2024

FOREST ENGINEERING HONOURS PROJECT

EVALUATION OF SUBGRADE STABILISATION METHODS FOR UPGRADING HISTORIC FOREST ROADS

FINAL REPORT

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Abstract

Forest roads are an important piece of infrastructure to link resource and market. In New Zealand these roads are experiencing increasing stress compared to previous rotations with increased log truck masses leading to a 60% increase in pavement damage. Due to this, many forestry companies are upgrading historic roads in the face of issues when attempting to utilise these in current harvesting operations. Currently Port Blakely is undercutting and backfilling historic roads, but high costs and environmental impacts have prompted further research.

Various soil stabilisation methods exist to improve subgrade strength, the majority of which have been tested extensively in new road construction but have limited research in road reconstruction. Three common subgrade stabilisation methods are undercutting, geogrid reinforcement, and lime stabilisation. These use either mechanical or chemical means to increase strength.

Trials were constructed on Bridgeman Road, Geraldine Forest, and Diamond Hill Road, Herbert Forest to test the effectiveness of these stabilisation techniques at upgrading historic forest roads. Strength testing was undertaken at selected locations along these sections prior to construction and one, two, three, and four months post construction. Additionally, soil moisture content in these forests was monitored and cost information for each section's construction was collected.

In both locations undercut exhibited the highest strength with wet CBRs of 39.47% and 28.04% for the Diamond Hill and Bridgeman Road trials respectively. Lime stabilisation was only minorly weaker than undercut, however the geogrid section was notably weaker. There were relative strength benefits in the wheel paths on Bridgeman Road, potentially from traffic movements, that show the inadequacy of the trial at enabling geogrid to enable its full strength through particle interlock.

Lime stabilisation was the most expensive method, followed by undercut then geogrid. Using cost information from Diamond Hill Road, undercut becomes more expensive than lime at an aggregate price of $90.78/m^3 undelivered, or $109.56/m^3 delivered, showing the financial viability of different methods based on aggregate price. Geogrid is the cheapest method at all realistic aggregate prices, and requires less than half the earthworks of the other methods. Therefore, although undercut performed the best during the trial from a strength and cost perspective, however the relatively low cost of geogrid and its potentially impaired performance during the trial warrants further testing for Port Blakely once the roads begin to serve regular traffic.

Soil stabilisation methods such as those used in this study can be site specific, with lime in particular requiring certain soil types to be effective. The soil types in the trial areas are firm and orthic brown, suggesting the applicability of the study results to other areas with these soil types. Strength testing of the trial sections following loading will allow this study's findings that undercut is the most effective method of upgrading historic forest roads in these areas to be proven.

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Introduction

Roads are a critical component of forest infrastructure as they provide the link between resource and market. It is estimated that there are 25,000km of forest roads throughout New Zealand with 1,500km of construction per year (NZ Forest Owners Association, 2020). The dominant road surface is unbound granular pavements. These roads are unique in the respect that they sustain very high loadings for a short period of harvesting operations then may not be utilized again until next rotation, often a gap of almost thirty years.

In the thirty years since last rotation, log truck masses have increased by over 25%. This causes higher stresses to be imparted on forest roads and realizes the limitation identified by Kennedy (1985) that significant expenditure will be required to upgrade forest roads to sustain increased loads. As an increase in axle load results in greater stress increases at depths below the road surface, simply improving the surface layer strength is not always an appropriate solution (Zhou, et al., 2022).

Various methods exist to improve road subgrade strength. These range from mechanical to chemical stabilisation alternatives. Many of these methods have been researched in the context of improving subgrade strength for new road construction but have not been tested in upgrading existing roads.

This project aims to determine which of three common subgrade stabilisation methods provides the most fit for purpose solution for reconstructing previous rotation forest roads to enable them to withstand stresses imposed by current harvesting operations. In this instance, fit for purpose means that roads can meet strength and environmental requirements at a feasible cost.

This report will begin with a literature review regarding log trucks and their required roading standards, as well as road construction practices and potential failure mechanisms of forest roads. Methods of measuring subgrade strength and other relevant parameters will be reviewed before the literature review concludes with an analysis of soil stabilisation methods. The objectives of the study will be stated and the methodology to achieve these outlined. To achieve this, information on the trial locations, pre-trial preparation, trial construction, post-trial data collection, and data analysis will be provided. The results of the trial will be discussed and used to make recommendations regarding the ideal method to upgrade previous rotation forest roads and the factors that may influence this.

Research Motivation

This project came about due to the issues a New Zealand forestry company is currently experiencing with utilizing previous rotation roads in current operations. These roads are not providing an acceptable level of service and are failing in the forms of rutting or pumping. To mitigate this issue, previous rotation roads are being upgraded before use in operations.

The current method being used to upgrade these roads by the company and other companies contacted is undercutting. This method creates fit for purpose roads but is expensive and generates large earthwork requirements. Therefore, this study was initiated to determine if undercutting is the most appropriate method with respect to producing roads of the required strength at the minimum cost.

Literature Review

Log Trucks

Log trucks and their allowable on-highway loadings have increased significantly in the past thirty years. In the 1990s log trucks had a maximum allowable Gross Vehicle Mass (GVM) of 44 tonnes whilst today it is common to run 50MAX trucks with GVMs of 58 tonnes (figure 1) (Taylor, 1989; Lyons, et al., 2022; TERNZ Transport Research, 2016). The usage and development of trucks with higher GVM has been enabled through legislative changes because increasing GVM increases productivity, decreases fuel emissions, reduces heavy vehicles travelling on highway, and does not compromise safety (New Zealand Forest Owners Association, 2009).


Figure 1: Log trucks used in previous rotation harvesting operations in Herbert (Davies, Old Photo Album cont., 2012). *Current 50MAX log trucks used* (TERNZ Transport Research, 2016).

An update to log truck size restrictions in 1987 enabled a maximum truck length of up to 20m for A-trains and B-trains, 19m for truck and trailer combinations, and 17m for articulated vehicles (Edgar, 1987). This allowable length has also increased, with B-trains used today able to have a length of 23m. For comparison, on a corner with a 12.5m radius a 20m 4-axle truck and 4-axle trailer similar to that used in previous harvesting operations experiences 2.90m of off-tracking whilst a 23m HPMV 50MAX B-train experiences 4.07m of off-tracking (TERNZ Transport Research, 2013).

The most economic log truck axle configuration to run in the 1990s was a four-axle truck combined with a three or four axle trailer (figure 2) (Taylor, 1989). It is now still common to use four-axle trucks however trailers have increased to five axles (Lyons, et al., 2022).

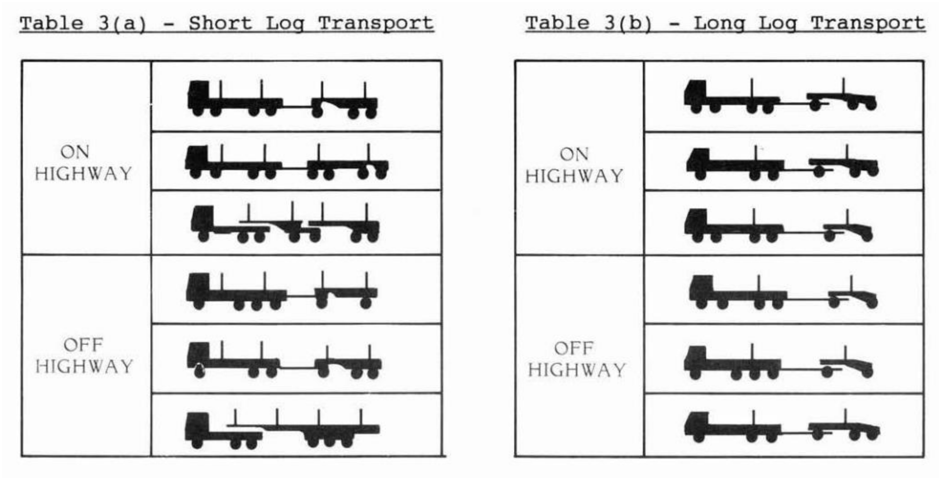

Figure 2: Most economical truck configurations in 1989 (Taylor, 1989).

The impact of these changes is that the traffic loading on forest roads has increased dramatically, with 54 tonne four-axle truck and five-axle trailer units estimated to impart 60% more pavement damage per pass than 44 tonne four-axle truck and four-axle trailer units (Harvey & Visser, 2024). This results in faster rutting and pavement distresses. In addition to the impacts of higher loadings travelling on forest roads, changes to log trucks pose other challenges for these roads. The impact of increased truck mass can be partially mitigated through the distribution of this over more axles, however there is likely to still be greater damage to roads (Varin & Saarenketo, 2014). Greater numbers of axles also mean higher numbers of successive loadings per truck pass. This provides insufficient time for the excess pore water pressures generated to dissipate, which decreases material stiffness and increases deformation. Overall, the changes in applied stresses resulting from the development of forestry machinery have created new serviceability requirements for forest roads (Madzhov, 2018).

Road Construction

The overarching design principle of previous rotation and current forest roads has remained unchanged – to construct roads that are "fit for purpose" (Lyons, et al., 2022). Roads meeting these criteria facilitate effective transport but are not over-engineered due to the unnecessary costs this would incur (Goldsack, 1988). Environmental factors have previously been considered to an extent but due to increased legislative requirements and scrutiny they are now key design considerations (Lyons, et al., 2022).

Previous Rotation Roads

Roads constructed by the New Zealand Forest Service (NZFS) prior to its disbandment in 1987 were designed by engineering officers or draughtsmen using a combination of aerial photographs, topographical maps, and manual surveying (Kennedy, 1986; M. Hetherington, personal communication, February 20, 2024). A typical road cross-section from this time is shown in figure 3.

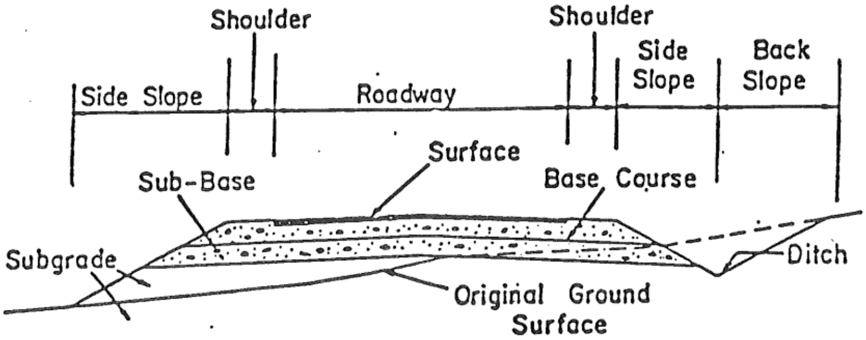

Figure 3: Typical road cross-section of previous rotation forest roads (Farley, 1985).

The roads were typically constructed by a bulldozer using sidecasting earthworks techniques. Because of the heavy reliance on bulldozers in road construction, the roads were often designed to sidle around contours for ease of construction (Kennedy, 1985). Following this water tables and culverts were installed then metal applied. The depth of aggregate used in construction was determined by the subgrade material type, subgrade strength, and number of heavy vehicle movements per day (figure 4) (Farley, 1985). When remediation was required to improve the subgrade strength in particularly wet areas it was common to excavate problem material and backfill with either a mixture of rock and clay or logging waste and clay (M. Hetherington, personal communication, February 20, 2024).

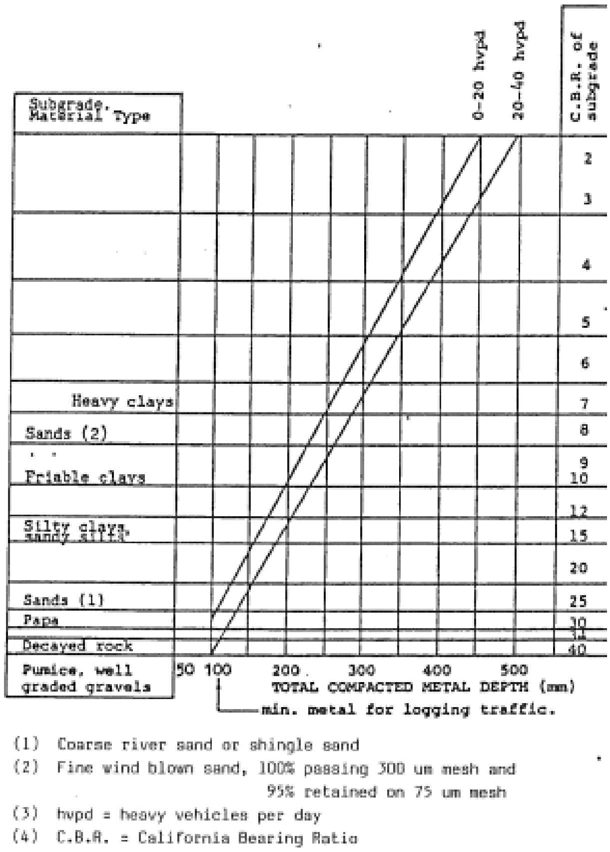

Figure 4: An example chart used to determine required aggregate thickness in previous rotation forest roads (Farley, 1985).

There was a lack of standard road classifications and specifications throughout New Zealand forests (Kennedy, 1985). Features pertaining to construction details such as pavement design, cross-sectional information, curve widening, and pavement testing procedures were not included in most roading standards and were instead determined by individual companies. This resulted in high variability in roading between different forests as well as between written standards and actual road construction.

New Road Construction

At the present time a combination of technical design and experience is utilised in forest road design and construction. A full geometric design is not always undertaken, instead being used only in particularly challenging or sensitive circumstances (NZFOA, 2011). The New Zealand Forest Road Engineering Manual (NZFREM) provides guidance on road design and construction in accordance with best practices. It outlines that in contrast to other roads, most New Zealand forest roads are constructed with a singular improved layer as opposed to a multi-layer pavement (figure 5) (NZFOA, 2020).

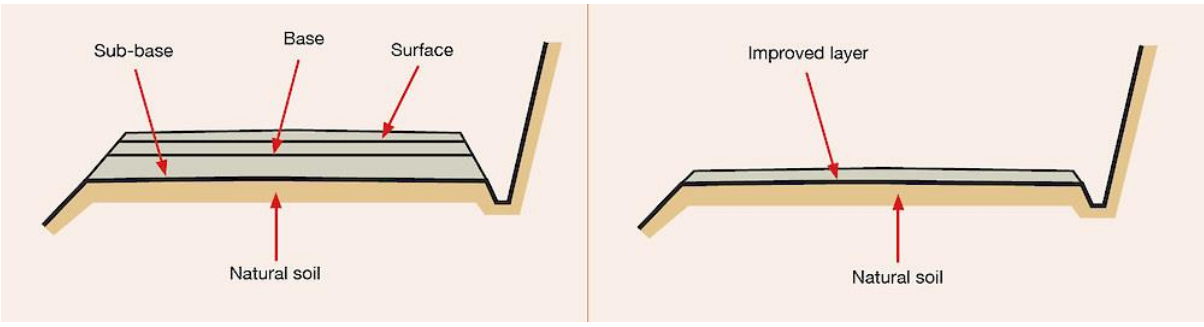

Figure 5: Typical pavement layer structures used in New Zealand Forestry (NZ Forest Owners Association, 2020).

Bulldozers and excavators are both now common in forestry earthworks which enables side casting, benching, or end haul earthworks (NZ Forest Owners Association, 2020). Figure 6 illustrates the recommended aggregate depth to overlay the subgrade from the NZFREM as a function of subgrade strength and the design equivalent standard axles (ESA), however in reality this depth is influenced heavily by the available aggregate particle size (Visser et al., 2017). Culverts and water tables are installed in accordance with guidelines given in the NZFREM. Subgrades with inadequate bearing capacity can be stabilized through means such as corduroy[1], geosynthetics, lime, and cement (NZ Forest Owners Association, 2020).

[1] Corduroy is where logs are laid underneath a road to improve the strength of a weak subgrade.

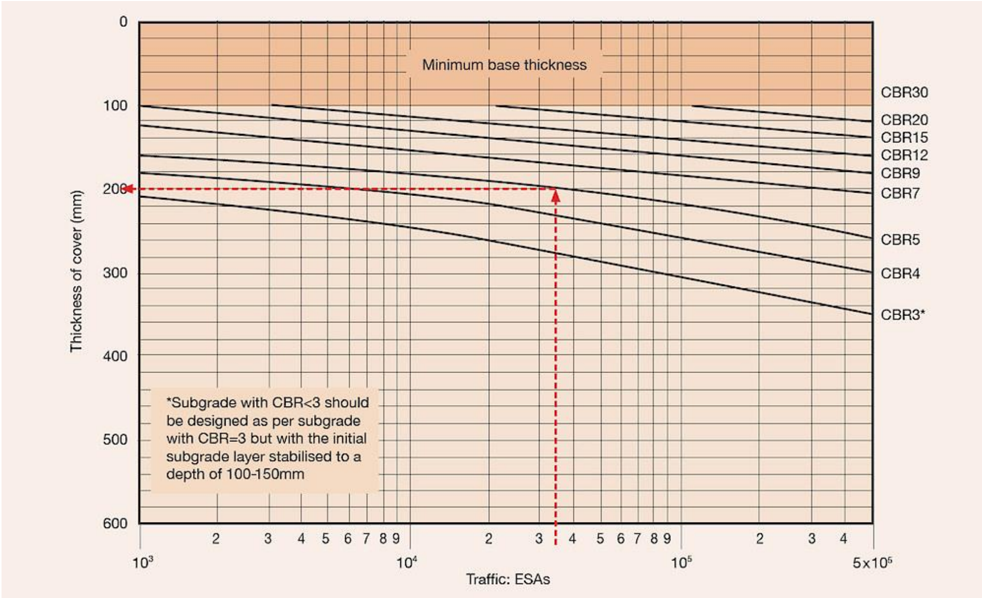

Figure 6: Chart for the determination of aggregate depth (NZ Forest Owners Association, 2020).

Road specifications vary significantly based on road class and terrain. On secondary roads in flat and rolling terrain a width of 7-8m is recommended whereas on spur roads in the same terrain this width reduces to 4.5m (NZ Forest Owners Association, 2020). A minimum corner radius of 18m is recommended with corner widening to account for trailer off-tracking (NZ Forest Owners Association, 2020). These specifications are designed to facilitate effective transportation on forest roads using 50MAX and HPMV trucks.

The additional requirements for forest roads to sustain log trucks used in present day harvesting operations compared to those used for last rotation are causing issues when attempting to utilise existing roads (NZ Forest Owners Association, 2020). Geometric properties such as corner radii are inappropriate and must be adjusted, and the load increase can cause road distresses and failures. Both surface and subgrade distresses can occur however since increases in axle load cause in greater stress increases further below the surface it is more often subgrade failures that are observed in these roads (Zhou, et al., 2022).

Road Failure

Subgrade failure often manifests in the form of rutting or soft areas in the road (NZ Forest Owners Association, 2020). It occurs in materials with insufficient bearing capacity to carry load without plastic deformation occurring, therefore is a function of material strength (Borden, et al., 2010). There are four different rutting mechanisms described by ROADEX Network (2024) which vary in which pavement layers are impacted but are all characterised by wheel path depressions. Solutions to rutting vary by mechanism but include ensuring adequate compaction, using higher quality aggregate, increasing the thickness of structural layers, and adding reinforcement (ROADEX Network, 2024).

Comparatively, pumping, another failure mechanism, is caused by inadequate material stiffness. It occurs due to shear and vertical stresses imposed by traffic causing "kneading" of the subgrade by the aggregate layer (ROADEX Network, 2024). The relative incompressibility of the subgrade means that excess pore pressures[2] generated must be dissipated through the subgrade or by penetrating through the aggregate layer to the road surface. For this reason, a low permeability subgrade such as low plasticity clay or silt increases the likelihood of this failure mode. The chance of pumping occurring can be decreased through subgrade reinforcement, geotextile separation of the subgrade and upper pavement layers, or using an open graded aggregate layer under the base course (ROADEX Network, 2024). Another option is to increase the time between loading cycles as this will give an opportunity for pore water pressures to dissipate (Varin & Saarenketo, 2014).

Rutting and pumping can occur together or individually and can cause damage such as that seen in figure 7.

Figure 7: Unbound low volume roads exhibiting rutting (left) and pumping (right) (ROADEX Network, 2024).

Subgrade Strength and Measurement

The failures mentioned above occur if the subgrade strength is inadequate to support the applied loads. The term "subgrade strength" refers to the bearing capacity of the natural soil upon which the pavement is constructed. It is a function of soil type, density, and moisture content (Al-Refeai & Al-Suhaibani, 2002). A weak subgrade necessitates either a thicker overlaying aggregate layer or stabilisation to meet strength requirements (NZFOA, 2011).

Subgrade strength is often quantified using the California Bearing Ratio (CBR). This measure compares the pressure required for a specified plunger to penetrate the material of interest to that required to penetrate California limestone aggregate (NZ Forest Owners Association, 2020). The New Zealand Forest Road Engineering Manual states that an 8% CBR is just adequate for construction, and below 4% CBR stabilisation will be needed. The majority of New Zealand forest road subgrades range between 3% and 15% CBR (NZ Forest Owners Association, 2020). A strong subgrade benefits road construction through reducing the required pavement depth as less strength compensation is required by the higher strength pavement layer.

[2] Soil pore pressure is the pressure of groundwater between soil particles.

Originally CBR was created to be determined through laboratory testing, however the impracticalities and cost of this has led to the development of various in-situ alternatives. The results of these tests can be empirically correlated with CBR values to calculate strength (NZ Forest Owners Association, 2020). Two commonly used in-situ CBR tests are the Dynamic Cone Penetrometer (DCP) and Impact Soil Tests. A number of procedures for to undertake these tests are given in the standards, some of which include moisture content and density measurement in conjunction with strength testing (ASTM International, 2002).

Dynamic Cone Penetrometer (DCP)

A DCP, or Scala penetrometer, consists of a 9kg hammer that is raised up a rod and dropped from a given height (Feleke & Araya, 2016). The number of hammer blows required to penetrate to a given depth can be correlated with CBR using various relationships including the chart shown in figure 8 that is recommended for use by the NZFREM (NZ Forest Owners Association, 2020).

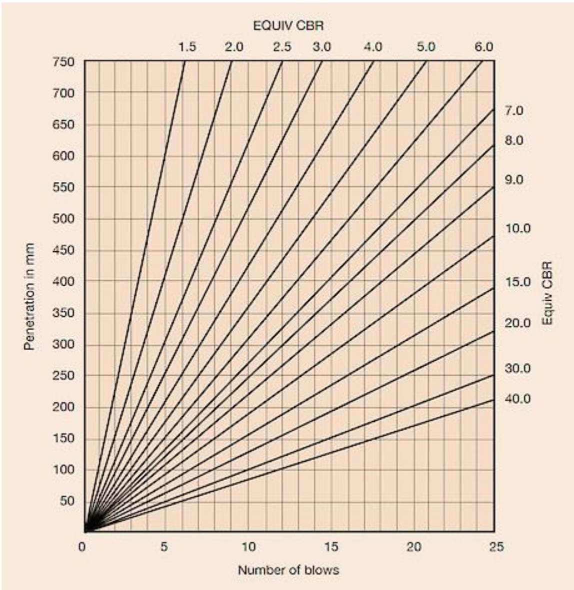

Figure 8: Chart to determine CBR from results of DCP test (NZ Forest Owners Association, 2020).

The key advantage of a DCP is that it provides a fast, non-destructive, simple, and cheap method of determining soil strength (Feleke & Araya, 2016). It can be used to calculate strength at different depths below the ground surface, making it useful for soil layer characterization. The test is limited by its ability to provide accurate results in sandy and gravelly soils or those with a CBR of less than 3% (NZ Forest Owners Association, 2020). Therefore, it is recommended that testing methods other than DCP are undertaken on these soil types.

Clegg Hammer

A Clegg Hammer is an impact soil testing device comprising a 4.5kg hammer inside a guide tube (figure 9) (Clegg Hammer, 2022). The hammer is manually raised to a standard height and dropped whilst an accelerometer measures the peak deceleration when the hammer impacts the ground surface (Shoop et al., 2012). The measured strength index, known as the Clegg Impact Value (CIV), can be correlated with CBR using correlations developed since the Clegg Hammer's development in the 1970s. Clegg Hammer measurements capture the strength of the material to a depth of at least twelve inches below the ground surface (Mathur & Coghlan, 1987-88).

Figure 9: Clegg Hammer testing apparatus (Clegg Hammer, 2022).

Similarly to a DCP, the Clegg Hammer is a valuable testing device to perform fast, easy, and relatively cheap soil strength measurements (Al-Amoudi et al., 2002). Its capability to measure strength throughout the road construction process can improve compaction and reduce roading costs through placing additional material only where strength is inadequate (Mathur & Coghlan, 1987-88). A notable limitation of CBR values obtained through Clegg Hammer testing is that CIV-CBR correlations must be used with caution as they are empirical and correlate the dynamic response captured by the Clegg Hammer to CBR, a static response parameter (Kim et al., 2010). Additionally, although it is known that the material to a depth of at least twelve inches impacts CIV, it is uncertain exactly how deep this influence depth lies. This limits the applications of this measurement technique for subgrade strength measurements in situations where there is a thick aggregate layer overlying the subgrade.

Moisture Content Measurement

Soil moisture content influences engineering properties and load-bearing capabilities (O'Kelly, 2005). There are multiple methods to measure this including oven drying, soil density gauge, and time domain reflectometry[3] (Sotelo et al., 2014). These methods all have limitations. Soil density gauge results are heavily material dependent and time domain reflectometers need significant calibration. The main issue with the oven-drying method is that it can encounter issues with some soil types if undesirable chemical reactions occur, however it is still considered to provide the most trustworthy results (O'Kelly, 2005).

[3] Reflectometry measures the reflectance of light off objects to determine their properties (Stanford University, n.d.).

Oxidation reactions that can occur during oven drying must be avoided to ensure calculated moisture contents are accurate (O'Kelly, 2005). This can be done through controlling the oven temperature and drying duration. For most soils it is appropriate to oven dry at 110 +/- 5°C for 12-24 hours however in organic soils the drying temperature should be reduced to 80-90°C. This temperature reduction avoids organic matter in the soil charring which would adversely impact results (O'Kelly, 2005).

Density Measurement

Soil density impacts the strength of the soil and can be taken as a measure of compaction in soil mechanics (Wooltorton, 1958). For many applications it is best to measure the dry density of soil as this is not impacted by variations in moisture content that arise from changing weather conditions. Additionally, the quantity of lime or cement required for stabilisation is determined based on the dry mass of soil to be stabilised (National Lime Association, 2004). Two commonly used methods for density measurement are the rubber balloon and nuclear gauge methods (Huber & Heyer, 2019).

In the Rubber Balloon method, a hole in the soil is dug and a water-filled balloon pushed into it to determine the volume of the hole (Huber & Heyer, 2019). The excavated soil is oven-dried and weighed. These two measures enable the calculation of dry density using volume and dry mass. This method is simple and is regarded as providing reliable results, however it is time-consuming and labour-intensive. It is also unsuitable for highly rocky or unbound granular soils due to issues determining the volume of the hole using the rubber balloon (Rathje, et al., 2006).

In a different approach, the Nuclear Gauge method measures radiation intensity to calculate soil density and moisture content (Huber & Heyer, 2019). This method is fast to perform and non-destructive but the device requires frequent calibration to ensure that accurate results in different materials are achieved (Wates, 1987). As well as this, the radioactive radiation material used by the device can pose a safety risk therefore operator training is needed for safe and effective operation (US Department of Transportation Federal Highway Administration, n.d)

Soil Stabilisation

Using strengths based on the measurement techniques outlined above, subgrades exhibiting inadequate strength to facilitate effective road construction can be stabilized by either chemical or mechanical means (NZ Forest Owners Association, 2020). Mechanical stabilisation changes the gradation of the soil whereas chemical stabilisation utilizes additives to change the soil chemical structure (Afrin, 2017). Traditional stabilisation techniques include undercutting, geosynthetics, corduroy, lime, bitumen, and cement (NZ Forest Owners Association, 2020). As well as these, non-traditional stabilisation methods including enzymes, polymers and resins are increasing in popularity but their documented used in forestry contexts is limited (Tingle et al., 2007). The most appropriate stabilisation method is site dependent and is a function of the soil properties, desired strength, economic situation, and environmental conditions (National Academies of Sciences, Engineering, and Medicine, 2009).

This study will focus on undercut, lime stabilisation, and geogrid as alternatives for reconstructing existing forest roads. Undercutting is the method currently being used by roading contractors in these situations whilst lime and geogrid have previously been used in New Zealand forestry contexts (Visser et al., 2017; NZ Forest Owners Association, 2020). The literature regarding these methods is primarily regarding implementing them in new road construction on inadequate subgrades as opposed to in reconstructing existing roads.

Undercutting

In the past, subgrade stabilisation has been performed through the excavation of unsuitable material and replacement with stronger granular materials (figure 10) (Ward et al., 2017). This method is known as undercutting. This method is very site dependent as the required excavation depth is until suitable bearing material is reached at the given location (NZ Forest Owners Association, 2020). Undercutting is guaranteed to improve subgrade strength if suitable replacement material is used, however depending on the required excavation depth and rock availability it can be an expensive option. It can also create significant volumes of excavated soil which can pose an environmental issue if not managed effectively.

Figure 10: Undercut section of roading being reconstructed (Courtesy of Neil Thomas, Port Blakely).

The long-term performance of undercut sections may be inferior to other stabilisation methods. Whilst Cote et al. (2012) found that deep undercuts exhibited a superior cost-performance ratio in initial cycles compared to a thin aggregate base course layer, this advantage decreased over further cycles. Although undercut road sections may perform well initially, the lack of external reinforcement can cause suboptimal long-term performance due to buildup of permanent deformation. The short lead time required with undercut in combination with good initial performance is advantageous in forestry situations as it means that these roads can be utilised immediately after construction (Ward et al., 2017).

Lime Stabilisation

Lime in either its burnt or hydrated form can be used to strengthen road subgrades and other structural layers (NZ Forest Owners Association, 2020). It is a potential long-term fix for forest road subgrade and surface failure. Potential benefits of lime stabilisation include increased bearing capacity, shear strength and optimum moisture content, and decreased plasticity and settlement (Péterfalvi et al., 2015).

The first mechanism by which lime stabilises soil is through Ca^{2+} ions from lime reacting with clay particles, removing water and other undesirable particles in a process known as "flocculation and agglomeration" (National Lime Association, 2004). This creates a soil with higher workability, compactability, and less dimensional change. Soil stabilisation occurs at higher lime dosages through an increase in soil pH facilitating clay particle breakdown. Calcium-silicate-hydrated (CSH) and calcium-aluminate-hydrates (CAH) are formed through the reaction between silica and alumina that is released in clay breakdown, and calcium from lime (Péterfalvi et al., 2015). These products are cementitious and create a permanent matrix structure in the soil with higher strength, durability, and impermeability.

The optimal lime dosage is dependent on soil characteristics and can be determined through laboratory testing under ASTM D6276 (National Lime Association, 2004). Studies have found maximum strength improvements at between 3% and 12% lime dosage by percent of dry mass (Afrin, 2017; Péterfalvi et al., 2015; Pancar & Akpınar, 2016; Mousavi et al., 2023). Past this optimum point there is no additional strength gain or in some instances even a negative impact on strength. Dhar & Hussain (2021) found a 5% lime dosage yielded maximum strength improvements in low plasticity clay whilst a 7% lime dosage provided the greatest improvement in high plasticity clay. In comparison, a different study found that a lime dosage of 5% provided the highest CBR increase in high plasticity clay (Mousavi et al., 2023).

The required stabilisation reactions between calcium ions and clay necessitate a clay content of at least 7% in the soil to be stabilised (National Lime Association, 2004). Likewise, high soil organic matter or sulphur contents can also inhibit lime stabilisation (Afrin, 2017).

Geogrid

Geogrid has been used for over fifty years to cost-effectively increase road strength (Visser et al., 2011). The product is an interconnected polymer network typically made of polyester (figure 11). Apertures can be square, triangular, or hexagonal, and the product acts to stabilise the soil through interlocking with soil particles. Benefits gained through using geogrid in road construction include decreased required aggregate thickness, potential cost savings, and decreased long-term pavement distresses (Ho et al., 2023; Visser et al., 2017).

Figure 11: Triaxial geogrid laid over a road subgrade (Tensar International Corporation, 2021).

While geogrid can be used to stabilise all soil types it is most effective in stabilising coarse-grained materials due to the greater interlock potential (Bagshaw et al., 2015). Finely graded aggregates also allow stresses to transfer through the geogrid to other pavement layers which reduces its effectiveness. The greatest strength improvements from geogrid have been observed in low CBR soils that enable subgrade deformation as this allows the geogrid to transmit stresses (Visser et al., 2017).

The use of geogrid as reinforcement can significantly increase the CBR of the road, especially when used to stabilise layers under 50cm thick (Ho et al., 2023) (Hufenus, et al., 2006). Geogrid can enable the reduction of the aggregate layer thickness without causing substantial strength loss (Visser et al., 2017). Other benefits include a reduction in rutting depth of up to 60%, and decreased long-term maintenance costs (Bagshaw et al., 2015; Ho et al., 2023). Whilst geogrid studies have primarily focused on improving new roads, Vischer (2003) proved its ability to stabilize weakened subgrades under existing roads.

Objectives

The principal objective of this study is to identify which of three soil stabilisation methods provides the most fit for purpose solution for reconstructing previous rotation forest roads to withstand the stresses of present-day harvesting operations. This is done through trialing these methods in two separate forests and measuring strength and cost. These results aim to provide forest owners with recommendations regarding which methods have the potential to be useful in upgrading their previous rotation forest roads.

Methodology

The trial was constructed in two separate forests with differing soil and meteorological conditions. Each trial section consisted of a 190m length of existing road and was split into three 50m reconstructed sections separated by 20m buffers as done by Purcell (2022) (figure 12). Including a buffer minimised the impact of each section on the adjacent section and provided room for materials storage and machinery. The section order differed in each forest based on access to avoid machinery travelling over newly constructed sections.

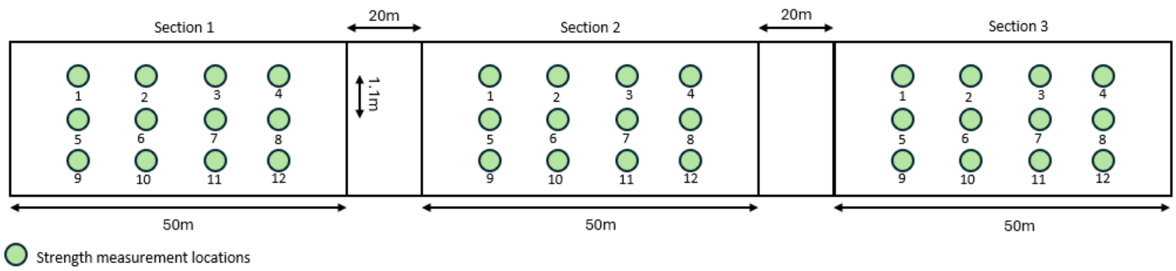

Figure 12: Study layout and measurement locations.

The trial roads were selected through consultation with Port Blakely. The roads used were suggested as they are both previous rotation forest roads awaiting upgrade before being used in upcoming harvesting operations. Both roads were constructed between 1960 and 1970 by the New Zealand Forest Service (NZFS) and were used for harvesting operations between 1997 and 2003. Thereafter they have not been used in harvesting operations and have received minimal heavy vehicle traffic. Low level maintenance including grading and adding running course has been undertaken periodically. Roads near those used in the trial have failed under recent log truck loads and have required extensive reconstruction to enable them to be used.

Along each road a section was selected to construct the trial on. The identification of a suitable section was done using a combination of aerial imagery and field observations. Each section was required to be relatively straight, 190m long, and of relatively uniform grade and aspect. As the trial was done on existing roads it was impossible to locate entirely uniform sections therefore discretion had to be used in selection. The aspect, width, and gradient of each trial section was found to use as background information and to determine the dry soil volume for lime stabilisation (National Lime Association, 2004).

Trial Locations

Site 1: Diamond Hill Road

Diamond Hill Road is in Herbert Forest in North Otago (figure 13). The trial section has an average width of 4.2m with an 8% grade and southeast aspect. It was last heavily used in 1997 harvesting operations. The road was constructed by NZFS workers using a D6 dozer with the roadline being put in by a Tapanui survey crew (Davies, 2008). A detailed soil survey in the area has not been undertaken but the soil is broadly classified as firm brown according to Landcare Research whilst the rock is metamorphic (Landcare Research, 2023; Landcare Research, 2020).

Figure 13: Location of Diamond Hill Road, Herbert Forest (Land Information New Zealand, Environment Canterbury | Environment Canterbury, 2024).

Trial construction took place from east to west and began with the lime stabilized section, followed by geogrid then undercut. This order was chosen due to the easier rock truck access from the western end. Straight after each section's construction, vehicle movements over the section were stopped to avoid differential load applications between sections. The infrequent use of Diamond Hill Road as a link through the forest and the absence of harvesting operations in the area meant that few vehicles travelled over the trial section during the measurement period.

Site 2: Bridgeman Rd

Bridgeman Road is in Geraldine Forest in South Canterbury (figure 14). The trial road section has an average width of 4.5m at a grade of 10% with a southwest aspect. It has not been used in harvesting operations since 2003 but has recently experienced occasional heavy vehicle movements. Following these it has exhibited unacceptable signs of distress considering the low number of load repetitions, illustrating the inadequacy of Bridgeman Road in supporting the traffic loads of harvesting operations.

Figure 14: Location of Bridgeman Road, Geraldine Forest (Land Information New Zealand, Environment Canterbury | Environment Canterbury, 2024)

According to Landcare Research the soil in the area is comprised of 60% brown loamy and 40% recent loamy soils (Landcare Research, 2024). All four soil siblings in the area have a silty texture and are well drained. The top 15-25cm of the soil is very permeable, and below this depth the soil has moderately slow to no permeability. Rock in the area can be classified as strong sedimentary (Landcare Research, 2020).

The trial was constructed from north to south beginning with lime, followed by geogrid then undercut. This order was chosen as the water required for the lime stabilized section was only accessible from the northern end of the trial. Similarly to on Diamond Hill Road, vehicle movements across the trial section were limited immediately post-construction. Through the trial period there were infrequent light and heavy vehicle movements across the section.

Pre-Trial Preparation

Soil samples were taken from the road sections around one month before construction to determine the soil type, properties, and profile of each trial section. This was important as lime relies on a 7% clay content to be effective (National Lime Association, 2004).

A mattock was used to dig through the pavement and expose subsurface layers. Disturbed soil samples of approximately 100-200g from both pavement and subsurface layers were taken for soil classification and moisture content determination. Although it is recommended that soil samples with particles up to gravel sized are at least 5kg (Carter & Bentley, 2016), smaller samples were taken due to oven-drying constraints. An additional sample was taken in each location to perform an in-situ soil plasticity test based on guidelines given in the NZFREM (NZ Forest Owners Association, 2020).

The subsurface layer was used to take two soil samples for dry density. Knowing the density of this layer is important as it is the layer that lime will be mixed through and therefore determines the lime quantity. The intended approach was to use a combination of the Rubber Balloon Method and the approach used by Veltman (2023), which involved excavating soil and filling a plastic liner with water to fit the excavated dimensions then weighing the water to determine volume. Upon attempting this method the difficulty of accurately filling the hole with water led to unacceptable inaccuracies in volume estimation.

This led to adaptation of the density measurement method. Soil was excavated by rotating a trowel on its vertical axis while applying downward pressure and creating a hole that could be modelled as conical. The displaced soil was removed periodically and placed into an airtight plastic bag to maintain in-situ moisture content. After a sufficient sample size was obtained, the depth of the trowel and its diameter at this depth were measured and used to calculate the volume of the hole using equation 1.

$$V = \frac{1}{3}\pi\left(\frac{d}{2}\right)^2 h \qquad (1)$$

There is no evidence as to the validity of the volume measurement component of this method, however its potential inaccuracies did not significantly impact the trial results. The measured density for each location was between the Landcare Research topsoil and subsoil values, and within this range the required lime quantity would not cause lime stabilisation to become cheaper than any other stabilisation method. This potential density inaccuracy may have led to a lime dosage of between 2.53% and 3.57% being applied.

Soil samples were transported to the University of Canterbury forestry laboratory for oven-drying. Tin dishes suitable for oven drying were labelled according to the conventions used in the field and their masses measured by electronic balance then recorded. Soil samples were placed into the tins and the combined mass of soil and tin measured before the initial soil mass was calculated using equation 2.

$$M_o = M_{soil+tin} - M_{tin} \qquad (2)$$

These samples were placed into a 110°C oven with the temperature selected based on the findings of O'Kelly (2005) as the soils are not highly organic. Sample masses were measured 24 and 48 hours after drying commenced. Despite O'Kelly suggesting that equilibrium is reached between 12 and 24 hours after beginning drying, to ensure that samples were fully dry an additional mass measurement was taken after 48 hours. A negligible mass change from 24 to 48 hours indicated an oven-dry sample.

The dry density and in-situ moisture content of the soil samples was calculated using equations 3 and 4 below. Moisture content was determined primarily for context whilst dry density was needed to calculate the quantity of hydrated lime to achieve the desired dosage.

$$\rho_{dry} = \frac{M_{dry}}{V} \qquad (3)$$

$$MC = \frac{M_{wet} - M_{dry}}{M_{dry}} \times 100(\%) \quad (4)$$

Relevant soil properties of the trial sections determined through pre-trial testing are given in table 1.

Table 1: Soil properties of the trial sections.

Location	Mean Subsurface Layer Dry Density	Subsurface Layer Moisture Content
Diamond Hill Road	1295kg/m^3	9.8-14.7%
Bridgeman Road	1289kg/m^3	20.3-22.8%

The Lime Association of Texas guidelines were used to determine lime quantity based on soil dry density (equation 5) (Lime Association of Texas, 2019). A 3% lime content was selected for the trial as this dosage may improve soil properties and stabilise materials (NZ Forest Owners Association, 2020). This is a relatively low dosage compared to the optimal dosages found in the literature, however it was chosen as it is likely to still provide strength improvement but keeps costs lower (Pereira et al., 2018; Dhar & Hussain, 2021; Keybondori & Abdi, 2021). When constructing "fit for purpose" forest roads, a certain level of strength is required to carry traffic but beyond this additional costs to further improve strength are often unjustified.

$$Q_{lime} = length \times width \times depth \times \rho_{dry} \times lime\ content \quad (5)$$

Materials were ordered based on the dimensions and soil properties of each trial section. Detailed calculations for material requirements are provided in Appendix 1.

Hydrated lime was obtained from Graymont Lime in Palmerston. A total of almost 2.5 tonnes was required to achieve the 3% dosage in both locations. This was supplied in a mixture of 20kg bags and 750kg sling sacks. Hydrated lime was used instead of quicklime as it does not require as much water during application and potential dust issues were not seen as a problem due to the isolation of the trial locations (National Lime Association, 2004). Reefton Hire arranged pick-up and delivery of the lime to the trial locations.

Geogrid was purchased from Geofabrics in Christchurch. Two rolls of Tensar TriAX TX160 were required for the trial as rolls are each 75m long. This product was chosen due to its use in previous New Zealand forestry projects and the wide range of CBRs it can be used with (Visser et al., 2017; Visser et al., 2011). A singular 3.8m width of geogrid was used on the trial roads which provides sufficient road width for trucks but does not cover the entire 4.5m spur road width (NZ Forest Owners Association, 2020). Previous studies have used two geogrid widths to get 4.5m of coverage but this doubles the cost and may render it financially infeasible for use in cost-sensitive forestry operations (Visser et al., 2017). The geogrid was transported to the trial locations by Port Blakely.

Base rock used in the trial was supplied by Port Blakely. It is the rock typically used in the undercutting method when reconstructing previous rotation roads which ensured consistency across all trial sections. In Herbert Forest this was a river run AP150 whilst in Geraldine Forest this was a fractured pit run from an in-forest quarry. This material was unscreened and ungraded therefore does not meet geogrid manufacturer specifications however it was used due to its low cost and availability for road construction (Visser et al., 2017). It was determined that this rock was better to use in the trials as opposed to the AP40 recommended by the geogrid manufacturer due to the high cost of AP40 making it unlikely to be used in future similar applications. The rock was transported from its source to the trial roads by rock truck during the trial construction.

A list of machinery required for trial construction was provided to Port Blakely and they contacted the roading contractors to ensure this was available for trial construction. The machinery needed was an excavator, grader, roller and rock trucks.

Trial Implementation

The trial implementation process was split into two key stages – preparation and construction. Details regarding these stages are given below. In addition to this format, a bullet point list was prepared for the roading contractors and is provided in Appendix 2.

Preparation

The trial area was marked out before construction to ensure section boundaries were distinct. This involved measuring out sections and ramming waratahs into the roadside at each measurement location and at section boundaries (figure 12). The purpose of this was to provide a precise method of locating strength measurement locations for repeat measurements. To do this a measuring tape was run across the road at each measurement cross-section and the distance from waratah to measurement location determined. This was noted alongside the corresponding location code and used for follow up measurements. In comparison to GPS systems with precisions of 1.72-12.55m under forest canopy, this method was repeatable with centimetre level accuracy (Tomaštík et al., 2021).

Initial strength measurements were taken using a Clegg Hammer the day prior to construction at the locations illustrated in figure 12. These measurements provided the current state of each location and were a baseline to compare post construction strength measurements to. Each strength measurement point in figure 12 represented the centre point in an arrangement of five points. These points were arranged in a cross shape 30cm from the central point (figure 15). The central point was located using a tape measure between the waratahs and the remaining four points were found using a ruler.

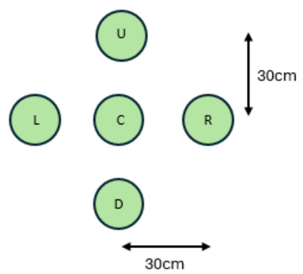

Figure 15: Arrangement of measurement locations around the central point.

The Clegg Hammer was selected as the strength measurement device due to its ability to provide repeatable measurements in test conditions. This device is accurate with a known +/- 2% deviation relative to traditional CBR tests (Clegg Hammer, 2023). Post construction strength measurements had to be taken with an aggregate layer over the subgrade, meaning the reliability of the DCP was inadequate (NZ Forest Owners Association, 2020). These factors alongside the availability of the Clegg Hammer drove the decision to use this instrument.

Clegg Hammer measurements were taken following the procedure outlined in ASTM D5874 (ASTM International, 2002). The Clegg hammer was calibrated in accordance with manufacturer instructions then the hammer was raised to a height of 457.2mm and dropped. This was repeated four times, and the maximum peak deceleration from these four readings was recorded as the soil impact value at each location. The impact value was correlated with CBR using equation 6. This equation, developed in 2002 by Al-Amoudi et al. (2002), is the relationship recommended for use by Clegg Hammer and is suitable for use in CBRs from 4% to 103%. It should be used with caution in soils with low CBR as it tends to overpredict the CBR of weak soils (Fairbrother et al., 2010).

$$CBR = 0.1691\ (CIV)^{1.695} \quad (6)$$

Construction

The construction stage was done over 1.5 days at each location by the roading contractors in each forest. These contractors are experienced and have previously undercut many sections of road, however had not used lime and geogrid before. This unfamiliarity may have resulted in slightly lengthened construction times leading to increased costs for these two sections. The methodology was discussed thoroughly before and during construction.

A cross-sectional view of each section as it was constructed is given in figure 16. The depth of each layer in the figure was the ideal scenario and was given to the operators as targets however due to the practicalities of reconstructing existing roads there were slight variations from these depths due to factors such as culverts or large boulders buried under the surface. A ruler was used periodically during construction to audit the thicknesses and provide the machine operator with a point of reference.

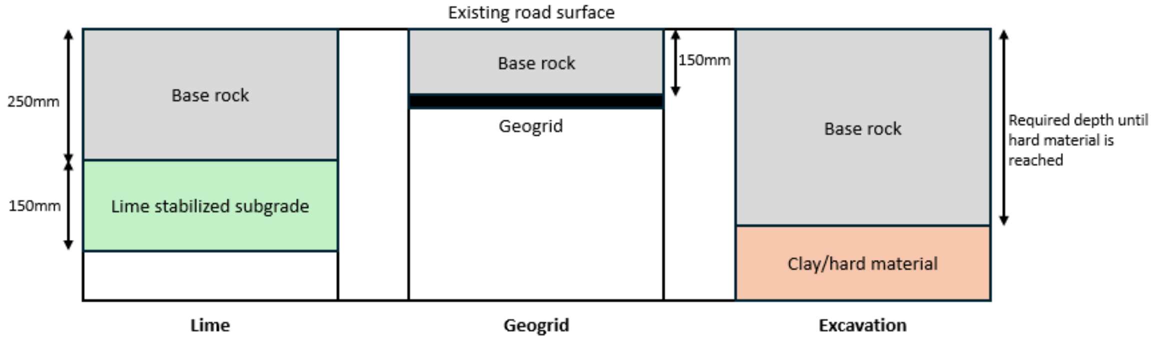

Figure 16: Cross-sectional view of the trial sections.

The machinery used in construction varied between forests due to availability. In Herbert Forest this consisted of a Volvo EC220DL crawler excavator, Volvo G946 motor grader, and Caterpillar CS563E vibratory smooth drum roller. In Geraldine Forest a Komatsu PC240LC excavator, Caterpillar 140G motor grader, and Dynapac CA2500D single drum vibratory roller were used. In both locations rock trucks were externally organized.

Throughout the trial construction the roading contractors used the hour clock on their machines to calculate the time spent by each machine in constructing each section. This was done in the same manner that they usually allocate time to tasks for invoicing purposes. Representative machine rates were provided by Port Blakely and used in conjunction with these durations to calculate machine costs for each section.

Undercut

This section was the "control" section in the trial as it is the current method used by the roading contractors to reconstruct previous rotation roads in Port Blakely forests. Therefore, construction was done using their current method. This adds utility to the results of the study as it enables direct comparison between what is currently being done and potential alternatives.

The existing road was excavated until hard bearing material was reached using an excavator (NZ Forest Owners Association, 2020). This excavation depth was variable across the section as only unsuitable material such as organic material and topsoil were removed. Following the removal of this material, base rock was used to backfill the excavation and return the road surface to its original level. The section was graded and rolled.

Geogrid

Firstly, the top 150mm of the existing road was excavated before placing the geogrid to remove large rocks and assist with installation (Visser et al., 2011). An excavation depth of 150mm was selected as it is the maximum particle size of the aggregate used in the Diamond Hill Road trial and governs the minimum layer thickness. The geogrid was applied in stages as described by Visser et al. (2011), however the initial stage of removing rocks sticking more than 5cm above the surface was skipped as excavation had already removed these.

The geogrid product used, Tensar TriAX TX160 geogrid, comes in rolls 3.8m wide by 75m long. To roll it out rocks were used to hold the ends of the roll in place whilst two people walked and unrolled the material over the excavated surface (figure 17). The trial sections were 25m shorter than the geogrid roll length so excess geogrid was cut off using wire cutters.

Figure 17: Installation of geogrid on Diamond Hill Road.

A 150mm layer of base rock was then spread over the geogrid to fill in the excavation and return the road to its original height. Although a thicker rock layer will likely provide greater strength benefits and durability, there is an associated extra cost on top of the geogrid. As Visser et al. (2017) found that there was no significant strength reduction in forest roads when a reduced aggregate layer thickness was used, this study used the minimum required thickness. The section was rolled and graded to finish.

Lime

The top 250mm of the existing road was excavated from the lime section to reach what became the top of the lime-stabilised layer. Excavating this material exposed the clayey layer which is suitable for lime stabilisation (NZ Forest Owners Association, 2020). The rippers on the grader were used to rip the clay to a depth of 150mm below the excavation. This 150mm of ripped material became the lime stabilised layer with its depth based on guidelines from the Queensland Department of Transport and Main Roads (2021) for an average daily ESA of less than 100 in the first year of opening.

High calcium hydrated lime was then spread onto the ripped soil. The 20kg sacks were spread manually whilst the 750kg sling bags were attached with chains to the excavator to spread. An effort was made to spread the lime evenly across the section by controlling the flow of lime out of the sling sacks, however it is acknowledged that the lime dosage was not perfectly uniform. The quantity of lime spread across the entire section was accurate however as this was controlled through using the correct combination of 20kg and 750kg bags. The mixture was moistened to just above optimum moisture content using water from a hose off a smoke chaser. The optimal moisture content of the soil was unknown so was estimated as being when soil squeezed together by hand sticks together but does not stick to the hand (NZ Forest Owners Association, 2020) (Department of Transport and Main Roads, 2021). After the mixture was suitably moistened the grader's rippers were used to mix and ensure the lime was spread evenly throughout the section (figure 18).

Figure 18: Grader beginning to mix lime through Diamond Hill Road.

Approximately 250mm of base rock was placed over the top of the stabilised subgrade after mixing was complete (NZ Forest Owners Association, 2020). Many lime manufacturers recommend an amelioration period before applying aggregate but in this case it was not implemented due to practical constraints and the findings of Young et al. (2017) that there is no resultant change in strength from the presence or absence of this period. The section was finished by grading and roller compaction.

Post Trial – Data Collection

Repeat Clegg Hammer strength measurements were taken using the same procedure as outlined above to measure strength development over time. These were taken approximately one, two, three, and four months after construction. A visual inspection of the sections was undertaken at the same time to ascertain whether any damage had occurred.

Cost information for the trial was collated to calculate the cost of constructing each section. Material cost was determined by invoices, and machine times and rates were used to calculate machine costs.

The weather at the trial locations was monitored for the four months between trial construction and the final strength measurements being taken. This information was used to provide context for strength measurements as weather events such as precipitation and freeze-thaw cycles can impact road strength. Similarly, the soil moisture content at the weather stations was monitored to gain information regarding the relative wetness of the soil at different times. This data was taken from Fire and Emergency New Zealand (FENZ) weather stations located in Herbert and Geraldine Forest. The weather stations are not located exactly at the trial locations, however they are nearby and provide a representation of weather conditions at the trial sites. The minimum and maximum temperatures, precipitation, and soil moisture content were monitored.

Data Analysis

Once strength data was obtained for the entire trial period, four months, the data analysis stage began.

Strength

Due to the known variability in subgrade strength (NZ Forest Owners Association, 2020), the strength values used in analyses were the average of the values within 1.5 standard deviations of the mean for each section, referred to as the representative strength. It includes 87% of values, therefore major outliers do not heavily influence the results. The representative strength was calculated after one, two, three, and four months for each section as a whole, in the upper wheel path, lower wheel path, and centre. As many previous rotation historic roads were sidecast, strength differences were expected across the road cross-section based on construction on a cut or fill slope (Kennedy, 1986). The representative strength over time for each method and location was plotted against soil moisture content information to establish the strength development of each method and its relationship to moisture.

Additional analyses were done regarding the variability of each technique's strength improvement between the wheel paths and road centre. Despite the limited traffic loading throughout the trial, this distinction enabled the completely undisturbed road centre to be compared with the lightly trafficked wheel paths and the slight wheel path compaction effect to be shown.

Costs

Road construction costs were calculated from machine rates and normalised for a 4.5m width then extrapolated to a kilometre cost for consistency between sections. The machine rates used are representative rates for each machine, while the materials costs were gathered from invoices (table 2).

Table 2: Unit costs used in analyses.

Unit Costs (excl. GST)	Unit	Diamond Hill	Bridgeman
Machinery			
Excavator	hr	$ 220.00	$ 220.00
Roller	hr	$ 165.00	$ 165.00
Grader	hr	$ 235.00	$ 235.00
Rock truck	hr	$ 150.00	$ 150.00
Materials			
Rock	m^3	$ 20.76	$ 4.00
Lime	t	$ 525.00	$ 525.00
Geogrid	m^2	$ 2.85	$ 2.85

Section costs were graphed against the lowest representative strength for each method at each location. The lowest strength was used as in all but one instance it was the strength in the wettest state. Flexible pavements are frequently designed using soaked CBR, the CBR after the material has been soaked for 96 hours, as it represents performance in the worst conditions (Muthu Lakshmi et al., 2021; The International Bank for Reconstruction and Development/The World Bank, 2018). In this study this is referred to as the "wet" CBR as it is similar to soaked CBR but specimens are not prepared in the same manner.

Since New Zealand forest roads are generally used year-round and must meet strength requirements even in their wettest state, the use of the lowest strengths in this analysis accounts for this. This graph also shows a CBR of 30%, the target design strength for these roads. A CBR of 30% was chosen as this is the CBR at which the minimum 100mm aggregate depth is required on unsealed pavements irrespective of loading (Fairbrother et al., 2010).

Earthworks

Earthworks volumes were calculated for each section as the volume of aggregate used since the roads had no net change in level. In the same manner as the costs, these volumes were normalised for a 4.5m width to ensure consistency between sections. These volumes were compared between sections and locations to determine the environmental impacts associated with the road upgrades.

Sensitivity Analysis

A sensitivity analysis regarding each method's sensitivity to different cost components was conducted on all methods. This involved analysing the sensitivity of overall section cost to a change in aggregate price. It was performed due to the large range of aggregate prices in New Zealand forests, and enabled suggestions to be provided as to which method other forest owners with forests of similar geological properties could be considering based on the price of rock in their forests.

Results

Site 1: Diamond Hill Road

Over the four-month trial period, the undercut section of Diamond Hill Road was consistently the strongest, followed by the lime then geogrid sections (figure 19). For the first two months post construction all methods increased in strength then for the second two months decreased in strength. This transition occurred alongside sizeable increases in soil moisture content.

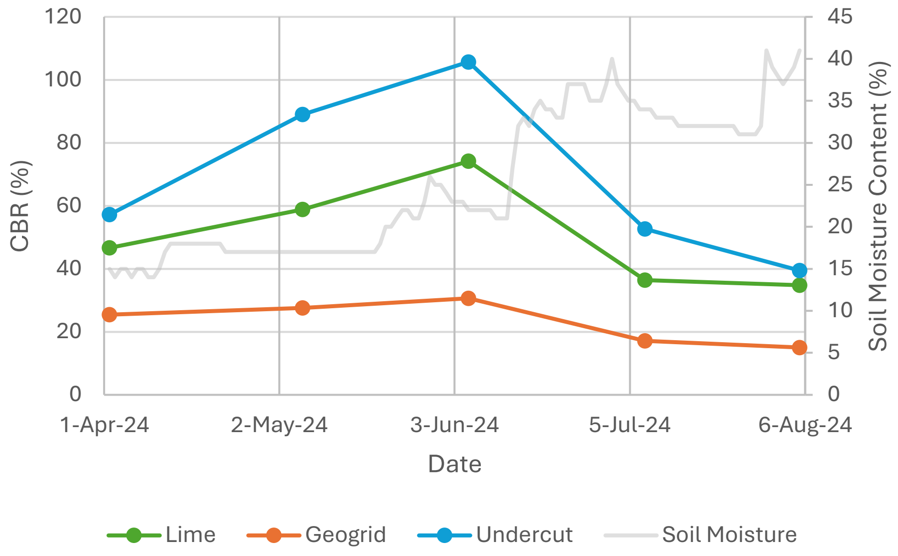

Figure 19: Representative strength of different reconstruction methods on Diamond Hill Road over time with superimposed Herbert soil moisture content.

Normalised costs for Diamond Hill Road are given in table 3. Lime stabilisation is the most expensive option at a cost of $89,507/km. The construction cost of the geogrid section is notably lower than the other two sections at only $50,885/km. Rock and its delivery costs make up the largest cost components for all sections.

Table 3: Diamond Hill Road construction costs.

	Cost/km for 4.5m width		
Section	Lime	Geogrid	Undercut
Lime	$ 11,107.28	$ -	$ -
Geogrid	$ -	$ 10,830.00	$ -
Rock	$ 25,054.34	$ 13,322.54	$ 28,331.49
Grader	$ 11,837.69	$ 5,035.71	$ 10,708.86
Roller	$ 3,324.63	$ 1,767.86	$ 3,759.49
Excavator	$ 15,514.93	$ 7,071.43	$ 10,025.32
Rock truck	$ 22,667.91	$ 12,857.14	$ 25,632.91
Total cost	$ 89,506.76	$ 50,884.69	$ 78,458.07

Geogrid required far lower earthworks volumes than undercut and lime (figure 20). The highest earthworks were in the undercut section, with 157.86m^3 greater volume than the lime section and 2.13 times the volume of geogrid.

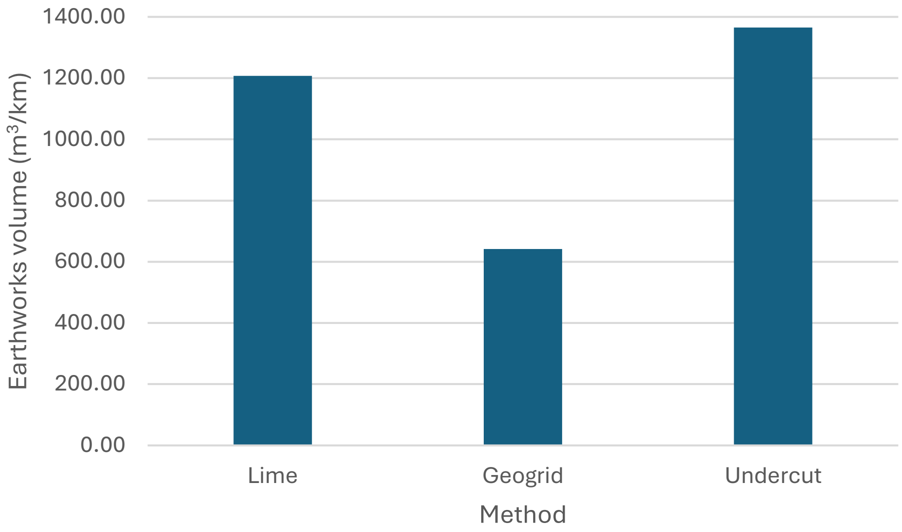

Figure 20: Earthworks required for each section on Diamond Hill Road.

Site 2: Bridgeman Road

All methods increased in strength from pre-trial to one month post construction (figure 21). The biggest improvement was the undercut section whose CBR increased from 24.31% to 35.75%. From one to two months the undercut and lime strength continued to increase but the geogrid section strength decreased slightly, by 2.44%. The three methods all decreased in strength between two and three months, and from three to four months the lime and undercut strengths continued to decrease but the geogrid strength increased slightly. Soil moisture content remained relatively constant for the first two months but increased by 3% each month to the three and four month measurements.

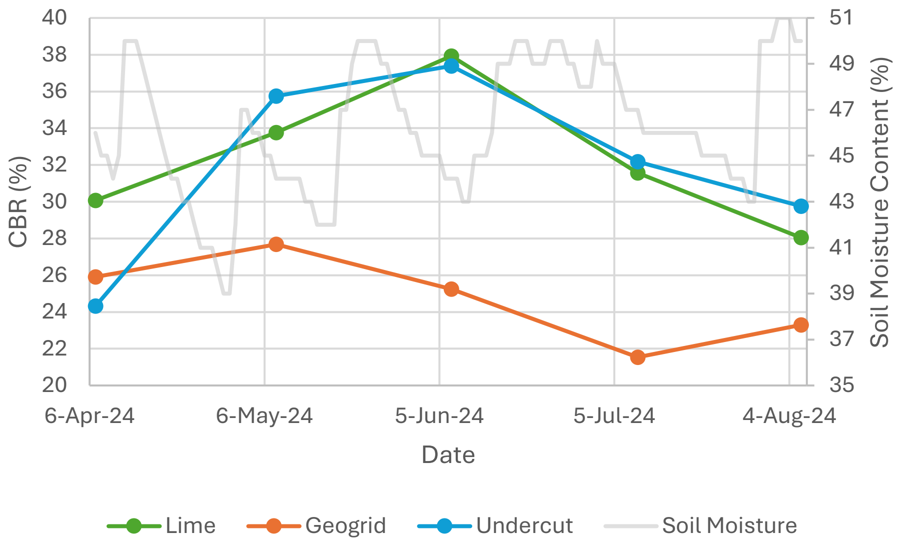

Figure 21: Representative strength of different reconstruction methods on Bridgeman Road over time with superimposed Geraldine Forest soil moisture content.

There is a considerable difference in construction cost between the lime section and the other two sections on Bridgeman Road (table 4). The lime section cost $63,639/km whilst the next expensive section, the undercut section, cost only $39,268/km. Geogrid and undercut had a minor cost difference of $1,251/km. The largest cost components in the lime and undercut sections were the excavator and rock truck machine hours while in the geogrid section the geogrid material was also a sizeable component.

Table 4: Bridgeman Road construction costs.

	Cost/km for 4.5m width (excl. GST)		
Section	Lime	Geogrid	Undercut
Lime	$ 12,409.81	$ -	$ -
Geogrid	$ -	$ 10,830.00	$ -
Rock	$ 4,564.53	$ 2,207.30	$ 5,124.09
Grader	$ 7,183.02	$ -	$ 4,631.39
Roller	$ 1,681.13	$ 1,625.91	$ 1,625.91
Excavator	$ 17,932.08	$ 13,007.30	$ 8,671.53
Rock truck	$ 19,867.92	$ 10,346.72	$ 19,215.33
Total cost	$ 63,638.49	$ 38,017.23	$ 39,268.25

Similarly to at the Diamond Hill Road trial, geogrid required far less earthworks than the lime and undercut sections (figure 22). Undercut had the largest earthworks volume of 1281.02m^3/km while lime had 1141.13m^3/km and geogrid 551.82m^3/km.

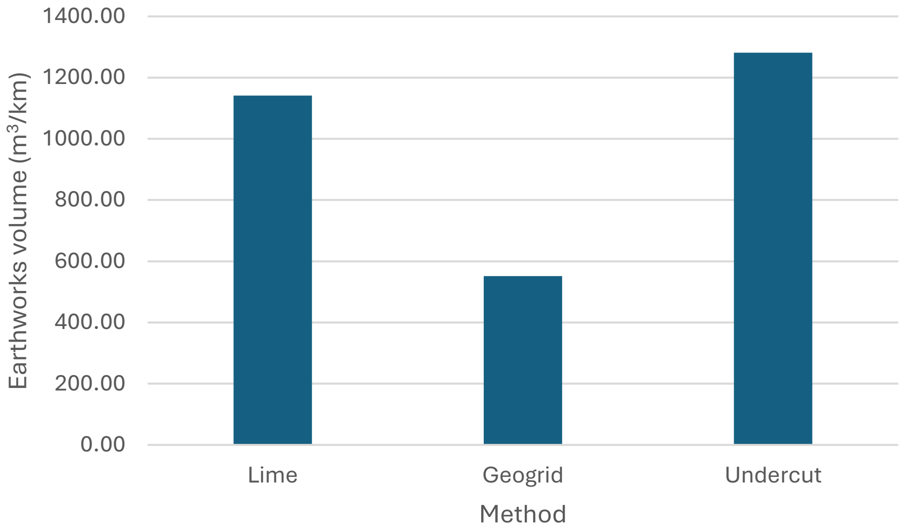

Figure 22: Earthworks required for each section on Bridgeman Road.

Discussion

Strength – Cost Relationship

During the trial the undercut section produced the highest wet CBR at both trial locations, suggesting that this method is the most suitable for upgrading historic forest roads based on strength. On

Diamond Hill Road the lime and undercut sections both reached a wet CBR of greater than 30%, the design CBR, but geogrid only reached 15.04% (figure 25). This means that although geogrid is the lowest cost method, it did not produce fit for purpose roads in this location. Undercut had a wet CBR of only 5% higher than lime, however its major advantage came through its considerably lower cost. The lime section had slightly lower rock, roller, and rock truck costs but these were insufficient to negate its higher materials, grader, and excavator costs. Overall the lime section was $11,049/km, or 14%, more expensive than the undercut section.

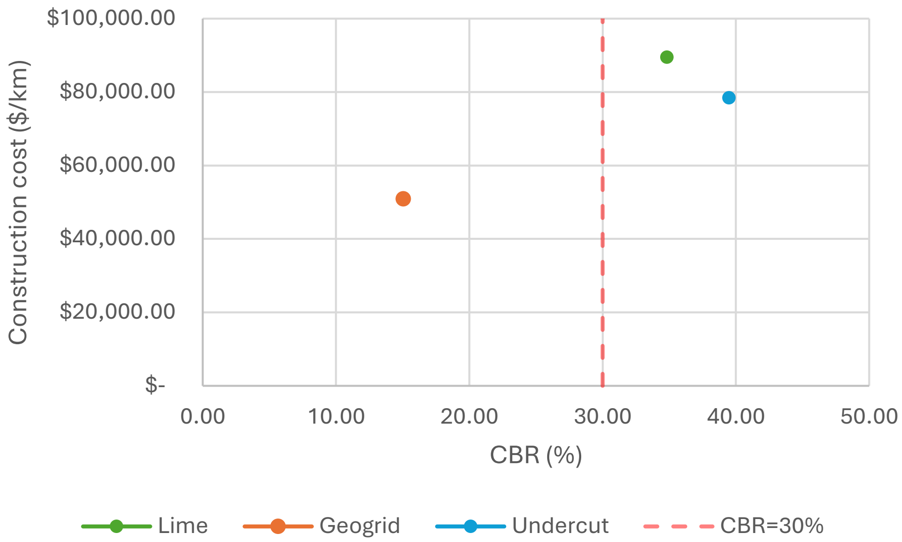

Figure 25: Construction cost compared to wet CBR for the three methods trialled on Diamond Hill Road.

On Bridgeman Road there was less than a 2% difference in wet CBR between the lime and undercut sections. None of the methods had a wet CBR of 30%, though the lime and undercut sections were close to this threshold with wet CBRs of 28.04% and 29.75% respectively (figure 26). These two methods had CBRs of over 30% at all measurement instances aside from the wettest, whereas geogrid never achieved a CBR of 30%.

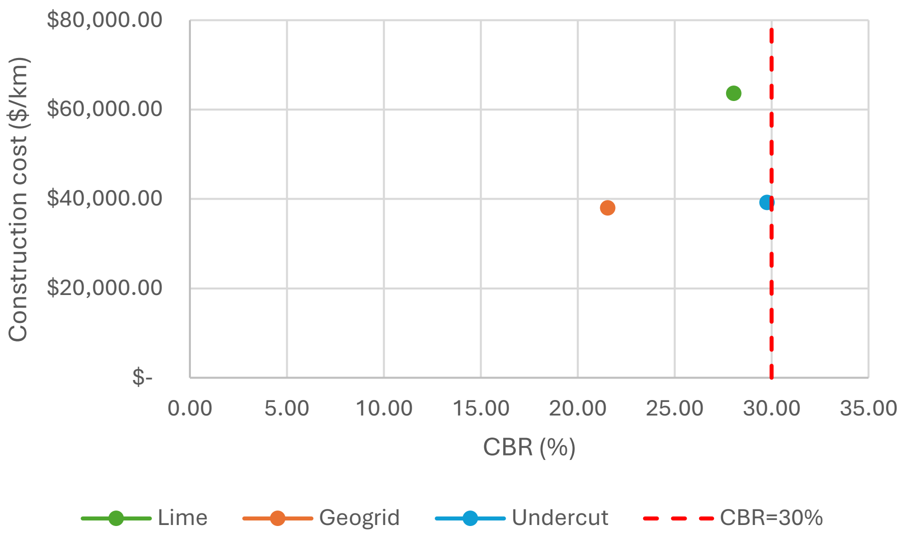

Figure 26: Construction cost compared to wet CBR for the three methods trialled on Bridgeman Road.

Although there is a low strength difference between undercut and lime on Bridgeman Road, there is a notable cost difference due to the very low \$4/m^3 undelivered aggregate price. This price means that the additional rock required for the undercut section did not substantially influence the overall section cost, while the lime and extra machine hours needed for the lime section increased costs considerably.

After the four-month trial period, the undercut method provided the best cost-performance trade-off in both trial locations when upgrading existing forest roads to cater for heavier log trucks. Of note is that Cote et al. (2012) found that in the first 10,000 loading cycles unreinforced aggregate sections were economical but when also considering post-rut repair cycles, lime stabilised sections were the most economic. Therefore, long-term monitoring of the different methods may yield different results to after the four-month trial period.

Over the two trial locations, geogrid only achieved a representative CBR of 30% at one instance. This subpar performance may have been because throughout the trial there were limited vehicle movements over the trial sections, meaning that the pavement experienced low strain. The strength development mechanism of geogrid means that its performance is based on the level of particle interlock that is achieved between geogrid and soil particles, therefore insufficient interlock may have been provided through compaction to fully mobilise strength (Qian et al., 2015). This agrees with the findings of Cote et al. (2012) that sufficient rut depth is required to fully mobilise its tensile strength. The lack of loading in this study due to the time frame and logistical constraints is likely to have inhibited geogrid strength development and is a limitation of this study.

Alternatively, geogrid may have not achieved sufficient particle interlock during the trial due to the aggregate used. The aggregate selection was based on availability and cost factors which resulted in river run AP150 being used on Diamond Hill Road and a fractured ungraded unscreened pit run rock being used on Bridgeman Road. Differing from the AP40 recommended by the manufacturer is unlikely to provide the same level of interlock and may have impaired performance.

Geogrid reinforcement did not produce fit for purpose roads during this study, however its relatively low construction cost makes it worthy of further investigation. The remainder of Diamond Hill Road will be upgraded in 2025 prior to harvesting operations, therefore to determine which method will be used trucks will be run along the trial section and the strength following this measured in the same manner as during the trial. A cost-strength comparison will be used to determine which method will be used for the remainder of the road. Further to this, additional strength measurements will be taken during and following harvesting operations on the upgraded road and across the trial section.

A limitation of this analysis is that the costs used are only associated with road construction and do not consider ongoing maintenance or life cycle costs. Sections that have more expensive upfront construction costs such as lime may require reduced maintenance or have a longer lifetime, and vice versa, but in the timeframe of this study this cannot be determined.

Spatial Variability of Strength

The wheel paths on Diamond Hill Road showed that undercut produced superior strength at both the strongest and weakest instances (figure 27). Geogrid was clearly the weakest method at both instances. There is a statistically significant difference at the 5% level between the methods after two and four months, though the significance is slightly higher at two months.

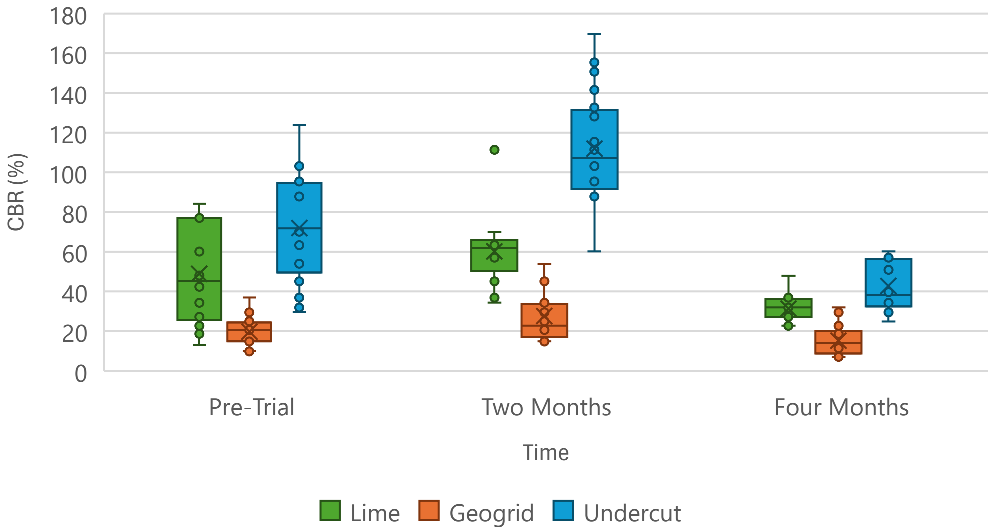

Figure 27: Diamond Hill Road wheel path representative strength for the different methods.

In the centre of Diamond Hill Road undercut and lime exhibited similar strength at the strongest and weakest measurement instances while geogrid clearly showed lower strength (figure 28).

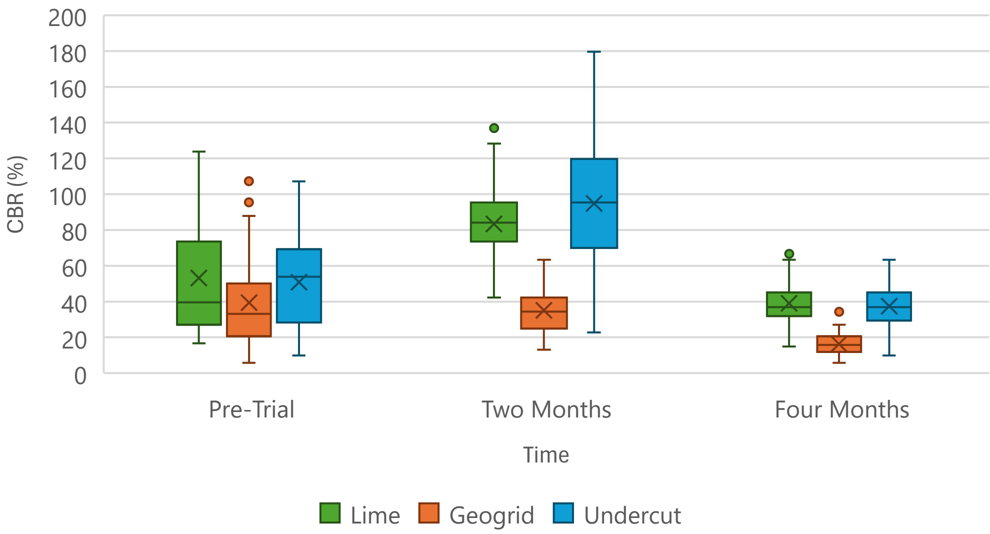

Figure 28: Diamond Hill Road centre representative strength by method.

The measured strengths in the wheel paths on Bridgeman Road were similar between the three methods (figure 29). Undercut had a higher median strength however there are overlapping 36 interquartile ranges between the methods. The statistical significance of the difference between the three methods decreased from two to four months and there is no significance at the 5% level between the wet CBRs, after four months.

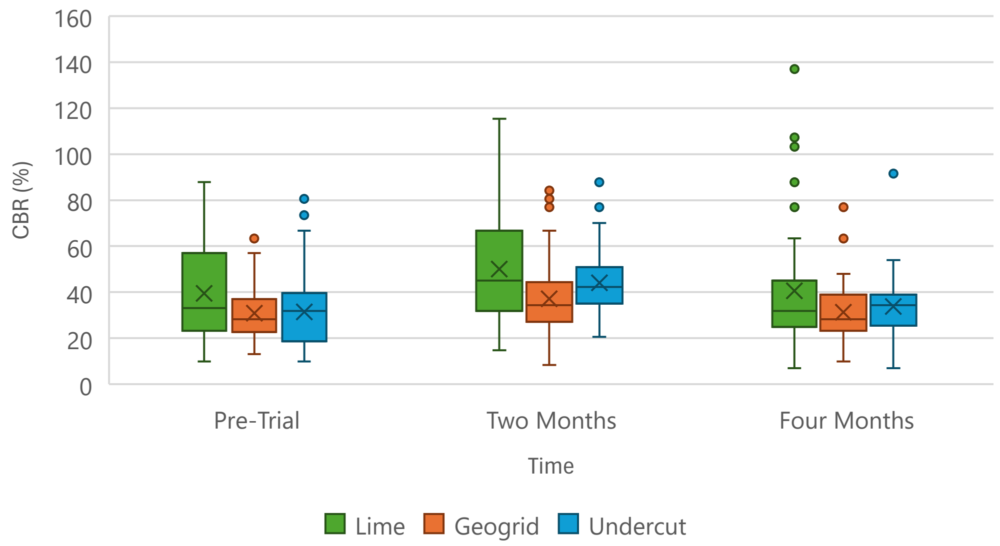

Figure 29: Bridgeman Road wheel path representative strength for the different methods.

In the centre of Bridgeman Road, the geogrid section is clearly weaker than the lime and undercut sections after two and four months (figure 30). All methods exhibited lower strength in the centre compared to the wheel paths at the strongest and weakest measurement instances, however undercut and lime still show similar strength. Considering the road centre was undisturbed by any traffic postconstruction, the higher wheel path strength shows both the potential role of infrequent traffic in assisting with compaction, and the strength development of geogrid after some loading.

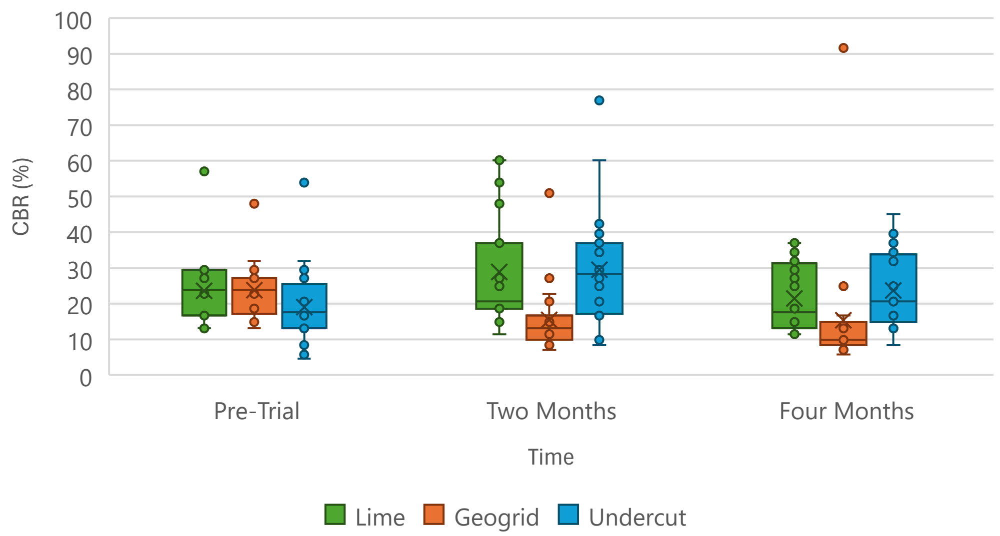

Figure 30: Bridgeman Road centre representative strength by method.

Although there were limited movements across both trial sections, Bridgeman Road was more frequently travelled than Diamond Hill Road over the trial period. The superior performance of geogrid in the wheel paths compared to the centre on this road but not Diamond Hill Road may illustrate that the vehicle movements that occurred may have mobilised a greater proportion of the geogrid tensile strength, resulting in higher CBR measurements. Alternatively, the centre may have been inadequately compacted at construction with the absence of vehicle movements not allowing further compaction to occur. This shows the importance of further strength measurements before and after traffic loading to conclude which of these factors contributed to the results.

The high range of strengths measured in all sections' pre-trial measurements raises the possibility that the entirety of existing roads may require upgrading, instead upgrading localised weak sections of road. The pre-trial measurements were however taken at a relatively dry time so should be used with caution. Measuring the strength of existing roads in their wettest states is likely to provide useful information regarding whether the entirety of the road should be upgraded in order for it to perform in its worst conditions or whether costs can be saved by upgrading selected portions of road.

Cost Sensitivity to Aggregate Price

At the current Diamond Hill Road aggregate price of \$20.76/m^3 undelivered, lime stabilisation is the most expensive option, followed by undercut then geogrid (figure 31). Geogrid remains the cheapest method at all aggregate prices, whilst undercut becomes more expensive than lime stabilisation at an aggregate price of \$90.78/m^3 undelivered. Delivery costs to Diamond Hill Road during the trial were \$18.78/m^3, therefore in the trial undercut becomes more expensive than undercut at a rock price of \$109.56/m^3 delivered.

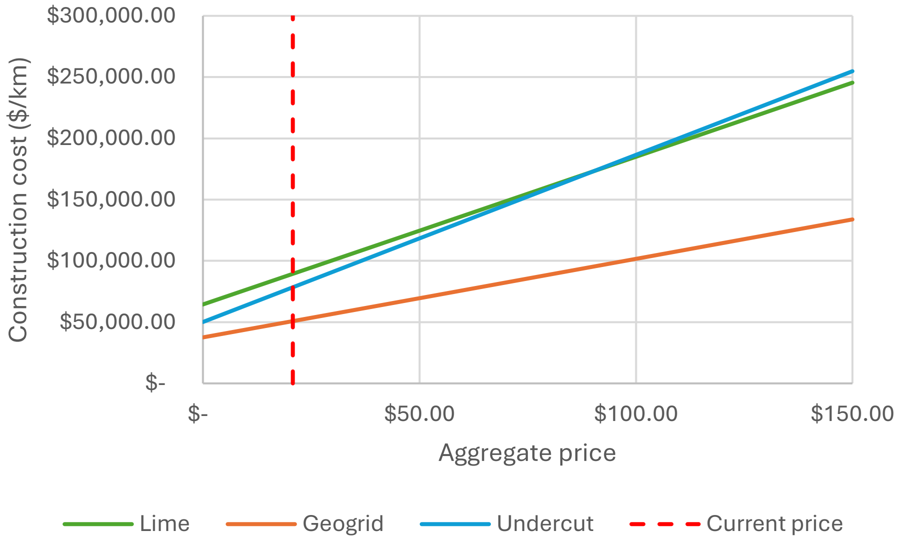

Figure 31: Sensitivity of different methods to changing aggregate price at Diamond Hill Road.

The cost of aggregate used on Bridgeman Road is a low \$4/m^3 undelivered with an additional \$17.41/m^3 delivery cost. Geogrid is the cheapest reconstruction method at all realistic aggregate prices, whilst lime is the most expensive option (figure 32). This is likely due to its high machine hours compared to the other methods.

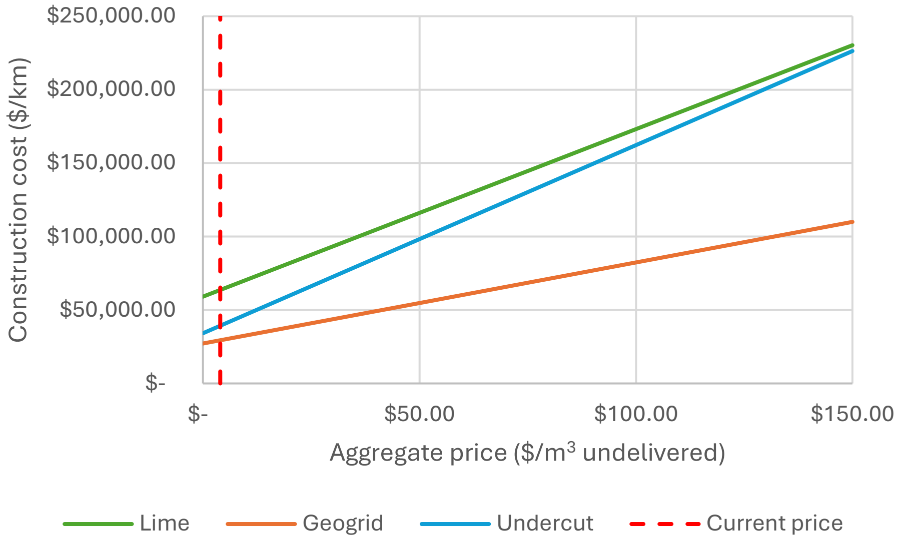

Figure 32: Sensitivity of different methods to changing aggregate price at Bridgeman Road.

Depending on the aggregate source and location, prices can vary considerably throughout New Zealand. After considering the delivery costs of the trial, Bridgeman Road has an aggregate price of $21.42/m^3. Utilising an in-forest quarry caused this low price, over $100/m^3 cheaper than prices reported in the Gisborne region. While delivery costs vary based on proximity to the aggregate source, the breakeven analysis for Diamond Hill Road illustrating that lime stabilisation becomes cheaper than undercut at an aggregate price of $109.56/m^3 delivered shows that although undercut is the cheapest option meeting strength requirements in the two trial locations, in other locations such as the East Coast with far higher aggregate prices lime may be a cheaper option.

Moisture Content – Strength Relationship

There was a negative correlation in both locations between soil moisture content and strength (table 5). On Diamond Hill Road, all methods increased in strength for the first two months post-construction, at which point the soil moisture content was 1.53 times that at construction. A 48% increase in moisture content between two and three months was accompanied by a percentage strength decrease of 44-51% for all methods whilst a further smaller increase in moisture content resulted in a 4-25% decrease in strength for the different methods.

On Bridgeman Road, the undercut and lime sections followed this trend, however the geogrid section exhibited a 9% decrease in strength from one to two months despite no change in soil moisture content. This section then increased in strength from three to four months despite an increase in soil moisture content. The strength decreases measured on Bridgeman Road were far lower than on Diamond Hill Road, potentially because the increase in soil moisture was far lower with the maximum only 1.11 times the as built moisture content.

Table 5: Change in CBR compared to moisture content for all sections.

			Percentage CBR change since previous measurement		
	Time	**Current Soil Moisture/Pre-Trial**	**Lime**	**Geogrid**	**Undercut**
Diamond Hill Road	Pre-Trial	1.00			
	One Month	1.07	26%	8%	55%
	Two Month	1.53	26%	11%	19%
	Three Month	2.27	-51%	-44%	-50%
	Four Month	2.80	-4%	-12%	-25%
Bridgeman Road	Pre-Trial	1.00			
	One Month	0.96	12%	7%	47%
	Two Month	0.96	12%	-9%	5%
	Three Month	1.02	-17%	-15%	-14%
	Four Month	1.11	-11%	8%	-8%

Bridgeman Road also may have been closer to optimum moisture content than Diamond Hill Road at trial construction. A moisture content at or above optimum when built results in a lower strength loss when the soil is saturated (figure 33). Therefore, the greater strength loss exhibited by Diamond Hill Road may have resulted from being constructed much drier than optimum moisture content then reaching a saturated state during the trial.

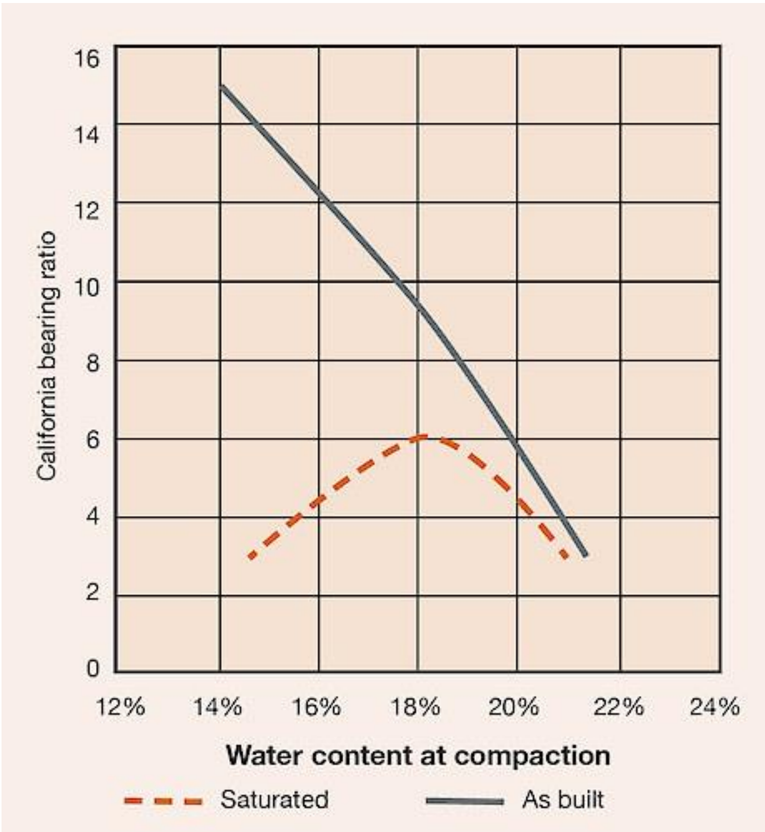

Figure 33: Soil moisture content at compaction compared to saturated strength (NZ Forest Owners Association, 2020).

These results illustrate the importance of understanding the soil moisture content at construction and its relationship with the soil's optimum moisture content. Forestry companies generally attempt to build roads in the summer months to facilitate firming of the ground, however the consequence of this is that there is a large potential strength decrease from when the road is built to its saturated state, as illustrated by Diamond Hill Road (NZ Forest Owners Association, 2020). The results of this study show that similar factors regarding moisture need to be designed for when upgrading existing roads as with new road builds. These considerations will enable roads to perform better in saturated conditions and facilitate year-round access.

Environmental Performance – Earthworks

At both trial locations there was less than 160m^3/km of difference between lime and undercut earthworks volumes, but geogrid had less than half the earthworks volume of these methods. Lime and geogrid earthworks volumes were set by the study specifications while undercut volumes were a function of the existing road as all inadequate material was removed.

A greater reduction in earthworks volumes was expected from lime compared to undercut than was observed, however due to the necessity for a clay content of 7% for lime to be effective it is incapable of successfully strengthening much of the soil that was removed (National Lime Association, 2004). Large volumes of topsoil with high visible organic matter contents were removed down to around 250mm, the specified depth for lime stabilisation, indicating that if this depth was reduced the lime stabilisation would not have been as effective.

Geogrid clearly provides benefits over the other two reconstruction methods through generating far lower earthworks volumes. The material removed in all methods is inadequate to be reused in the upgraded road so must be disposed of in a suitable manner, whether this is side cast, benched, or end hauled. Exposed fill can cause adverse environmental effects including erosion and sedimentation if not adequately managed, therefore to comply with National Environmental Standards for Commercial Forestry (NES-CF) standards this exposed soil must be stabilised through methods such as benching, vegetation, compaction, or geosynthetics (NZ Forest Owners Association, 2020). This adds costs to methods with higher earthworks volumes and makes reconstruction options such as geogrid that require lower earthworks volumes more attractive.

According to Rutland (2012), a new 4.5m wide road with 1m shoulders and 0.6m water tables constructed with balanced cut and fill and a 133% cut slope generates 1.42-7.36m^3/m of earthworks for terrain slopes of 10-35%, terrain slopes at the trial locations. All trial methods at both locations had earthworks volumes lower than the lowest reported by Rutland (2012) for the relevant terrain slopes, with undercut on Bridgeman Road being highest at only 1.36m^3/m. This shows the environmental benefits of reconstructing existing forest roads as opposed to building new roads on a different roadline to access the same area.

Study Applicability to Other Situations

The effectiveness of these reconstruction methods is very site specific as it is dependent on underlying soil geology and climatic conditions. Based on this, the results from the Diamond Hill Road and Bridgeman Road trials are likely to be most applicable to areas with the same soil types, firm brown and orthic brown respectively. The seven different soil groups that come under the brown soil order cover 43% of New Zealand's land area (figure 34) (Landcare Research, n.d.). This suggests that there is likely to be applicability of these study results to forests in these areas given the similar soil conditions, however it does not guarantee that the same results as seen in this study will be observed in other locations.

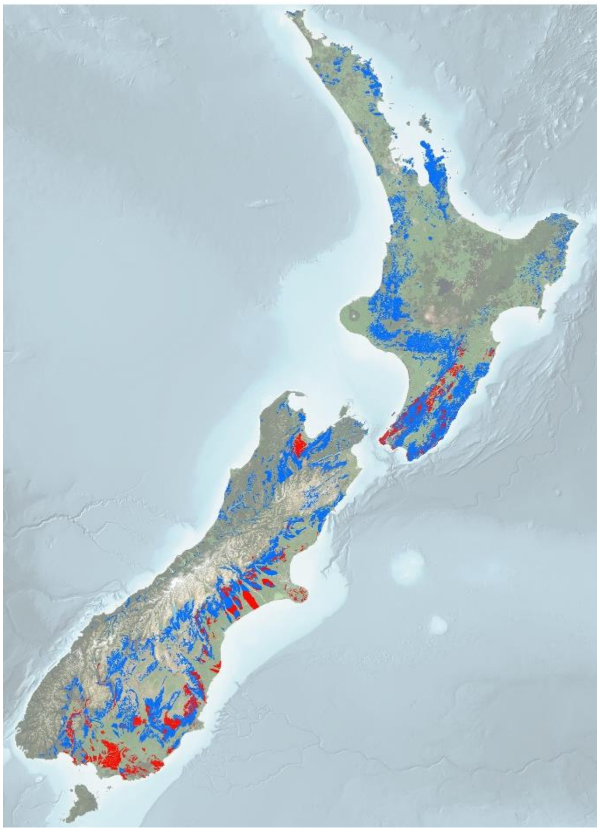

Figure 34: Distribution of firm brown (red) and orthic brown (blue) soil in New Zealand (data from LINZ).

Further Research Opportunities

This study did not measure rutting or deflection however this is a potential area for future research in a trial that includes a loading period. Rutting is a sign of subgrade failure and can severely inhibit the serviceability of a road, therefore measuring this parameter would enable conclusions to be drawn regarding the effectiveness of each method at solving one of the problems observed on historic roads.

Conclusion

Major changes that have occurred in log truck loadings and configurations since last rotation are causing stresses to be imparted on historic roads that they are incapable of sustaining. Distresses including pumping and rutting are manifesting when utilising historic roads in current harvesting operations. To utilise these roads, considerable reconstruction may be required. One New Zealand forest management company is currently implementing undercutting and backfilling method however the high cost of this has led to the exploration of alternatives.

Lime stabilisation and geogrid are two strength improvement techniques that have been utilised previously in new forest road construction. Whilst the research into these in the context of upgrading existing roads is limited they provide viable alternatives for further research. Different levels of improvement can be expected in different soil types, with strength measurement devices such as Clegg Hammers or Dynamic Cone Penetrometers capable of quantifying this.

Although the wet CBR of all methods aside from undercut on Bridgeman Road was lower than pre-trial measurements, prior to a major increase in moisture content the strength of all methods followed an increasing trend. This illustrates the suitability of subgrade stabilisation methods in the niche application of upgrading existing forest roads to cater for higher log truck loads. The negative correlation between soil moisture content and strength illustrates that similar to the construction of new roads, the time of year of road reconstruction should be considered as to how the road will perform under load.

This trial illustrates the effectiveness of the current method of upgrading existing roads in Port Blakely forests, undercut. While the strength of lime stabilisation and undercut was similar the lower cost of undercut makes it a more fit for purpose solution in these locations. Geogrid reinforcement provided inadequate strength in both situations which may have been as it was not loaded therefore its full tensile strength was not mobilised. Therefore, this method warrants further research as its relatively low cost and earthworks volumes make it an attractive option for upgrading historic forest roads.

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Appendix 1 – Materials Calculations

Lime

Diamond Hill Road:

$$Q_{lime} = length \times width \times depth \times \rho_{dry} \times lime\ content$$
$$= 50m \times 3.6m \times 0.15m \times \frac{1.2948g}{cm^3} \times 3\%$$
$$= 1.05\ tonnes$$

Bridgeman Road:

$$Q_{lime} = length \times width \times depth \times \rho_{dry} \times lime\ content$$
$$= 50m \times 4m \times 0.15m \times \frac{1.2889g}{cm^3} \times 3\%$$
$$= 1.16\ tonnes$$

Geogrid

Both sites:

One 75m roll required for each site's 50m trial with some excess to be cut off.

Base Rock

The undercut depth used in calculations is an approximate average required excavation depth based on previous experience in the surrounding area.

Diamond Hill Road:

$$Q_{rock} = Q_{rock,geogrid} + Q_{rock,lime} + Q_{rock,undercut}$$
$$= (length \times width \times depth)_{geogrid} + (length \times width \times depth)_{lime} + (length \times width \times depth)_{undercut}$$
$$= (50m \times 3.6m \times 0.15m)_{geogrid} + (50m \times 3.6m \times 0.25m)_{lime} + (50m \times 3.6m \times 0.3m)_{undercut}$$
$$= 126m^3$$

Bridgeman Road:

$$Q_{rock} = Q_{rock,geogrid} + Q_{rock,lime} + Q_{rock,undercut}$$
$$= (length \times width \times depth)_{geogrid} + (length \times width \times depth)_{lime} + (length \times width \times depth)_{undercut}$$
$$= (50m \times 4m \times 0.15m)_{geogrid} + (50m \times 4m \times 0.25m)_{lime} + (50m \times 4m \times 0.3m)_{undercut}$$
$$= 140m^3$$

Appendix 2 – Contractor Instructions

Day	Tasks	Resources
1	**Whole site:** - Transport geogrid to site - Mark out trial sections - Take pre trial strength measurements - Take pre trial soil samples	- *Waratahs + rammer* - Measuring tape - Ruler - Clegg Hammer - Trowel - Spray paint
2	**Lime:** - Excavate 200mm below existing road surface - Rip below excavated surface to a depth of 150mm - Spread lime onto road with excavator - Add water to mixture and mix again – enough to improve compaction - Grade material - Place 200mm of base rock over lime stabilised layer - Grade and compact **Geogrid:** - Excavate down to 150mm below existing road surface - Suitably place excavated material - Remove rocks sticking 5cm above surface and smooth surface - Position geogrid on subgrade - Hold down corners using rocks - Unroll geogrid over subgrade with two people - Cut additional length of geogrid off - Fill in excavation with base rock - Grade and compact **Excavation:** - Excavate down until hard is reached	- Geogrid - 2 people - Wire cutters - *Excavator* - Base rock for all sections - *Smoke chaser filled with water* - *Roller* - *Grader*