimize road length. Localized road failure, such as rutting on short sections of road post-construction, is also considered acceptable and in most cases readily fixed by simply adding an additional layer of aggregate or reshaping using a grader. While forestry companies would prefer a design procedure that guarantees success, most accept that at least some road failures provide them with confidence that they are not over-designing their roads.

Reinforcement geosynthetics have been used to improve the construction of unpaved roads since the 1970s (Giroud & Han 2004). Geosynthetics can be differentiated into three main categories: geotextiles, geocells, and geogrids. Geosynthetics, such as geotextiles, geogrids, and geocells, are proven technologies that enhance the structural performance of resource roads. Geosynthetics may also be used to mitigate any impacts that forest roads have on wetland hydrology. There are five primary functions of geosynthetics: separation, reinforcement, filtration, drainage, and confinement. Perforated geocells (also called cellular confinement) are manufactured to form honeycomb-shaped structures. The geocells confine the infill material, which increases the material's resistance to deformation from loading, allowing the geocell and the infill material to act as a platform that distributes loads over the subgrade area. Fine-grained material,

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such as sand, can be used with a geocell, and the perforations in the cell walls provide for lateral drainage.

Geotextiles typically provide a long-term separation to avoid contamination of the aggregate layer (i.e. mixing of excess silt and clay-sized particles with the aggregate surface layer), thereby keeping its strength (Giroud & Noiray 1981). Reinforcement geotextiles can also provide subgrade stabilization when they are placed between the base course and subgrade. Geogrids are geosynthetics formed by a regular network of integrally connected elements to facilitate interlocking of aggregate materials and reinforcement of pavement layers (GeoCHEM, Inc 2015). Geogrids are inert to biological degradation and are resistant to naturally encountered chemicals, alkalis, and acids. Geogrids are commonly used for retaining walls, stabilizing steepened slopes, embankments over soft soils, but also pavement reinforcing. The concept is to create a composite soil mass of increased strength (Figure 1). Geogrid will perform best on soils with a relatively low CBR rating where the subgrade will deform and allow the geogrid to develop lateral and longitudinal strength (Giroud et al. 1985).

Reinforcement of unsealed roads with geogrid can potentially reduce the required amount of aggregate needed when compared to an un-reinforced road (Haas et al. 1988; Giroud & Han 2004; Hufenus et al. 2006; Kestler 2009). Giroud and Han (2004) developed a theoretical design equation for aggregate depth as a function of traffic, geogrid strength, and soil subgrade strength. Archer (2008) incorporated the equation developed by Giroud and Han (2004) into a review on the use of geogrid to improve subgrade strength, demonstrating that for a range of subgrade strengths, geogrid required thinner overlying aggregate layers (Figure 2). Other studies found that 30% less aggregate was required for geogrid-reinforced roads in comparison to roads without geogrid reinforcement (Haas et al. 1988; Hufenus et al. 2006). Sigurdsson (1991) also showed strength improvement using geogrid, but noted that similar results were achieved using thicker aggregate layers. Vischer (2003) reported success when rebuilding failed roads with geogrid on a forest campground. Légère and Blond (2002) noted that using geogrid over a bog area in Canada resulted in no significant settlement of the road over a 1-year period. They also compared it with corduroy, a common forest road construction practice where lower value logs are placed sideways across the road and aggregate placed over the top. They found that geogrid was an economical option when the net value of corduroy logs is greater than about \$3/m^3 (Canadian dollars) or for short road segments (i.e. < 50 m). Furthermore, the use of geogrid does not tie up logging equipment necessary for felling, extracting, processing, and placing the corduroy logs. Manufacturers typically also promote their product using demonstration type case studies (e.g. Maccaferri 2011).

Figure 1. TriAx™ TX160 geogrid being laid down on a compacted forest road subgrade and covered with a well-graded aggregate.

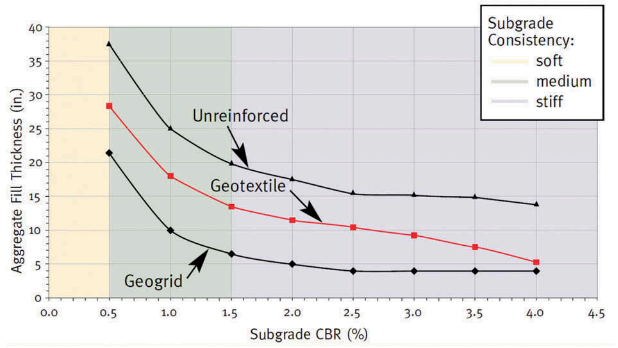

Figure 2. Required aggregate thickness (inches) as a function of subgrade strength (California Bearing Ratio (CBR in percent)) for roads without reinforcement and roads with geotextile or geogrid reinforcement (see Archer 2008).

New Zealand forestry companies have used geogrid on an infrequent basis. Most have used it as a product of last resort, often in areas that are very wet and/or have very weak soils where simply adding aggregate has not solved the problem. A number of such geogrid applications have not resulted in positive outcomes, but clearly the product has been used outside any reasonable extrapolation of its design limits. A research gap exists regarding the application and performance of geogrid in forest road construction. The potential for geogrid to reduce forest road construction costs (i.e. through a reduction in the required depth of aggregate surface layers) and provide fit-for-purpose road strength has not been clearly demonstrated in the field.

A series of trial sections were installed on corporate forest roads to demonstrate geogrid installation procedures and design considerations, as well as to ascertain performance and changes in road strength. The primary objective of this research was to determine if thinner aggregate surface layers could be used in conjunction with geogrid reinforcement without significant reductions in road strength. A secondary objective was to identify the conditions (i.e. delivered cost and required depth of aggregate) under which geogrid becomes a cost-effective solution for forest road construction. We hypothesized that the Geogrid treatment should have similar or greater strength than the Control.

While geogrid is known to perform well when installed according to design specifications, this study applied the geogrid to existing forest road construction practices in New Zealand. Low-volume forest roads typically use a single aggregate layer overlying a subgrade soil (Sessions 2007). Aggregate layer thickness depends on factors such as subgrade strength, design traffic, and aggregate physical properties (i.e. maximum particle diameter), but is commonly 150–200 mm before consolidation (Sessions 2007). In New Zealand, this aggregate surface layer is usually composed of lower quality and oversized aggregates (Fairbrother 2011b). If thicker layers of well-graded, high-strength aggregate were used as recommended by geogrid manufacturers, then the cost would be prohibitive and it would be challenging to improve our understanding about geogrid's potential benefits for existing forest road construction practices.

Methods

Test sites

Ten trial sites were selected on newly-constructed haul roads at five operational forests located in Napier, Rangiora, Oamaru, Dunedin, and Invercargill (Table 1). Site selection criteria included planned traffic during the winter period (April–August 2011), a relatively straight road section and continuous gradient for 75 m, and a consistent soil type and aspect. Representative soil samples (20 kilograms) were collected for each 75-m trial length and classified in the laboratory using the Unified Soil Classification System (ASTM D2487-11).

Each trial segment consisted of three 25-m treatment sections that were randomly configured within each trial. The Control section was representative of existing company standards for pavement design, which consisted of a base course aggregate layer (ranging in thickness from 200 to 350 mm) above a compacted subgrade soil (Table 1). The Geogrid and Geogrid Reduced (GeoRed) sections used TriAx^{TM} TX160, a geogrid developed by Tensar International. The geogrid was placed at the interface between the subgrade and the aggregate layer. This product has high radial stiffness developed from the polypropylene sheet forming triangular apertures. For a given trial location, the Geogrid section used the same depth as the Control section, whereas the GeoRed section used a thinner aggregate layer. The target thickness for the GeoRed section was 50–100 mm less than that of the Control section. If company construction standards used a running (top) course, then the pavement was finished with this top layer.

Aggregate layer thickness was also dependent upon the maximum rock diameter of locally available aggregates. Trials 3 through 6 used aggregate sourced locally from borrow pits (i.e. small in-forest quarries). This material, called pit-run, was uncrushed and unscreened (Table 1). Trials 1 and 2 used uncrushed river rock aggregate and Trials 7 through 10 used quarry aggregate that was crushed and screened to a maximum particle size of 65 mm (All Passing or AP65). Thus, the use of locally-available aggregates (to reduce construction costs) meant that they were generally oversized compared to the preferred fill gradation for roadway applications as outlined in the TriAx geogrid installation guide, which recommends a well-graded crushed aggregate fill with a maximum particle size of 38 mm and less than 10% fines (Tensar International, Atlanta, Georgia, USA).

As this was an operational study, traffic intensity was not controlled, but instead dependent on the number of logging crews working in the area and the timing of post-traffic tests. Therefore, each test location (i.e. Napier, Rangiora, Oamaru, Dunedin, and Invercargill) had a different cumulative traffic volume representative of one winter logging period (Table 1). The traffic load for each trial was provided by the forest management company in terms of total volume extracted across that segment of road between April and August 2011. Off-highway 5-axle truck and pole-trailer units, with a gross weight of approximately 60 tonnes carrying stems from the harvest area to a processing yard, were most commonly used at the Conway site (Trials 3 and 4). At all other sites, on-highway 7-axle truck and trailer units were most common and have a gross weight of 42–44 tonnes, of which 27 tonnes is payload (Figure 3).

Road strength measurements

A 4.5 kg Clegg Hammer was used to measure road strength for three different testing periods representing increasing levels of compaction. The first measurement period occurred after preparation and compaction of the road subgrade ("Subgrade"). These measurements provided a baseline for road strength. For the subgrade, most of the trial road segments were cut to a "hard and final grade,"

Table 1. Site description of subgrade soil type, aggregate layer characteristics (i.e. depth, aggregate source, and design specification for maximum particle diameter), and log truck traffic (i.e. total number of loaded trucks and cumulative payload) passing over each site during the winter period of April–August 2011. Soil type was classified with the Unified Soil Classification System (USCS) (ASTM D2487-11).

Trial	Location	Subgrade soil type	Aggregate depth on Control & Geogrid, and aggregate type	Reduced aggregate depth	Tonnes of payload *(# loaded trucks)*
1	Maungataniwha, Napier	Silty sand	200 mm river run-uncrushed	No section	11800 *(440)*
2	Maungataniwha, Napier	Silty sand	200 mm river run-uncrushed	150	11800 *(440)*
3	Conway, Rangiora	Clayey sand with gravel	350 mm pit run-uncrushed + 75 mm of AP42[a]	250	30000 *(670)*
4	Conway, Rangiora	Clayey sand with gravel	350 mm pit run-uncrushed + 75 mm of AP42	250	30000 *(670)*
5	Ruru, Oamaru	Lean clay	200 mm pit run-uncrushed + 50 mm of AP40	100	25000 *(930)*
6	Ruru, Oamaru	Lean clay	200 mm pit run-uncrushed + 50 mm of AP40	100	25000 *(930)*
7	Dunedin River, Dunedin	Silty Sand	200 mm quarry run AP65	150	7700 *(285)*
8	Dunedin River, Dunedin	Poorly graded sand with gravel	200 mm quarry run AP65	150	7700 *(285)*
9	Donaldson, Invercargill	Lean clay	250 mm quarry run AP65	150	33900 *(1220)*
10	Donaldson, Invercargill	Lean clay	250 mm quarry run AP65	150	33900 *(1220)*

[a]"AP" means All Passing, or the maximum particle diameter in the aggregate.

Figure 3. A commonly configured on-highway 7-axle log truck being loaded at a landing.

but not compacted with a roller (Trials 3, 4, and 7 through 10). Trials 1 and 2 were track-rolled with a 12-tonne excavator. Trial 6 was a fill section that was track-rolled, graded, and shaped with a bulldozer. Thus, construction traffic was the predominant method of subgrade compaction. Strength measurements were repeated after completion of the road pavement, but prior to log truck traffic ("Before Traffic"). Again, construction traffic was the predominant method of compaction following aggregate placement. Trials 1 and 2 were track-rolled with a 12-tonne excavator, while Trials 3 and 4 were compacted with a roller. These different compaction practices help illustrate the variability of road construction standards between forestry companies in New Zealand. Finally, strength measurements were repeated in August 2011 following log truck traffic ("After Traffic") with the log truck traffic providing additional compaction.

The Clegg Hammer uses a compaction hammer guided by a vertical tube. The hammer is lifted by the operator to a known height and dropped, which strikes the surface being tested. An accelerometer measures the peak deceleration in units of Clegg Impact Value (CIV). The use of the Clegg Hammer for this study followed the test procedure outlined in the CIST/883 Clegg impact soil tester operator's manual Ver. 1.14b4b-AU. Higher CIVs are indicative of greater road strength and are correlated with California Bearing Ratio (Clegg 1986; Mathur & Coghlans 1987; Al-Amoudi et al. 2002; Pattison et al. 2010). While it is recognized that there will be variability with soil type, Clegg (1986) provides the following approximate relationship (http://www.clegg.com.au/information_list12.asp): $CBR = (0.24\ (CIV) + 1)^2$

Road strength measurements occurred at 15 points within each treatment. Measurement points were located along transects established at distances of 7.5, 12.5, and 17.5 m from the beginning of each treatment section (Figure 4). Five road strength measurements were made along each transect. One measurement point was located in the center of the road and two measurement points were located 800 mm and 1200 mm to the left and right of the road center to capture the most likely path of the dual tires of log trucks. Strength measurements were made in the same positions for each testing period and this facilitated a direct comparison of treatments to establish any differences after traffic.

Statistical analysis

Within-site variability in road strength among treatments

Analysis of variance (ANOVA) in R was used to test for differences in mean road strength by treatment (Control, Geogrid, and GeoRed) at each of the 10 road test sites during the Subgrade, Before Traffic, and After Traffic testing periods (alpha = 0.05). Tukey's honest significant difference (HSD) test was used to determine post-hoc differences among treatments with a 95% family-wise confidence level. The Subgrade testing period was representative of baseline road strength at the time the subgrade was prepared, whereas the After Traffic testing period was representative of road strength following one winter of log truck traffic. Changes in mean road strength, calculated as the difference between the Subgrade and After Traffic testing periods were also assessed with the aforementioned methods.

Overall variability in road strength among treatments

For each testing period (Subgrade, Before Traffic, and After Traffic) linear regression analysis was used to test for significant differences in road strength (i.e. across all sites) as a function of Treatment (Control, Geogrid, and GeoRed), Position (Left tire track, Right tire track, and Road Center), soil type, and their interactions. Akaike Information Criterion (AIC) was used to compare linear regression models and select the one with the lowest AIC value, which represents the best case compromise between variance explained and model complexity (Burnham & Anderson 1998). Model fit was evaluated by analyzing standardized residuals for heteroscedasticity.

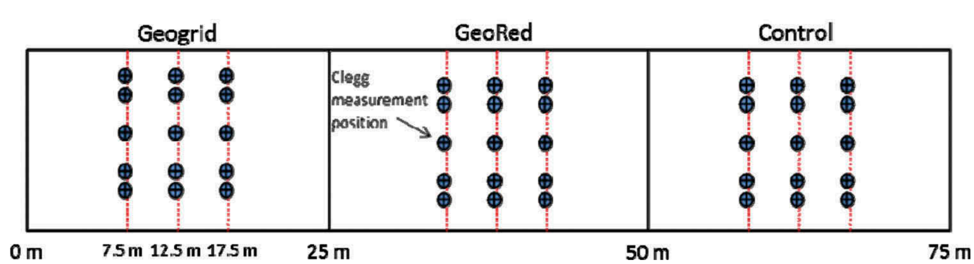

Figure 4. Plan view of a 75-m long trial road segment comprised of three 25-m long road segments. The treatments were randomly configured within each trial. The transects perpendicular to the road show the locations where the Clegg Hammer was used to measure road strength during the Subgrade, Before Traffic, and After Traffic testing periods.

Installation

The TriAx product used in this study comes standard as 75-meter rolls that are 3.8 meters wide (Figure 5). The rolls weigh about 75 kilograms and are easily man-handled by two people. For straight sections of road they are simply rolled out along the subgrade. Some advantage is gained by tensioning the geogrid so that it will develop strength faster when loaded, and this can be achieved by using pegs to hold the edges in place. A smooth prepared subgrade, devoid of rock material is best for rolling out geogrid. Any rocks jutting above the subgrade surface by more than about 5 cm can cause localized tension in the geogrid, which may be cut with the application of the overlying aggregate layer and under loading.

Geogrid lengths can be made to fit a curve by either folding a triangular segment into one side, or cutting approximately three-quarters of the way across and then overlapping to form a triangular section (Figure 6). Folding is awkward to achieve and caused problems when putting aggregate on top. Geogrid is very springy and has a tendency to pop up and stand proud of the surface. The manufacturer recommendation is a 1–2 meter overlap of product to ensure continuity of strength, but this can quickly add to cost.

While a 3.8-m width of geogrid readily accommodates the technical legal truck width in New Zealand of 2.4 meters, it does not cover the typical road design width of 5.5 meters. Once covered by aggregate, the exact placement of the geogrid is no longer visible and it is probable that trucks will drive over road sections without the benefit of geogrid. This problem is exacerbated on corners where off-tracking from trailers almost guarantees that the rear wheels of the trailer will not be on the geogrid. A logical solution is to simply increase the width of the geogrid using two sections side by side, but this doubles the cost per lineal meter.

Ideally, a calibrated dump truck will spread the aggregate with the truck only traveling over the road once the designed aggregate depth is achieved. This is an important consideration for sections of road with soft subgrades as dump trucks can push the geogrid into the soil and cause rutting. The Triax geogrid installation guide recommends a compacted aggregate depth on top of the geogrid of about 150 mm during dumping and spreading (Tensar International, Atlanta, Georgia, USA). The next best alternative is to use an excavator to spread the aggregate over the geogrid where the operator is in a good position to at least estimate aggregate depth (Figure 7). When using lower quality aggregates,

Figure 5. Placing a 25-m long section of geogrid into position.

Figure 6. Geogrid placement to fit a curve on a forest road.

Figure 7. Covering geogrid with aggregate can be achieved with a dump truck (left) or excavator (right). Note that the maximum rock size in this aggregate is too large and can easily cut the geogrid.

Figure 8. A grader being used to spread aggregate over geogrid. Note that it is very difficult to judge aggregate depth using this technique.

another benefit is that the excavator can push larger rock fragments to the side. However, excavators are rarely used to place aggregate and this represents an additional cost.

A final alternative is to use a grader to spread aggregate onto the geogrid (Figure 8). However, it is almost impossible for the operator to judge aggregate depth. At one location, a grader blade came in contact with the geogrid, ripped the product and pulled up a larger section. Also, once a geogrid-reinforced road segment is badly deformed, geogrid must be cut away or pulled out completely to allow for repairs to the subgrade.

Results and discussion

Subgrade strength

Subgrade strength measurements varied both laterally and longitudinally within the treatment plots, even if the soil condition appeared relatively uniform (Figure 9). Mean Clegg Impact Value (CIV) by trial was highly variable, ranging from 5.0 to 21.0, with an overall mean value of 11.4 (Table 2). Across all trials, mean CIV by treatment was 11.9, 11.7, and 10.7 for the Control, GeoRed, and Geogrid treatments, respectively (F = 1.325, p = 0.27). Thus, subgrade strength was statistically similar among treatments across all sites.

However, within the separate trials, mean CIV by treatment was statistically different at the alpha = 0.05 level for Trials 2, 3, 7, and 10 (Table 2). At Trial 2, the Control and GeoRed treatments were stronger than the Geogrid treatment. At Trials 3 and 7, the Control treatment was stronger than both the Geogrid and GeoRed treatments. However, at Trial 10, the Control treatment was weaker than both the Geogrid and GeoRed treatments.

Higher soil moisture content at the time of testing was associated with lower strength. For example, Lean Clay soils with gravimetric moisture content around 30% (Trials 9 and 10) had a mean CIV of 5.8, whereas Lean Clays with mean moisture content of 11% (Trials 5 and 6) had a mean CIV of 19.3. Similarly, Silty Sand soils with a mean moisture content of 34% (Trials 1 and 2) had a mean CIV of 6.6, whereas mean CIV was 12.6 when moisture content was 16% (Trial 7). Soils classified as "Clayey sand with gravel" that had a mean moisture content of 15% (Trials 3 and 4) had a mean CIV of 11.0. The highest mean CIV was 21.0, where the soil type was poorly-graded sand with gravel and the mean moisture content was 6.0% (Trial 8).

Road strength before traffic

Across all sites, mean CIV increased from 11.4 to 27.5 (i.e. by 141%) from the Subgrade to the Before Traffic testing

Figure 9. While the subgrade may look uniform, geotechnical testing, such as California Bearing Ratio tests or soil plasticity tests often indicate that forest road subgrades vary significantly over relatively short stretches, making exact design difficult.

Table 2. Mean Clegg Impact Value (CIV) by trial and treatment (Control, Geogrid, and GeoRed) for the Subgrade, Before Traffic, and After Traffic test periods. Different letters indicate statistical differences among treatments within each trial and test period. Changes in road strength, calculated as the difference in CIV from the Subgrade to the After Traffic test periods, were evaluated among treatments at each trial site.

Trial	Treatment	Subgrade	Before traffic	After traffic	Difference: after traffic-subgrade
1	Control	5.4^{a}	15.4^{a}	53.0^{a}	47.6^{a}
	Geogrid	6.6^{a}	14.5^{a}	45.4^{a}	38.8^{a}
2	Control	9.7^{a}	13.5^{a}	47.9^{a}	38.2^{ab}
	Geogrid	3.8^{b}	16.3^{a}	46.4^{ab}	42.6^{a}
	GeoRed	7.7^{a}	16.8^{a}	37.5^{b}	29.8^{b}
3	Control	12.1^{a}	30.3^{a}	30.3^{b}	18.3^{b}
	Geogrid	9.0^{b}	23.2^{b}	42.0^{a}	33.0^{a}
	GeoRed	9.6^{b}	17.6^{b}	31.9^{b}	22.3^{b}
4	Control	12.7^{a}	25.5^{a}	23.9^{ab}	11.2^{b}
	Geogrid	11.2^{a}	24.9^{a}	31.5^{a}	20.3^{a}
	GeoRed	11.6^{a}	20.3^{a}	21.8^{b}	10.2^{b}
5	Control	15.9^{a}	31.1^{ab}	51.0^{a}	31.1^{a}
	Geogrid	19.2^{a}	26.5^{b}	54.5^{a}	31.4^{a}
	GeoRed	19.8^{a}	35.9^{a}	51.3^{a}	27.4^{a}
6	Control	21.3^{a}	46.5^{a}	72.5^{a}	46.9^{a}
	Geogrid	18.2^{a}	45.9^{a}	63.5^{a}	41.8^{a}
	GeoRed	21.1^{a}	33.9^{b}	64.0^{a}	36.6^{a}
7	Control	14.3^{a}	28.7^{a}	47.1^{a}	32.8^{a}
	Geogrid	11.9^{b}	23.3^{a}	42.1^{a}	30.2^{a}
	GeoRed	11.5^{b}	23.7^{a}	37.3^{a}	25.9^{a}
8	Control	22.9^{a}	38.9^{a}	40.8^{a}	17.9^{a}
	Geogrid	21.1^{a}	32.0^{a}	40.6^{a}	19.5^{a}
	GeoRed	18.8^{a}	23.3^{b}	25.5^{b}	6.7^{a}
9	Control	4.7^{a}	36.2^{a}	43.1^{a}	38.5^{a}
	Geogrid	4.9^{a}	34.5^{a}	42.5^{a}	37.5^{a}
	GeoRed	5.3^{a}	31.1^{a}	45.0^{a}	39.7^{a}
10	Control	5.5^{b}	31.0^{a}	39.4^{a}	33.9^{a}
	Geogrid	7.2^{a}	27.8^{a}	38.4^{a}	31.2^{a}
	GeoRed	7.2^{a}	29.7^{a}	41.8^{a}	34.6^{a}

periods. In other words, road strength increased when aggregate was placed and compacted on top of the subgrade soil. Mean CIV by trial site ranged from 15.0 to 42.1 (Table 2). Mean CIV by treatment was 29.7, 26.9, and 25.8 for the Control, Geogrid, and GeoRed treatments, respectively. Linear regression analysis of mean CIV by Treatment, Position, the interaction of Treatment and Position (Treatment*Position), and Soil Type showed no significant differences among treatments. Therefore, prior to trafficking, geogrid reinforced road segments had statistically similar strength compared to Control road segments. Mean CIV in the road center (15.2) was significantly lower than those of the left and right tire track (30.6). This can be explained by the construction process of track rolling and the construction traffic from passing metal trucks.

Within each trial, mean CIV by treatment was statistically different at the alpha = 0.05 level for Trials 3, 5, 6, and 8 (Table 2). At Trial 3, the Control had greater strength than the Geogrid and GeoRed treatments. At Trial 5, GeoRed had greater strength than Geogrid. At Trials 6 and 8, the Control and Geogrid treatment had greater strength than the GeoRed treatment.

Road strength after traffic

After trafficking, mean CIV across all sites increased from 27.5 to 43.2 (i.e. by 57%). Mean CIV by trial site ranged from 25.7 to 66.7 (Table 2). Mean CIV by treatment was 44.9, 44.7, and 39.7 for the Control, Geogrid, and GeoRed treatments, respectively. Linear regression analysis of mean CIV by Treatment, Position, Treatment*Position, and Soil Type showed no significant differences among treatments. Therefore, after trafficking, geogrid reinforced road segments had statistically similar strength compared to Control road segments. Mean CIV in the road center (25.4) was again significantly lower than those of the left and right tire track (47.7).

Within each trial, mean CIV by treatment was statistically different at the alpha = 0.05 level for Trials 2, 3, 4, and 8 (Table 2). At Trial 2, the Control had greater strength than the GeoRed treatment. At Trial 3, Geogrid had greater strength than the Control and GeoRed treatment. At Trial 4, Geogrid had greater strength than the GeoRed treatment. At Trial 8, the Control and Geogrid treatments were similar, but had greater strength than the GeoRed treatment.

In terms of overall strength increases after trafficking (i.e. the difference in strength from the Before Traffic to After Traffic test periods), the Geogrid treatment increased the most (by 66%), followed by the GeoRed treatment (54% increase), and the Control (51% increase). Therefore, after winter trafficking from April to August 2011, Geogrid may be on a better trajectory for road strength in the long term as cumulative log truck traffic increases.

For seven of the 10 trial sites, there were no differences among treatments in terms of strength gained from the Subgrade to the After Traffic testing period (Table 2). At Trial 2, Geogrid gained more strength than the GeoRed treatment, but was statistically similar to the Control. At Trials 3 and 4, Geogrid gained more strength than both the Control and GeoRed treatment. These findings reinforce the point that overall, there were no clear differences in strength among the Control, Geogrid, and GeoRed treatments.

Several factors related to studying operational forest roads are thought to have contributed to a lack of clear differences among treatments. They include a relatively low traffic volume passing over the sites, as well as variability in aggregate thickness and quality within and among sites. The number of truckloads per site over one winter season (April–August 2011) ranged from 285 to 1220, but this level of traffic may have been insufficient to show longer-term trends in road strength among treatments. Previous research has established that many of the aggregates sourced from in-forest quarries in New Zealand are poorly graded. Aggregates tested by Fairbrother (2011b) were described as lacking in fine-grained material (i.e. particle sizes < 0.074 mm), while being excessively coarse. Fairbrother (2011b) found that aggregates contained between 1 and 16% fines. In this study, it is thought that these "bony" aggregates were able to gain strength in the Control segments (i.e. without geogrid reinforcement) by mixing with the finer subgrade material. With continued traffic loads, aggregate contamination with excess fines could result in a loss of strength. Conversely, aggregate contamination is hypothesized to be less for the geogrid-reinforced roads, because the geogrid keeps the aggregate from getting pushed down into the subgrade (Palmeira & Antunes 2010). This may help to maintain their strength in the long-term.

Furthermore, while every effort was made to install the treatments according to design, changing the depth of aggregate between the 25-m treatment segments was problematic for contractors constructing the trial sections. In addition, companies had different pavement design standards which resulted in variable aggregate depths across all sites (Table 1). Finally, the aggregates used were often sourced locally (i.e. from in-forest "borrow pits" or nearby quarries) to minimize transportation costs. While the quality of aggregate differed across sites, all were oversized compared to the preferred fill gradation for roadway applications, as outlined in the TriAx installation guide, which recommends a well-graded crushed aggregate fill with a maximum particle size of 38 mm and less than 10% fines (Tensar International, Atlanta, Georgia, USA) (Table 1).

To account for this variability, strength differences were tested among treatments within each trial, as well as across all 10 trials. Ultimately, these operational road segments had similar strength among the various treatments used in this study. The Geogrid treatment was not stronger than the Control (despite having similar aggregate depth) under trafficking conditions representative of short-term use. This finding supports the common practice of simply adding more aggregate to achieve a desired road surface strength, as long as aggregate is cheap and readily available. Conversely, the GeoRed treatment was similar in strength to the Control, demonstrating that it is possible to reduce aggregate depth with Geogrid without significant losses in road surface strength. Therefore geogrid could be a viable option when aggregate costs are high or for short road segments with very wet or weak soils (i.e. trouble spots).

Cost-benefit analysis

TriAx geogrid currently costs about NZ$15 ($10.5 USD) per lineal meter (3.8 meter width), with geogrid products approximately twice the price of geotextiles used for separation. To make the use of geogrid positive in terms of cost-benefit, its application must be able to carry more traffic, increase the life span, reduce the depth of aggregate, or reduce the quality (and cost) of the subgrade preparation. New Zealand forest management companies pay NZ$10 to NZ$60 per cubic meter of aggregate delivered to the construction site (i.e. NZ$10/$m^3$ for locally available pit run and NZ$60/$m^3$ for a higher quality aggregate from a commercial quarry). Furthermore, the depth of aggregate used on forest roads in New Zealand can range from 100 to 600 mm, depending on factors such as road standards (i.e. design life), subgrade strength, and the delivered cost of aggregate. It is possible to carry out a break-even analysis for a range of aggregate costs and various aggregate thicknesses to identify the point at which using geogrid becomes the more economical option.

Studies by Haas et al. (1988) and Hufenus et al. (2006) found a reduction in aggregate depth of approximately 30% could be achieved with geogrid reinforcement. Haas et al. (1988) completed their study in a laboratory using asphalt as the top pavement layer. Hufenus et al. (2006) found the same result, but their study was completed using an operational unsealed road, which is more comparable to this study. The underlying assumptions of the break-even analysis used here include a 30% savings in aggregate when geogrid is used, a road width of 5.5 m, a geogrid cost delivered to the site of NZ$15 per lineal meter, and an additional laying and spreading cost of $4 per lineal meter (assuming an 8–10 tonne excavator is used). The cost comparison is based solely on the pavement structure. Therefore, it is representative of initial road construction costs. Under these assumptions, and using a NZ$30/$m^3$ cost of delivered aggregate, the break-even depth of aggregate is about 300 mm (Figure 10).

The underlying trend is that with increasing aggregate cost and aggregate layer thickness, geogrid becomes more economical to incorporate into a forest road. Companies purchasing aggregate for NZ$10/$m^3$ will observe an increased cost of reinforcing their roads with geogrid because cheap aggregate can be spread liberally to achieve a desired pavement strength. Conversely, at NZ$60/$m^3$ delivered, geogrid is more economical as there is a clear benefit of reducing the required depth of aggregate. It is important to note that this cost-benefit analysis relates to the initial cost of pavement construction. For forest roads with longer design lives (i.e. arterial and secondary roads), a cost-benefit analysis would

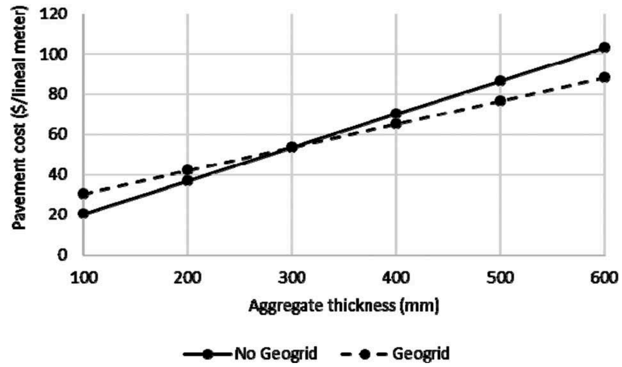

Figure 10. Break-even analysis to identify the required aggregate depth at which using geogrid becomes more economical than simply adding more aggregate. The underlying assumptions of this analysis include: 5.5 m road width, $4/lineal meter to lay and spread aggregate, $30/m^3 delivered cost of aggregate, 30% savings in aggregate when geogrid is used, and $15/lineal meter delivered cost of geogrid.

need to include the life cycle costs, including road maintenance, for roads with and without geogrid reinforcement.

Conclusions

This study incorporated geogrid into the pavements of operational forest roads in New Zealand to demonstrate installation and design considerations, as well as to test for road surface strength differences among road segments with and without geogrid reinforcement. There were no clear differences in road strength with or without geogrid reinforcement following one winter of log truck traffic. However, an alternative viewpoint is that the treatment that used a thinner aggregate layer with geogrid (GeoRed) was not statistically weaker after trafficking than the Control, indicating that it is possible to reduce aggregate depth by using geogrid without significant losses in road strength. For forest managers, this study demonstrates that when aggregate is cheap and readily available, it makes sense to simply add more aggregate, as is often currently done to achieve the desired strength. Furthermore, logging roads that will only be used for the short term (i.e. lower-standard spur roads) are not ideal candidates for geogrid application because costs will likely be prohibitive. Break-even analysis from this study demonstrated that when aggregate costs are high or very thick layers of aggregate are required, geogrid installation in forest road pavements can become a viable option.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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