Investigation of sub-grade stabilisation in the Bay of Plenty and Waikato region

Tane Purcell

26503487

19/10/2022

Abstract

Forest roads are an integral part of New Zealand plantation forests, and the network continues to expand. Forest roads are a substantial cost to forest owners in terms of both construction and maintenance. With more forests being harvested on marginal land and further away from established quarries, road costs will increase drastically. This report aims to evaluate stabilising options that can reduce roading costs by requiring less aggregate.

Stabilising the subgrade is a recognised method to reduce aggregate depth. This can be done through either physical or chemical means. This study focuses on chemical stabilisers including PolyCom, Burnt lime and Portland cement. These stabilisers were applied on two forest roads. The first road was a spur road situated in Omataroa, an Eastern Bay of Plenty forest. The second road was an access road that passes through pastoral land in Waerenga, situated in the Waikato region. The stabilisers were applied in 50m trial sections and the study period was from the 27th of June to the 8th of September. There were six trial sites in total with sites numbered 1-3 in Omataroa and 4-6 in Waerenga. PolyCom was applied at site 1 and 4, Lime was applied at site 2 and 5, and lime & cement was applied at sites 3 and 6.

Chemical stabilisers behave differently depending on their surrounding soil type and environment. Therefore, in-situ soil tests were conducted. In Omataroa the soil was classified as a yellow and brown pumice with high organic content still on the road surface. In Waerenga the soil was classified as clay loam with two distinctive clay colours these being reddish/orange and grey. Rainfall was also recorded over the curing month (June – August). It was found that for both forests the rainfall was higher than historic data for June and July. In Omataroa the rainfall was double and triple the historic data for June and July, respectively.

Pre-stabilisation and stabilised soil strength tests were conducted at each site. With 12 test positions in each site. The strength was tested using a Clegg Hammer and an inferred CBR (California Bearing Ratio) value was determined. An average CBR was calculated for each site to show the strength difference between the stabilised soil and un-stabilised soil. For Omataroa it was found that the PolyCom site had an increase in average CBR from 15 to 21, the Burnt Lime site decreased from 23 - 14 and the Burnt Lime & Portland Cement increased from 30 to 37. In Waerenga the PolyCom increased the average CBR from 9 to 28, both the Burnt Lime and Burnt Lime & Portland Cement stabiliser did not change the strength of the soil after stabilisation. They stayed the same with an average CBR of 6 and 8, respectively.

In terms of cost this study found it was cheaper to apply more aggregate than to introduce stabilisers. This was based on applying an aggregate depth until the road CBR was greater than 30 and was based on the AUSTROADS diagram. A break-even analysis based on the Waerenga PolyCom results showed that if more than 420mm of aggregate was needed then it would be cheaper to apply the PolyCom stabiliser. With increased aggregate prices it would be cheaper to apply a stabiliser for lower aggregate depths.

Table of Contents

Introduction

Subgrade strength is recognised as a large factor contributing to the success of an effective road. A recognised option for improving the quality and strength of subgrade soils is to stabilise them. This is through chemical or physical means. This study focuses on chemical stabilisers such as lime, cement, and polymers. Lime has been used in clay soils as a stabiliser for thousands of years. Polymer-based stabilisers such as PolyCom used in this study are new to the market, so this study is an effective way to compare the two products.

The main purpose of chemical stabilisation is to improve the material properties of the sub-grade and/or aggregate layers. Stabilisation can reduce the aggregate required or allow the low quality of aggregate to be used, it can reduce maintenance and can modify materials to overcome their deficiencies, creating a layer within the road with increased strength and rigidity. These factors lead to a lower overall roading cost.

Testing was completed in two forests managed by Rayonier Matariki Forest (RMF). They were based in the Eastern Bay of Plenty and Waikato regions. To complete the trial Seamus Bardoul the Tauranga-based harvest planner organised roading crews for both forests and introduced an expert in soil stabilisation. The trial period was from the 27th of June to the 8th of September. This gives the stabilisers plenty of time to cure.

The objective of this study was to investigate the performance of stabilised subgrade in terms of strength and cost. With this information, a recommendation was made on the stabiliser that would be best suited for the forests and those with similar attributes.

Literature review

Forest road construction in New Zealand

Unsealed flexible pavements are the common roads found in forests around New Zealand. The unsealed flexible pavement allows the loads from heavy vehicles such as loaded log trucks to disperse their load into the subgrade at levels it can bear. When the subgrade strength has been determined a depth of aggregate can be calculated. depending on the strength of the subgrade more aggregate may be needed to disperse the loads as the subgrade is often too weak to support the axle loads. An alternative to applying more aggregate is to increase the strength of the subgrade which is investigated in this study. The image below shows the common pavement layers found in New Zealand Forest roads.

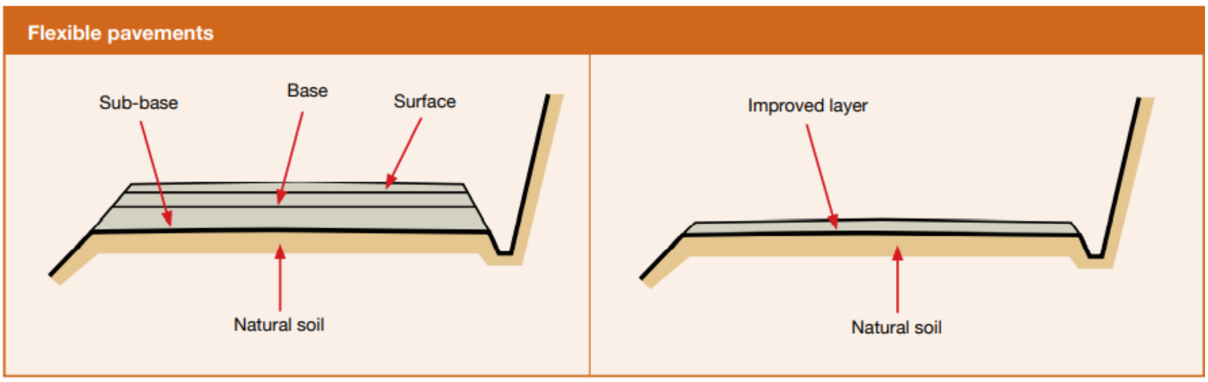

Figure 1: pavement layers described by the NZ Forest Road Engineering Manual

The surface layers (Running course) role is to provide low permeability with a smooth surface to reduce ravelling and scouring. It is usually only found on steep adverse grades where a good surface is needed. The common aggregate size used is an AP20 meaning the aggregate particles are less than 20mm in length. The bases' role is to withstand the highest loading stresses and then distribute the load to the lower levels. Therefore, the base aggregate should have high crushing strength and many broken faces. The size of aggregate used as a base course is typically an AP65. In some areas of New Zealand forest companies do not have access to correct sized and quality aggregates and often spend copious amounts of money getting them delivered.

Currently, chemical stabilisers are rarely used in New Zealand. However, with the potential increase in roading cost due to poor subgrade strength in marginal land forests and aggregate sources being further away. There is an opportunity for stabilisers to increase subgrade strength and therefore lower the depth of aggregate required to withstand axle loads placed upon them. This is the reason there is an interest to conduct this study.

Soil stabilisation

Soil stabilisation is the alteration of soil properties through chemical or physical means, enhancing the engineering quality of the soil. The qualities that are being enhanced include the soil's bearing capacity, resistance to water and permeability. The reason for soil stabilisation is due to the importance of the subgrade strength as it is a large factor in creating an effective road. It can reduce costs in terms of cutting out soft spots, carting better material and use of less aggregate.

Forestry roads around New Zealand have high levels of silts and clays, their properties cause them to swell and become plastic in the presence of water, shrink when wet and expand due to frost. There are many methods to counter these problems including adding more aggregate, carting away poor soils, applying a poly sheet, or strengthening the soil through chemical stabilisation. The latter option is what is investigated in this study, using Burnt lime, Portland cement and PolyCom.

Lime stabilisation

For adequate results chemical stabilisers must be applied in the correct soil type and have sufficient water present. When lime is mixed into a soil with the correct measurements, the pH of the soil quickly increases to above 10.5, thus enabling the clay minerals to break down. The breakdown process releases silica and alumina, these then react with the calcium in the lime to create calcium- silicate-hydrates (CSH) and calcium-aluminate-hydrates (CAH). These form a matrix, that has equivalent properties to Portland cement. It turns the soil from a sandy, granular material to a hard, impermeable layer with significant load-bearing capacity (Taha Jawad et al., 2014).

There are two-time frames that which lime stabilisation is effective, these being immediate and long term. The immediate effects can be seen as the increase in soil workability and a slight increase in bearing capacity, factors that lead to this are:

- Reduction in soil plasticity index
- Maximum dry density drops
- Optimal water content rises
- Easier to compact due to the factors above
- Improvement in bearing capacity

It is found that in most cases after two hours the treated soil will show a CBR value that is 4 to 10 times higher than the untreated soil (Taha Jawad et al., 2014). However, most of the strength durability and compressibility of the soil are associated with the long-term treatment (Efthymiou, 1996).

There has been extensive research on lime stabilisation for soils. The following study investigates alternative stabilisation methods for forest roads, the study investigates lime, lime + NaCl, cement and fly ash. For testing they gathered 10kg of soil samples for lab testing, the soil types found were clay soils (CL, CH), loam soils (ML), sandy clay to sandy loam soils (SC – CL) and sandy loam soils (GL – CL). They state that lime is the most effective when used in granular materials and lean clays, also 5 to 10 per cent by weight is required to stabilise most soils (Efthymiou, 1996). The results from their soil tests can be seen in *Figure 2.*

Soil type	W_L	I_p	Lime content %	Optimum dry density γd Kg/m³	Optimum Moisture W %	Compressive strength Kg/cm²	
						7 days	28 days
1.CL	35	17	0	1750	15		
	33	14	4	1720	16.2	7.2	7.8
	32	12	6	1670	17.1	7.6	7.6
	32	12	8	1680	18	8	9
2. SL-CL	27.1	9	0	1860	14		
	28	9	4	1720	15.2	8	9.2
	28.2	9.2	6	1600	17	8.5	9.7
	29	10	8	1510	18	9	10
3. ML	24	3.2	0	1790	14.5		
	25	3.5	4	1720	1407	7	8
	26	3.6	6	1650	16.9	7.5	8.5
	26.1	4	8	1600	18	8.2	9
4. CL	40	21	0	1760	16.8		
	39	15	4	1680	17.6	6.8	9.5
	38	14.5	6	1600	18.2	8	10.2
	38	13	8	1580	19	8.9	12
5. CH	51	18	0	1500	23		
	47	15	3	1440	25	5.2	10
	46	14	5	1430	27	7.5	11
	40	8	7	1410	31	8	13
6. CH	62	39	0	1600	21.5	1.4	1.7
	57	30	3	1480	25.1	1.6	3.4
	56	20	6	1430	25.5	1.9	4
	56	18.5	9	1420	26.5	2.3	4.8
7. CL	35	20.8	0	1860	14.8		
	39	16	3	1730	18.5	2.6	4.5
	41	17	5	1690	19.7	4.4	6.2
	41	16.5	8	1660	20.2	4.8	7.5

Figure 2: soils treated with varying lime contents

The results are expressed in terms of the liquid limit (WL), plasticity index (IP), lime content, optimum dry density, optimum moisture content and compressive strength on days 7 and 28. With the liquid limit being defined as the water content where the soil starts to behave as a liquid (Rajapakse, 2016) and the plasticity index being defined as the difference between the liquid and plastic limits of the soil, this represents the range of water content over which the soil is plastic (Dhir, 2017).

The results from this research found that plastic soils can be successfully improved after stabilisation with lime and are stabilised well with 6 – 8% by weight of soil. The improvements that can be found in *Figure 1* include improvement of the optimum moisture content, decrease of the dry density, increase in compressive strength and plasticity index decrease.

A decrease in IP enables the clay soil to have a rapid increase in processing ability, while the soil stability limits are improved. Which are important properties as they contribute to maintaining the strength of the soil, its volume under the influence of water and frost and traffic loads to acceptable limits. Finally, the additions of fly ash and NaCl saw improvements in strength values and stabilisation costs respectively but overall did not make significant differences.

A final study investigates the possibility of adding pumice into the lime and clay mix, this I thought was important as it has been mentioned that the forest has high pumice contents. The study focuses on stabilised expansive soil using pumice mixed with lime for subgrade road construction. It was found that if the percent content of lime increased so did the CBR but if the content of lime decreased with an increasing pumice content the CBR value only had a slight increase. With this, they recommended a 7% lime and 3% pumice mixture to stabilise clay soil (Mesfun et al., 2019).

From these studies, it is evident that lime works as a good stabiliser for clay soils which is found in many NZ forests. A precaution found in the studies is that lime has minimal impact on organic soils, high sulphate soils and soils with low clay content (Inc, 2020).

Cement stabilisation

Cement is another common stabiliser used around the world for subgrade improvement. When mixed in soil it creates cementitious hydrates, which increases cohesion between soil particles, acting as a glue that joins particles together forming a stronger mass (Inc, 2020). It is often mixed with lime, slag, or bitumen as it makes the application process more workable, reduces the likelihood of cracking and reduces the cost of using large amounts of cement. Unlike lime stabilisation, cement cannot be reworked following initial mixing and there is only a limited time before setting occurs.

Improvements in soil properties that cement brings include a decrease in density and liquid limit, and an increase in plastic limit with a corresponding decrease in the plasticity index (IP). The increase in plastic limit is accompanied by a corresponding increase in optimum moisture content (Efthymiou, 1996). The study by (Efthymiou, 1996) also investigated the performance of cement in silty loam and clay soils. The results can be seen in *Figure 3* below.

Soil type	Cement content %	Compressive strength Kg/cm^2	
		7 days	28 days
1. SC-CL	5 7 9	16 22 27	19 24 32
2. GC-CL	5 7 9	22 25 30	26 28 34
GC-CL	5 7 9	27 29 33	31 38 49
4. SC-CL	5 7 9	20 27 32	26 36 47
	5	21	27

Figure 3: Concrete stabilisation of silty loam and clay soils

The figure shows that there is an increase in compressive strength with respect to lime stabilisation and un-stabilised soils. It was also stated that the optimum addition of cement ranges at 7% because at higher percentages the construction would become too expensive.

To combat the problem of cement workability and increase the compressive strength of the soil through lime treatment an approach that involves mixing the two has been implemented around the world and is a recommendation in the road engineering manual. A study by Khemissa and Mahamedi on cement and lime mixture stabilisation of clay provides an extensive number of results on the matter. They tested the clay for its CBR in both soaked and unsoaked conditions. An unsoaked test is conducted to simulate what would happen to the soil if it were exposed to 7 days of rain (Bhandakkar, 2020), which can be helpful knowing when constructing forestry roads as this can sometimes happen. They tested a range of mixtures, and it was found that the best result obtained was a mixture of 2% cement and 10% lime for soaked CBR and 8% cement and 4% lime for un-soaked CBR (Mahamedi, 2014). *Figure 4* below shows the testing results of the soaked and unsoaked CBR testing.

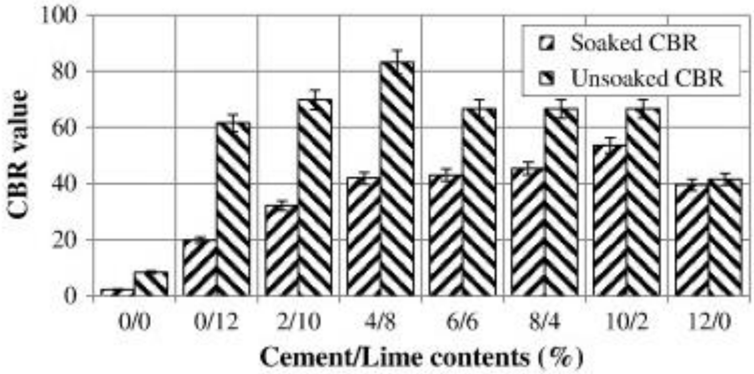

Figure 4: Soaked and unsoaked CBR testing

They also tested for linear swelling with the same ratios, the following results were found.

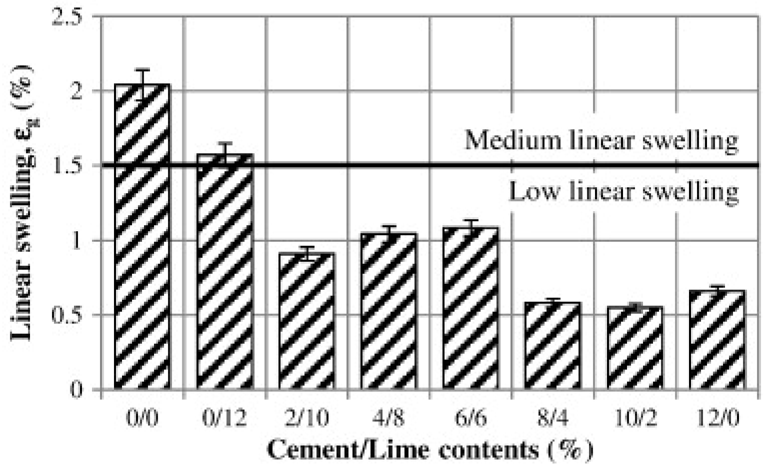

Figure 5: linear swelling

The results show that for a clay soil the optimum mixture would be 10% cement and 2 percent lime, with 8% and 4% being close by. They concluded from their studies on high plastic clay that a mixture treatment leads to a decreased plasticity index, increased soaked and unsoaked CBR values and an increase in the shear strength of the clay. It was determined through the different testing that the best performance came from a mixture of 8% cement and 4% lime (Mahamedi, 2014).

PolyCom stabilisation

The final stabilisation method proposed for testing was PolyCom. It is a polymer-based additive that improves the strength and durability of a range of soil types. Polymers are substances composed of monomers, which are held together by covalent bonds, they come in two forms natural and synthetic. In general, PolyCom provides physical bonding between soil particles rather than introducing a chemical reaction to stabilise the soil like lime. PolyCom has been growing in popularity due to it being able to increase the strength of the soil, decrease its permeability, and has the possibility of reducing maintenance and transport costs (Georgees et al., 2015).

Two studies were found that used a synthetic polyacrylamide (PAM) called PolyCom. The first study conducted by M. Padmavathi discovered that after Polycom application the strength of the clay soil almost doubled the in-situ soil strength in very little curing time.

It was also found that longer curing times lead to increased unconfined compression test (UCS) values, but they had not yet discovered the optimum curing time. Finally, they found that both the cohesion and angle of internal friction increased for Polycom treated clay and sand samples, thus increasing the soil's shearing strength (Padmavathi, 2021). The second study which was conducted in Australia also went into depth on why Polymeric stabilising was a good option compared to the traditional methods. They tested three soils with one being a clay soil, it was found that the use of PAM increased the dry density and that soils with a greater fines content recorded the greatest increase in dry density. All the soils produced increased UCS values with the greatest increases found when the compaction was greater than 35 blows per layer. The UCS increases had a range of 22.9% to 95.2% when compared with the untreated samples (Georgees et al., 2015).

Measuring Sub-base strength In-situ

There are many ways to test for soil strength in the field but for this study a Clegg Hammer was used. This was done because it was available for hire, and it provide accurate and fast soil strength tests. It was first developed by Dr Baden Clegg in the 1970s and has been used around the world since. It measures the deceleration of a hammer free-falling onto the surface of the soil. Four successive blows of the hammer on the same spot constitute one test (Clegg, n.d.). The speed and ease of use enable many tests to be performed over a wide area and as many as 250 tests can be performed in half a day (Ground test equipment, n.d.). A photo of a Clegg hammer can be seen below in *Figure 6*.

Figure 6: Clegg hammer

The reading that the CH provides is an Impact Value (IV) and to convert it into an inferred CBR value the following equation was used $CBR = 0.07 * IV^2$.

Objectives

The objective of this project was to investigate the performance of chemical stabilisers in subgrade soil. With the performance based on the strength increase and cost benefits. The study was conducted on two forest roads with different weather and soil conditions/properties. This allowed the stabilisers performance to be analysed in different conditions. The final goal of the project was to provide a recommendation on what stabiliser to use in certain conditions.

With the potential for road costs to increase immensely in certain areas of New Zealand this project could provide alternatives to purchasing more aggregate. Therefore, lowering costs in specific areas.

Methodology

Road locations

Testing occurred in two forests in the Bay of Plenty and Waikato regions, the first forest being Omataroa and the second being Waerenga. Their locations can be seen below in *Figure 7*. These forests were tested for soil strength on the 27th of June and 6th of July with a Clegg Hammer supplied from Geotechnics Tauranga.

Figure 7: location of forests

Tests were taken in plots which are shown in *Figure 8*, these were chosen to cover four positions along the 50m treatment section and three across. The across positions were chosen to represent where the logging trucks and Ute's wheel tracks would go through (1.1m from the centre). The positions along the treatment sections were marked out using a range finder and the across positions were done with a tape measure.

There was a total of 6 sites with 1-3 in Omataroa and 4-6 in Waerenga. Both forests were treated so that Polycom was in the first site, lime in the second and a mixture of lime & cement in the third. An example of the treatment set up is shown below in *Figure 8*.

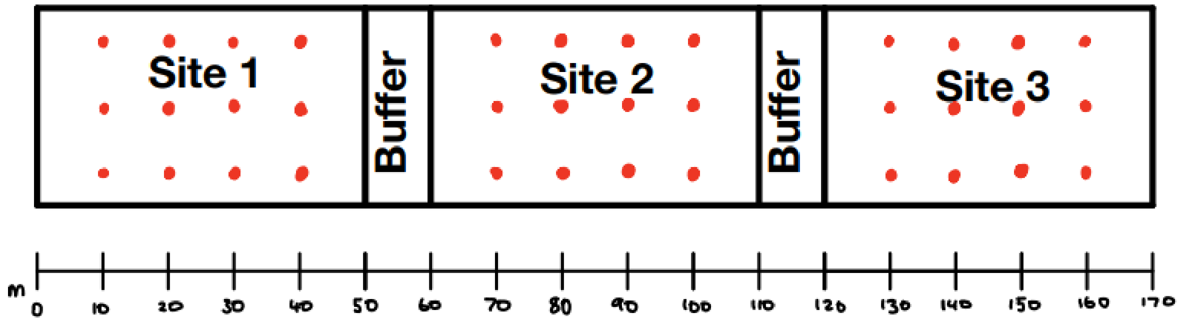

Figure 8: Site diagram

Testing method

A Clegg Hammer (CH) was used to test the subgrade soil for its strength. The first step involved an initial check to make sure the CH was calibrated correctly. Following the steps provided by Geotechnics showed that the CH was calibrated and could be used to accurately measure the strength of the soils in-situ. Calibration tests were repeated at each forest to make sure it was accurate and excess soil was wiped off the end of the hammer after each test so that the next test was not affected.

The process of using the Clegg Hammer involved holding it level, lifting the hammer to a pre-determined height (450mm), and then letting it fall freely to hit the soil surface. This was repeated 4 times at each test point and then the IV was recorded. An example of the Clegg Hammer on a test site can be seen below in *Figure 9*.

Figure 9: Clegg Hammer onsite

Treatment method

To apply the treatments a roading crew and the following equipment was organised. An excavator, grader, roller, water truck and metal truck. All three treatment techniques were in powder/granular form, so they needed to be spread and ripped through to mix in with the subgrade soil layer. Firstly, the Burnt lime and Portland cement was delivered to the forests via a metal truck. Next the rippers on the grader broke up the soil in the treatment areas to a depth of 150mm. This allowing the stabilisers to penetrate the soil and create an improved layer. The PolyCom was spread using an electric seed spreader. The 2kg of PolyCom granules stabilise 50m^3, so 1kg was applied to each forest site. This was less than recommended as there was approx. 30m^3 of soil at each site. The Burnt lime was spread using an excavator as it came in 1.2 tonne sling sacks. An image can be found below in *Figure 10* of how the lime was applied, it was mixed in at a rate of 4%. The Burnt cement came in 40kg bags, and the 38 bags were hand spread every 1 – 1.5m. This gave a mixture rate of 3%. So, the Burnt lime and Portland cement mixture was at 4% and 3% respectively.

Figure 10: Excavator spreading burnt lime

The lime and cement after spreading was clumped together due to the excessive amounts of powdered treatment applied. To spread this eventually throughout the soil, the graders rippers were used again. The grader and water truck worked alternatively so that the stabilisers were mixed into the soil and the water applied allowed them to react. The process of ripping and watering repeated for 4-6 times until all the stabilisers had completely reacted. Images of the grader and water truck working can be seen below in *Figure 11 and 12*.

Figure 11: Grader ripping in the lime/cement mix

Figure 12: Water truck on its last pass

The final stage involved shaping and rolling the road, this was done with the grader and roller to create a crown profile shape. This process was repeated in both forests and these sections of road were not rocked until after post-stabilisation tests were done.

Results

Weather

Roading during winter is always a risk due to the increased chance of rain and this year in many reigons peak rainfall was experienced. Graphs can be found below to show the rainfall in the different forests over the trial period. The rainfall has been displayed to show results from 2022, 2021 and historic data. This way comparisons can be made. *Figure 13* below displays the rainfall for Waerenga.

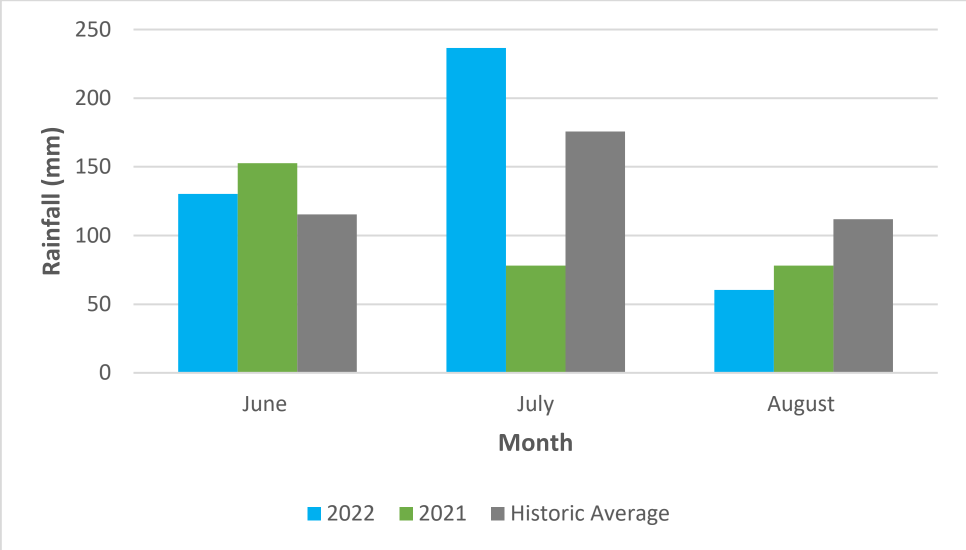

Figure 13: Rainfall in Waerenga region

As seen in the figure there was high rainfall in June and July (higher than the historic average). This meant that the stabilisers could not be applied in the same week as the Omataroa ones. Instead, the stabilisers were applied on the 12th of August, and it was done by the roading crew. The reason they were not applied at the same time was because too much water effects the performance of the stabilisers. The image below shows the state of the road when the pre-stabilisation tests were done. As pictured, there is water in the water tables and the soil is semi saturated. This meant that the machinery could not get up the hill and therefore the stabilisers could not be applied.

Figure 14: Top of Waerenga road (6th July)

The weather conditions Southeast of Waerenga at Omataroa were similar with high levels of rainfall occurring over the winter months. This can be seen below in *Figure 15.*

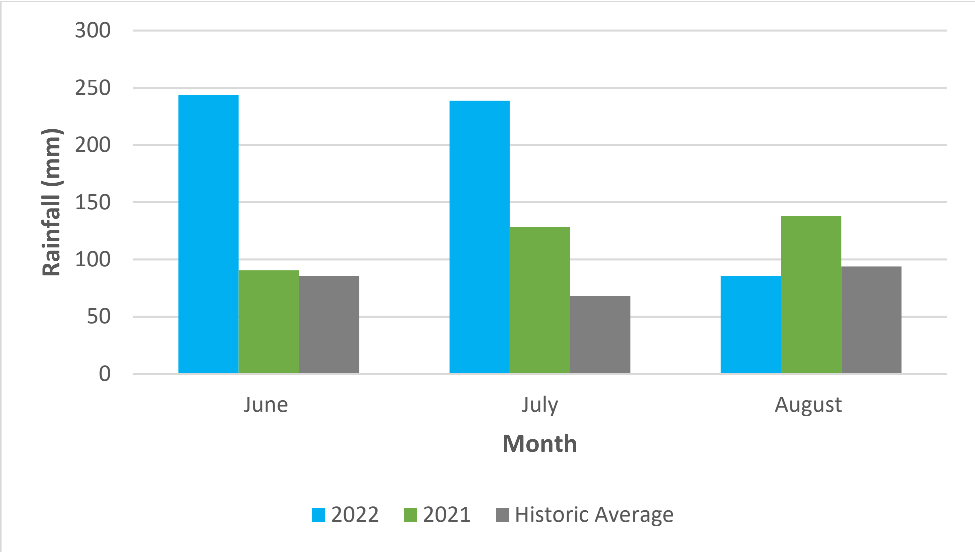

Figure 15: Rainfall in the Whakatane region

As seen in the graph June and July has exceeded the historic averages by enormous amounts. In June 243.6 mm of rain fell this is 2.8 times the historic average and in July 238.6 mm of rain fell this is 3.5 times the historic average for this month. The road is in its second rotation but has had trees on it for the past 24 years and has only been exposed for the last 10 months and during the last 3 months the soil has been exposed to the highest rainfall for many years. The road was treated with Polycom on the 28th and lime and cement on the 4th of July this was due to wet weather and delivery delays. During the days of treatment, the weather was fine and the days to follow had light showers between sun, so the treatments had enough time to react. *Figure 16* shows the day that the road was treated with lime and cement.

Figure 16: Weather on 4th July

The curing times for the two roads are different and as stated above so are the curing times for the lime & cement and Polycom for Omataroa. *Table 3* below expresses the different time variables associated with testing, treatment date and curing time.

Table 3: Dates of pre-testing, treatment, post testing and the curing time

	Pre-Testing	Treatment		Post Testing	Curing time	
		Polycom	Cement & Lime		Polycom	Cement & Lime
Omataroa	27th June	28th June	4th July	8th September	72 days	66 days
Waerenga	6th July	12th August	12th August	8th September	27 days	27 days

The table shows that there is a significant difference in cure times but the roads were both exposed to the weather for similar times and 27 days gives the treatments plenty of time to react with the soil particles.

Another factor affecting the roads performance is day light hours and these vary between roads for many reasons. The Omataroa road is situated in forest, it has a roadline clearing of approx 20m on each side and the road runs in a North to South orientation. Site 3 had the most day light hours due to being at the end of the road which had been opened for the skid, as the day went on the sun made its way down the road but in the short winter days it only just made it to the end of Site 1. Estimates from the day are as follows Site 3 had sun from 9:30am – 4:00pm (6.5 hours), Site 2 had sun from 12:30am – 4pm (3.5 hours) and Site 1 had sun from 2:00am – 4:00pm (2 hours). On *Figure 17* below the sun can be seen hitting Site 3 and through out the day it makes it towards the left hand side of the photo cauing it to shine over Sites 1 and 2.

Figure 17: Photo taken at site 1 at 10:08am

This is a common road within forestry and shows the importance of having the trees removed from the sides of the road. So the maximum amount of sunlight hours can reach the soil to dry and harden it.

A benefit to the road in Waerenga is that it goes through farmland, therefore gets no shading from trees. The road is positioned on an Northeast to Southwest bearing and over the day gets a lot of sunlight (approx. 7 hours). Which was evident with how much the soil had dried out between visits. The photo in *Figure 18* below shows the sun hitting the road at 4:35pm.

Figure 18: Waerenga at 4:35pm (8th September)

Soil type

Another factor influencing the effectiveness of each stabiliser is the soil type and the forests had vastly different soil types. Onsite tests were done, and online mapping tools provided by local councils are shown below to confirm the soils and provide soils near these roads. Onsite tests were done by using a method called the Texture by Feel develop by S.J Thien in 1979, which can be seen in the diagram below.

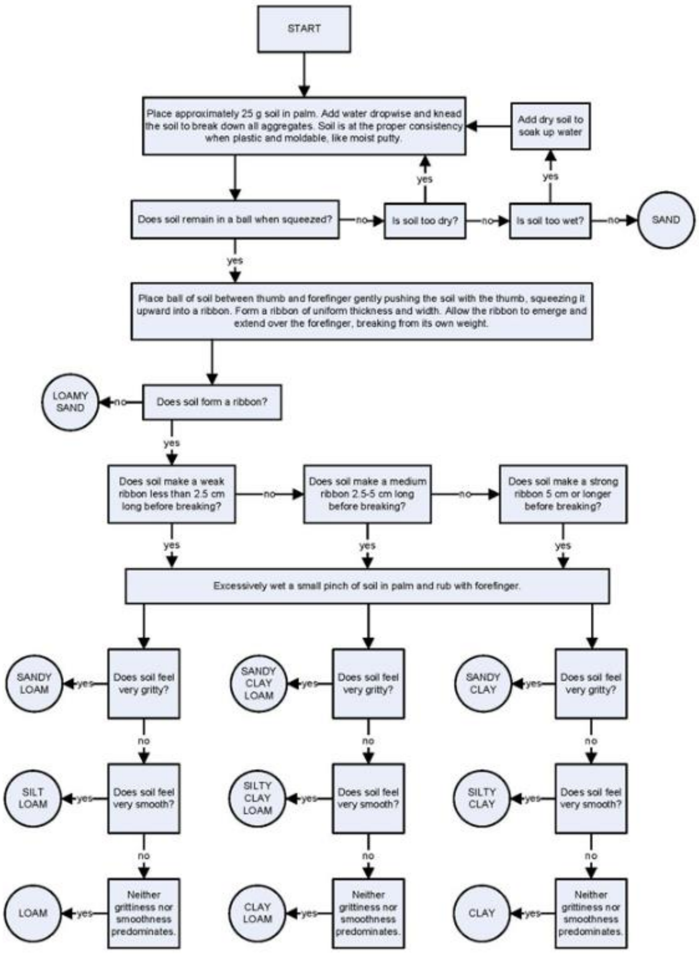

Figure 19: Flow chart to determine soil texture by feel

This chart was followed for both forests and because the soil change in Omataroa was obvious three tests were done. The first test was done on the organic soil and the other two on the yellow-brown soil underneath, photos of these soils can be seen below.

Figure 20: Omataroa soil

Picture 2 shows a soil which fits the discription of a sandy loam clay. This is because it made a ball and a ribbon around 2.5 – 5cm could be formed which felt very gritty. The third photo shows a soil which was classified as a sandy loam. It was like soil 2 but it could only make a small ribbion before it broke. Accoring to the BOP reigonal council soil map which is found below these soils are what are expected in the reigon.

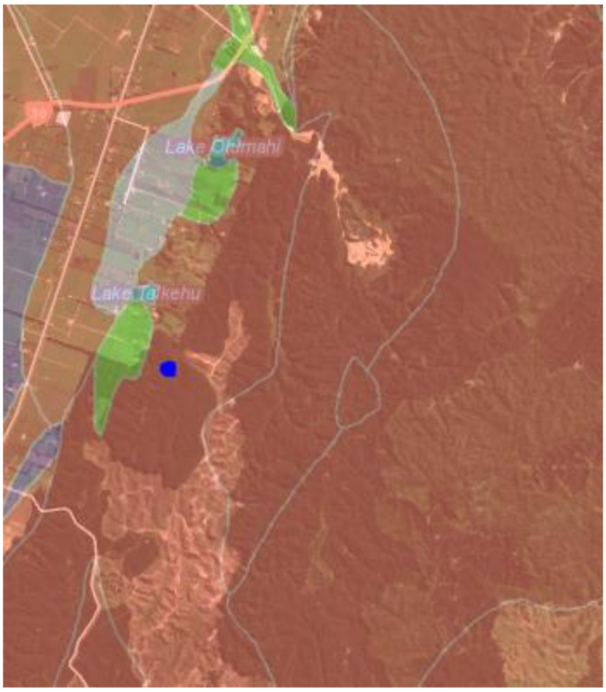

Figure 21: Soil map of the Omataroa forest

The blue dot represents where the road has been constructed, the red shade represents Manawahe hill soils with a NZ genetic class of composite recent soil on yellow and brown pumice soil. This representing the kind of soil found from the onsite tests. The blue shade represents a peaty sand, and the green represents a sandy loam which can also be found in the forest. In addition to these soil types volcanic ash has also been found in the forest.

The soils in Waerenga were classified using the same technique. There were very low amounts of organic soils on this road compared to Omataroa as it had been scrapped off. Visually there was two clay types, one was grey and the other was a reddish/orange colour. These were tested and felt like they had similar texture, so they were classified as a Clay loam. A soil with higher amounts of grains was also tested and it was classified as a sandy clay.

Omataroa

Site 1

Site 1 is situated at the start of the stub road it has a slight inclination of 3% with two soak holes at the start of the road positioned on either side. Like the rest of the road, it has previously been used as a skidder track for the road line crew. The soil type consisted of silts with lesser amounts of organics and sands. The stabilising treatment for this site was PolyCom and the photo below shows the site from its starting point.

Figure 22: Site 1 Stabilised with Polycom

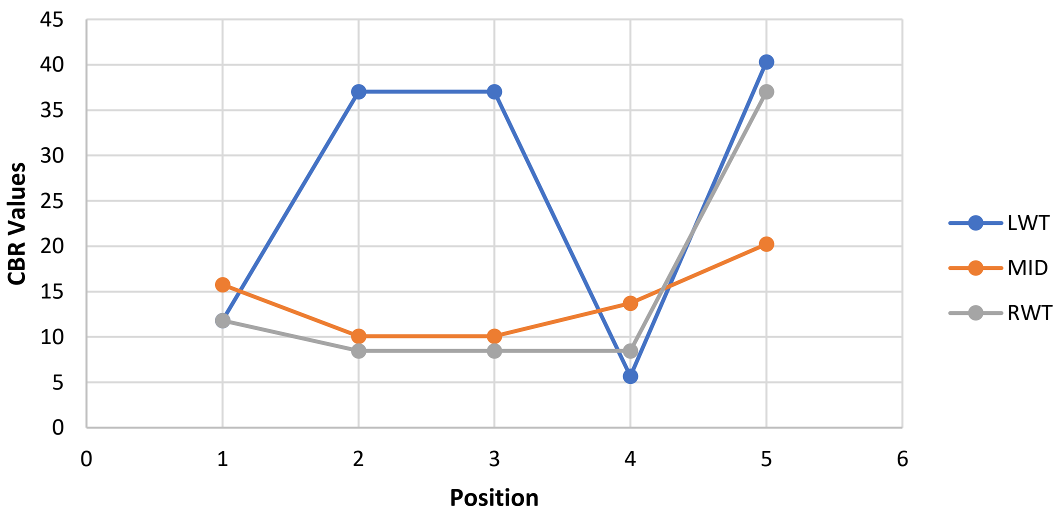

Figure 23: Site 1 Pre-stabilisation

The average CBR for this site was 15 with a Standard Deviation (SD) of 10.7. As shown on the graph the LWT has much higher CBR values for three positions along the site, with the middle and RWT (Right Wheel Track) having similar values from positions 1 – 4. A reason for the lower value for LWT at position 1 and 4 is that they have soak holes positioned near them so the water and loose materials travel through these spots releasing softer soils. Reasons for the higher values in the LWT could be due to the longer sunlight hours on this part of the road and the scattered gravels and rocks found on this Site.

The methodology section outlines that there are 4 treated test positions, so the fifth position found in *Figure 23* represents the buffer zone values. This is the same for Sites 2, 4, 5 and 6. The buffer zone values have also been left out of the CBR and SD calculations.

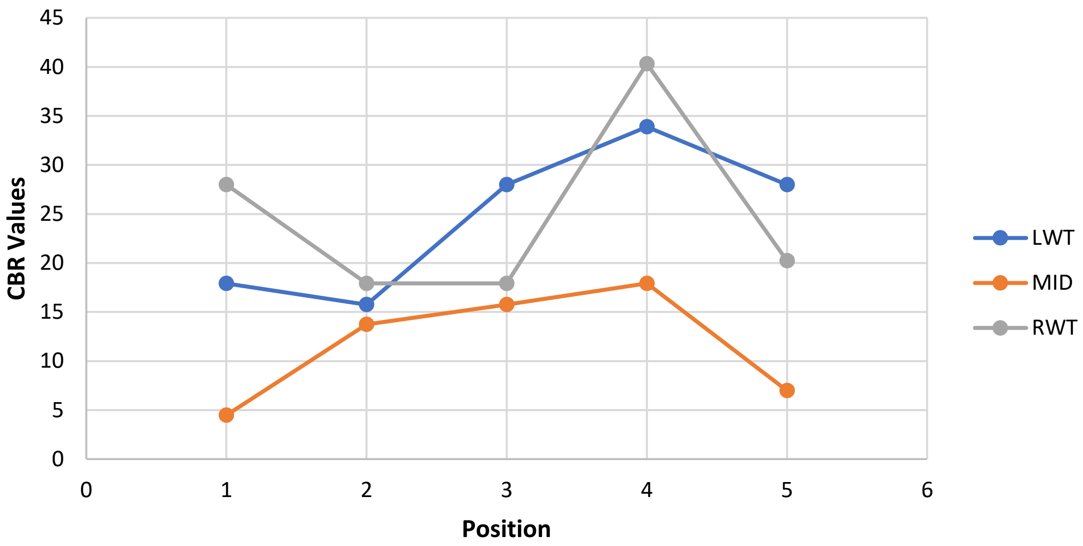

Figure 24: Site 1 post-stabilisation

After treating with Polycom, the CBR increased from 15 to 21 this giving an increase of 6, the SD was determined to be 9.8. It can be seen on the graph that the centre of the road had lower CBR values overall compared to the left and right wheel tracks. The reason for the low value at position 1 in the middle was due to the water running through this test position which deposited sand and other softer soils, a photo of this can be seen below.

Figure 25: water flow through the middle testing site

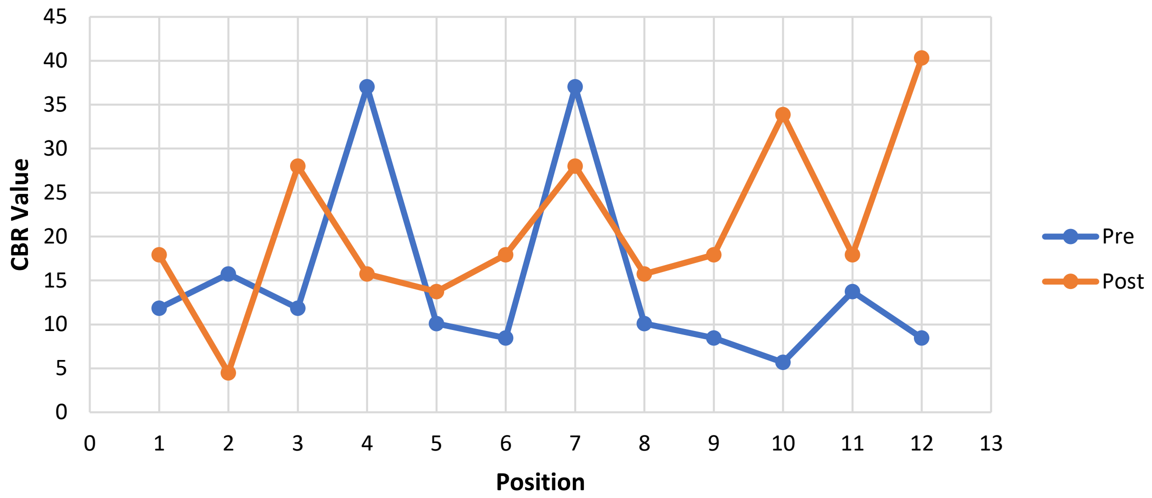

Figure 26: Site 1 pre and post stabilisation using PolyCom

Overall, the graph shows that once the soil was stabilised with PolyCom most of the test spots increase in CBR. There are some outliers within the data which can be explained as being soft spots and places where rocks where present. If the outliers were removed, the pre-treatment CBR values range from 8-15 and the post treatment values vary from 15-20. This shows that the PolyCom has made a noticeable improvement to the soil in terms of strength.

Site 2

Site 2 was treated with Burnt lime. It had a slope of 3% leading upto the 30m mark and then declined at 3% after this. The soil type varied along site with orgainic, sand and small stones making up most of the matter. This site had excessive amounts organic soil between positions 2 and 4 (20m) which can be seen in the photo below.

Figure 27: Site 2 after grater has ripped up the soil

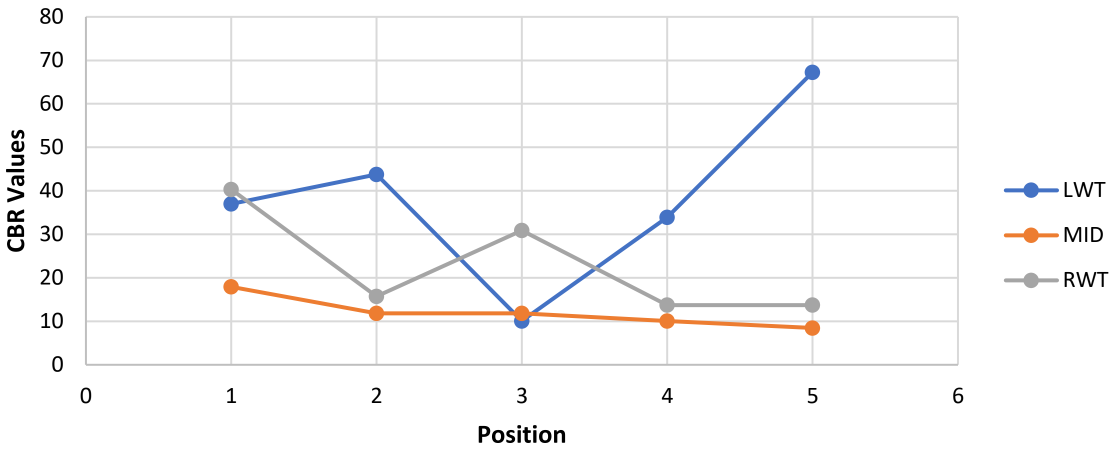

Figure 28: Site 2 pre-stabilisation

The average CBR for Site 2 before stabilisation was 23 with a SD of 12.9, these values are higher than both the pre and post treatment values for site 1. There is a remarkably high CBR value of 67.3 this position received the most sunlight and had high rock content in the soil. It was common to find that the lower values were on soils that were surrounded by sand and organic soil types. These soil types were common along this stretch of road and photos displaying this in positions 1, 3 and 5 can be seen below.

Figure 29: Site 2 variation in soil

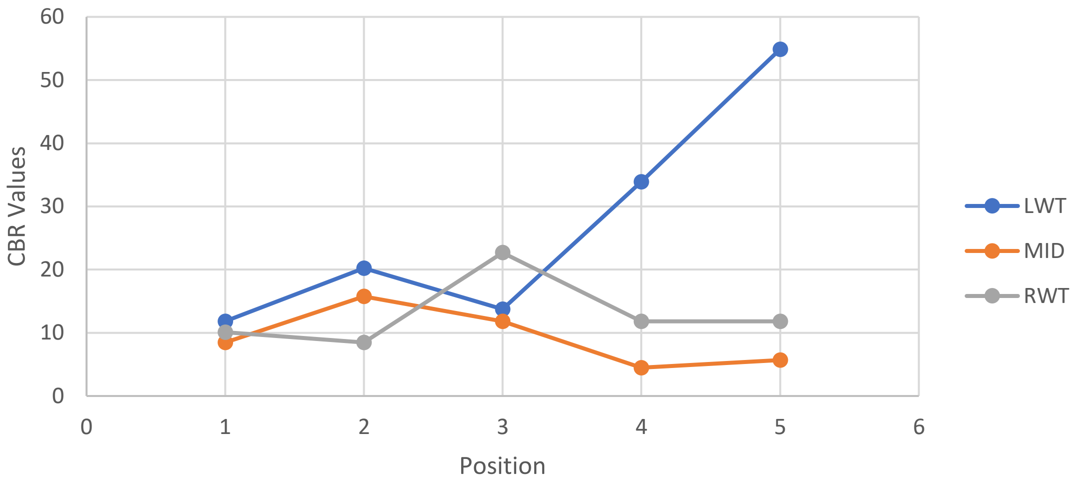

Figure 30: Site 2 post-stabilisation using burnt lime

The average CBR post stabilisation was determined to be 14 with a standard deviation of 7.9. This meaning the CBR decreased by 9 after stabilisation. The CBR ranges from 5 – 22 for most of the values, with 2 values above 30. This leading to the site having a lower SD after treatment. The photo below shows a section of the site after treatment. It is evident that there is substantial amounts organic soil present and there is a high amount in the centre which looks like it has not had as much compression with the roller in comparison to pre-stabilisation tests. This demonstrates the importance of getting the physical stabilisation factors correct.

Figure 31: Site 2 post-treatment

This photo shows the test results from position 4, comparing it with the results in *Figure 31* the high value found in the LWT has come from the part of the road which has become hard after reaction and the low value in the centre and RWT has come from the poor compaction and high organic matter. The photo also shows residue lime on the surface of the road, which has not reacted with the soil.

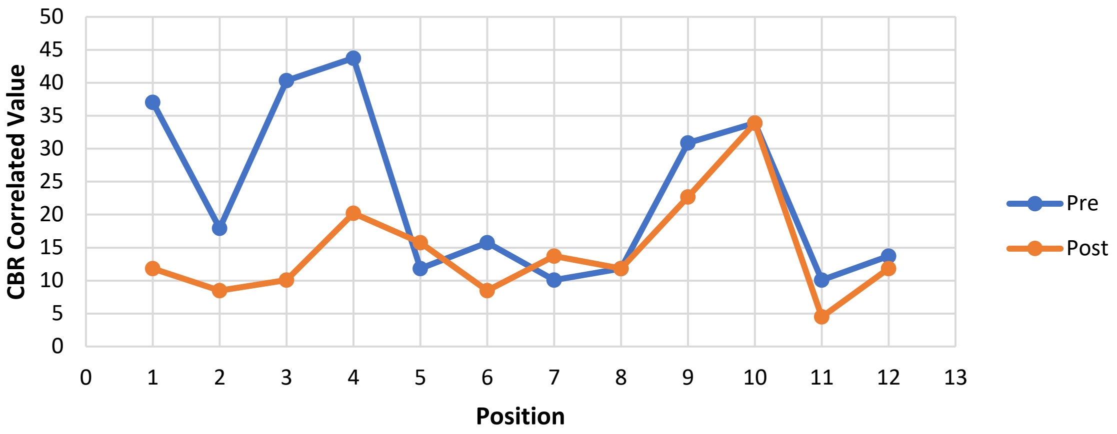

Figure 32: Site 2 pre and post stabilisation values

As seen on the graph the post treatment results are less than the pre-treatment for most cases. The lime has made no improvement to the soil and ripping up the soil has distributed the bonds between soil particles causing a lower CBR value. This can also be credited to the poor compaction from the roller in this section. The fact that lime was not effective on this site could be due to many reasons such as high organic and low clay contents, high rainfall over the winter months, treatment technique and/or not enough sunlight hours.

Site 3

Site 3 is the last section which was tested on the Omataroa stub road. It was treated with a mixture of Burnt lime and Portland cement. This section had a slope of 11% which runs down to the skid. It gets the most sun hours compared to the other sites in this forest and has water controls at the 20m and 30m positions. A photo of the site can be seen below along with the pre-stabilisation results.

Figure 33: Site 3 before treatment

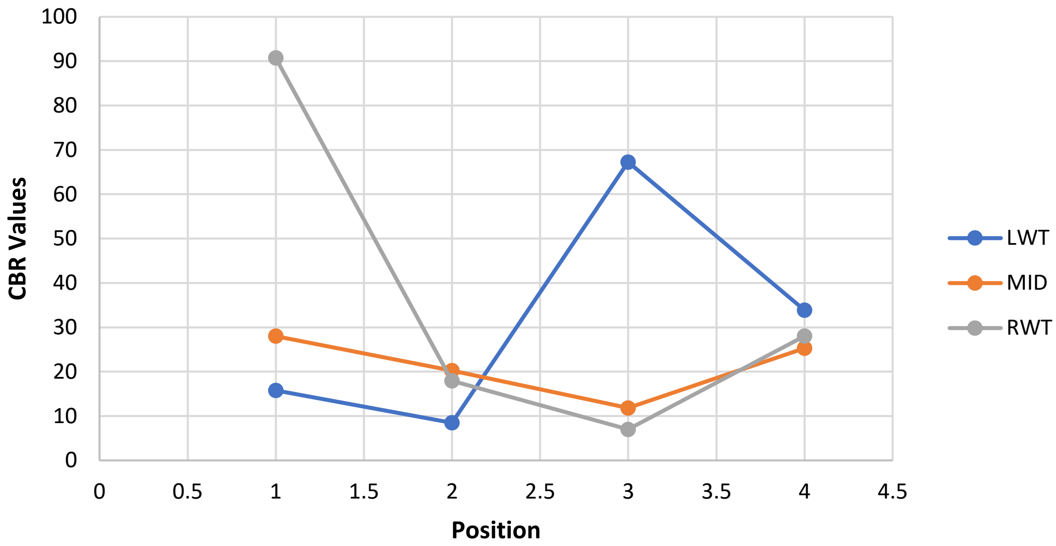

Figure 34: Site 3 Pre-stabilisation

This site had the highest pre-stabilisation average CBR value, which was determined to be 30 with a standard deviation of 25. Underfoot the soil was noticeably harder than the other sites which felt due to the increased day light hours and rock content. It still however had soft spots where the sand and organic matter were evident. These factors lead to the SD being high which represented the high variability on this site.

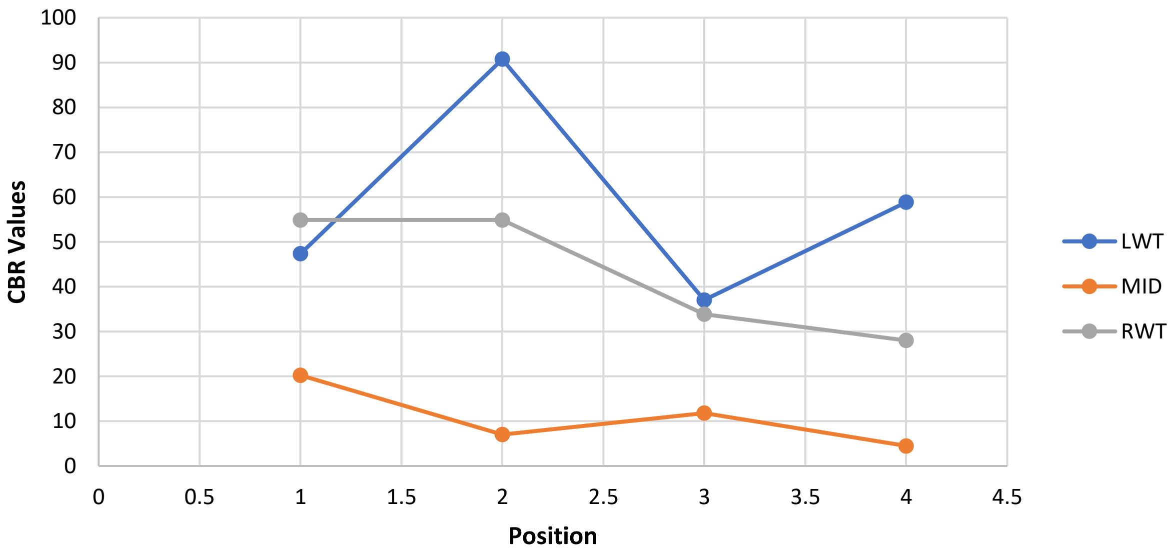

Figure 35: Site 3 post-stabilisation using lime & cement

After stabilisation, the average CBR increased from 30 to 37 and the standard deviation stayed the same (25). CBR values found in the LWT and RWT were like the values tested on the main road. The poor values expressed in the centre of the road can be explained through the lack of compaction which can be seen in the photo below. Another contribution to this would be the high organic content found in the centre of the road which does not react well with both the lime and cement.

Figure 36: Site 3 position 3

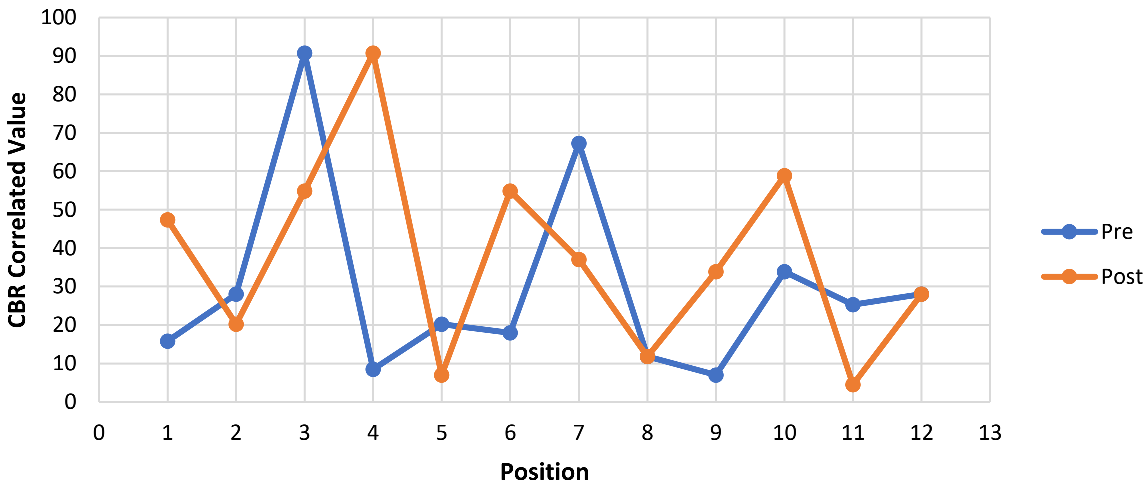

Figure 37: Site 3 pre and post stabilisation values

As seen in the graph both the pre and post stabilisation tests have huge variation in CBR values, this showing that even though a high CBR can be achieved there are still many areas that have low CBR values which represent soils that have not been stabilised. The addition of concrete has improved the strength of the soil, but the benefit of lime is unknown due to having poor results in Site 2.

Waerenga

Site 4

Site 4 was situated at the top of the entrance road which had a gradient of 11%. This road had previously been used as a farm track but has been widened to accommodate forest machinery. The soil consisted of clay, silts, and gravels/stones. Like Site 1 in Omataroa this section was treated with

PolyCom. The photo below was taken during the day of pre-stabilisation testing and shows that rain had semi saturated the soil.

Figure 38: Site 4 Waerenga

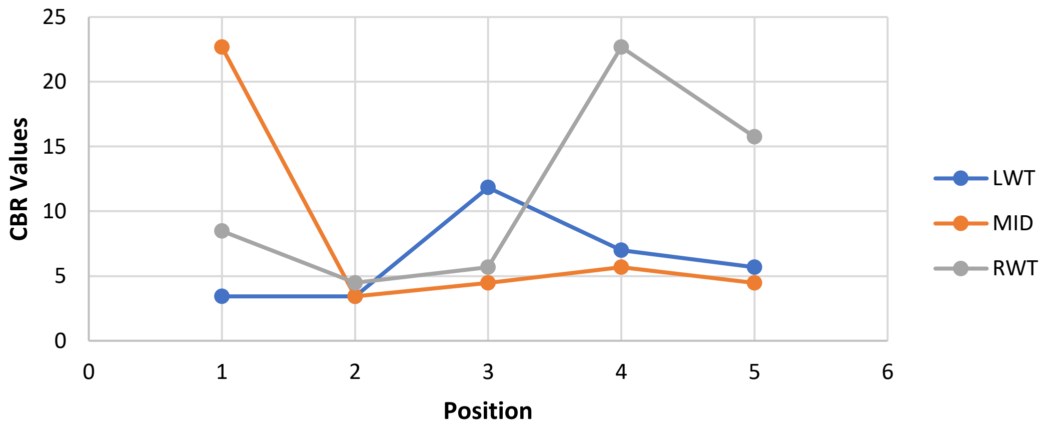

Figure 39: Site 4 pre-stabilisation results

This site had an average CBR of 9 with a SD of 7. In comparison to Omataroa the CBR of this soil is much lower which could be due to having a higher moisture content, more clay and only being used a farm track previously. Most of the data on this site varies between 3 and 11, with 3 outliers which could be due to the rock content in patches of the road. Photos of positions 1, 2 and 3 are displayed below to show the variation in soil types along this site.

Figure 40: Site 4 at positions 1,2 and 3

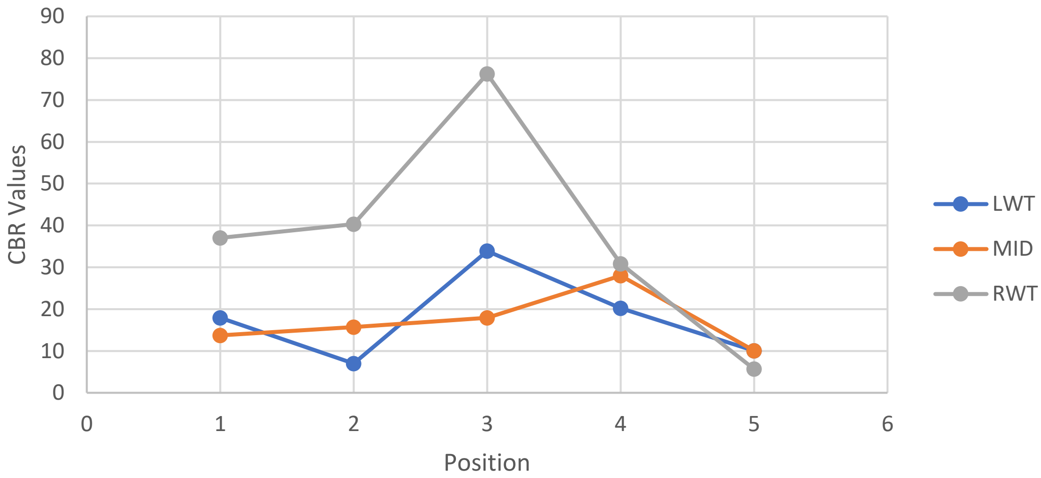

Figure 41: Site 4 post- stabilisation results

The average CBR for this site after treating with PolyCom was determined to be 28, this value has increased by 19. The standard deviation value was 18, this showing that even though there was a significant increase in CBR that the site still had many spots that were low in strength. The graph shows that these values range from 10 – 35, which is a good range increase compared to the pre-stabilisation values.

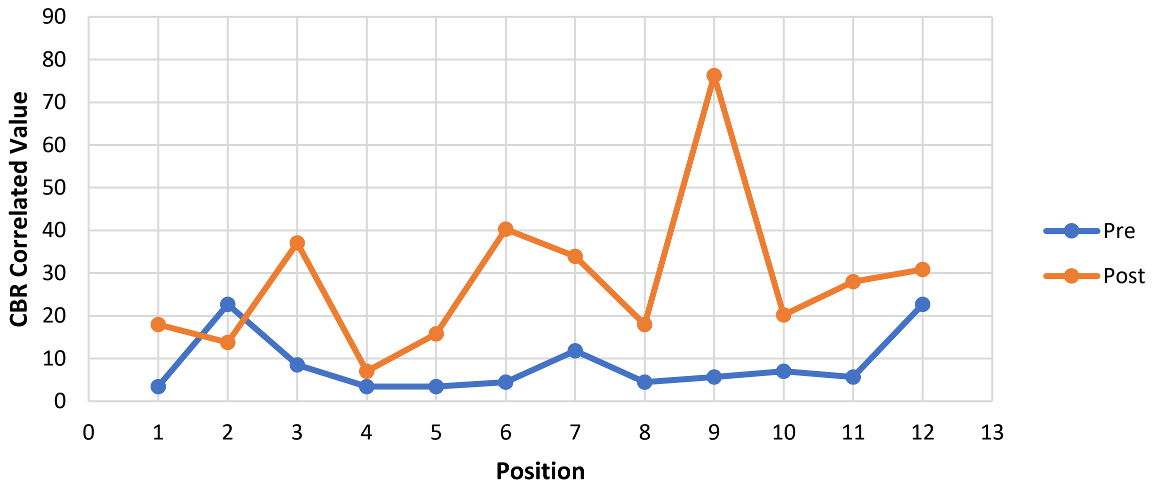

Figure 42: Site 4 pre and post stabilisation values

This graph shows that all positions but 1 has increased after being treated with PolyCom which is a great outcome, and it can be said that the PolyCom can be used as a suitable stabiliser for this site. This graph also shows that most of the test positions have increased in CBR by at least 8, with some sections increasing by larger amounts.

Site 5

Site 5 is situated in the middle section of the Waerenga road and was treated with Burnt lime. The road has a gradient of 11% with water runoffs on both sides of the road. The soils were like those in site 4 and on the day of pre-testing these soils were also semi-saturated. In contrast, on the day of post-stabilisation the soils were dry and had been baked. The site can be seen below in *Figure 33*, with the pre-stabilisation on the left and post-stabilisation on the right

Figure 43: pre and post stabilisation photos of Site 5

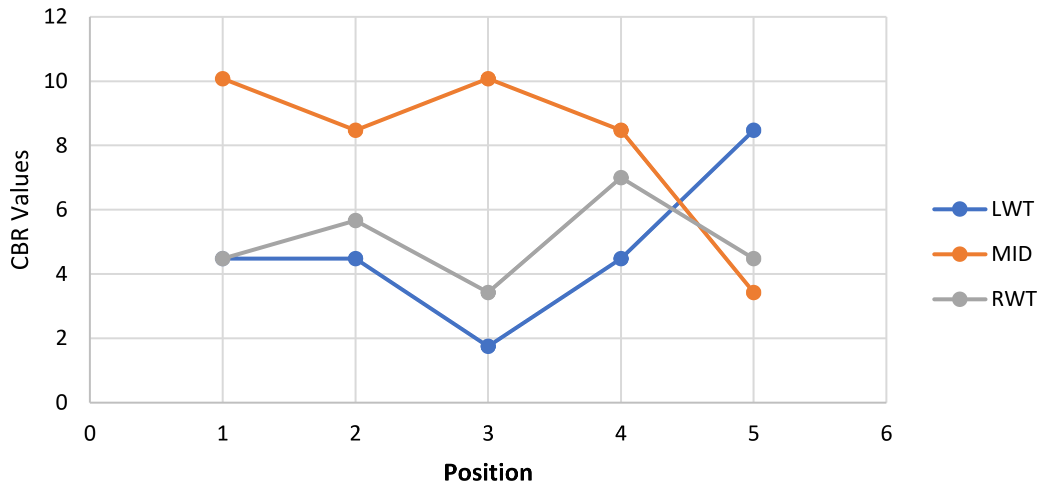

Figure 44: Site 5 pre-stabilisation results

The average CBR was determined to be 6 with a SD of 2.7. The data shows low values which range between 1.75 and 10. These values can be expected as the soil was previously exposed and has become wet instead of dry due to the weather. The graph shows that the harder surface was found in the middle of the road and lower values in both wheel tracks. This was due to the higher rock content in the middle which was noted in testing. The post-treatment results can be found below in *Figure 45.*

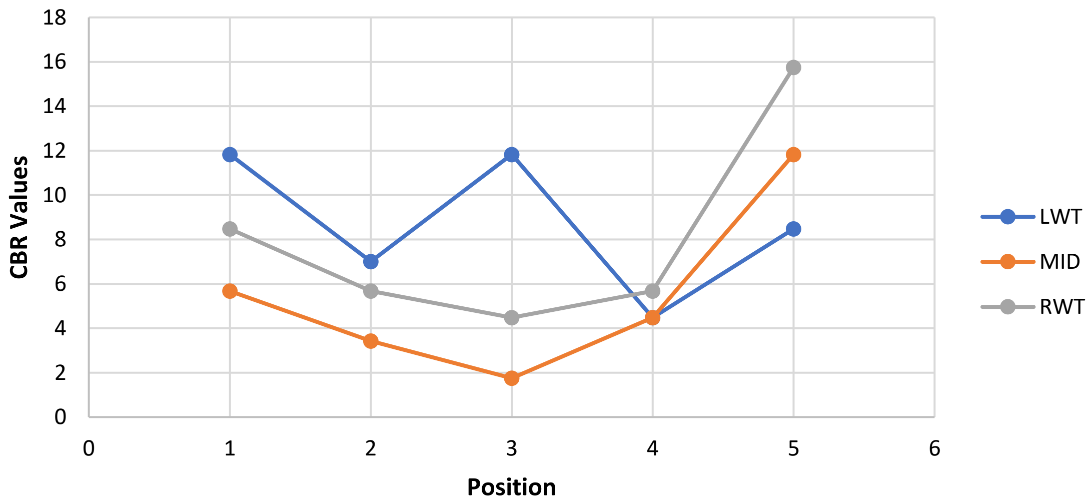

Figure 45: Site 5 post-stabilisation results

The average CBR for post-treatment was determined to be 6 this shows that there was no increase after stabilisation. The SD value for this site was 3.1 showing a slight increase. The graph shows that the middle and RWT follow similar trends along the site section, however the middle has lower values which is due to a wet strip running down the middle of the road. This was caused by cattle walking up and down the road which can be seen in *Figure 43* above. Like the lime treatment in Omataroa it was also found to make no improvement to the soil properties, which was not expected in this forest as it had a higher clay content and lower organic content.

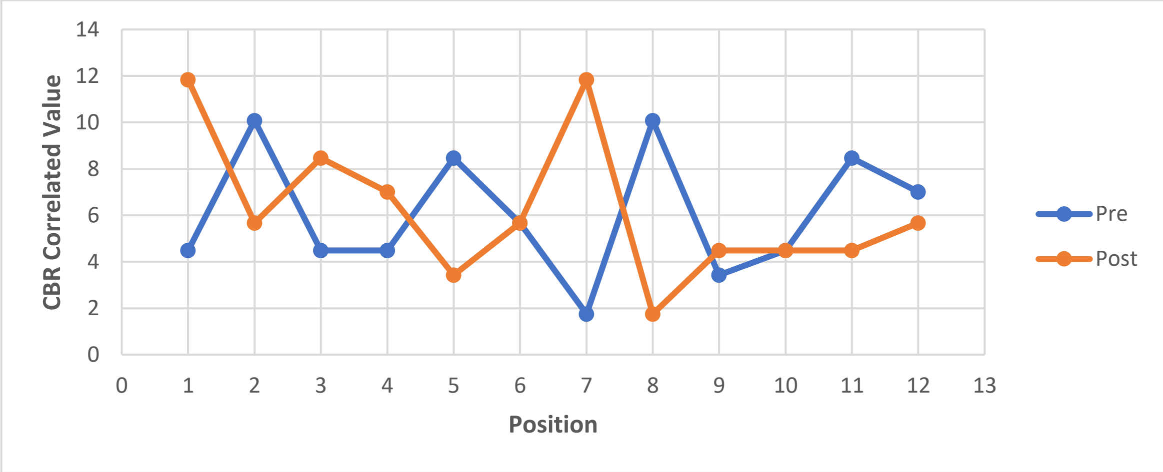

Figure 46: Site 5 pre and post stabilisation results

As shown in the graph the values for both tests are similar and fluctuate between being larger and smaller in terms of CBR at each point. There was also a difference in soil condition when testing, on the day of the pre-stabilisation testing the soil was semi-saturated and during post-treatment testing the soil was baked. So, the increase in some positions in Site 5 could be due to the dried/hardened soil and not because it was treated with lime.

Site 6

Site 6 was the final site, which was tested, and it was stabilised with a mixture of Burnt lime and Portland cement. This section also had a slope of 11% and had a water table on the right-hand side of the road (looking down). The soils were like those in the sites above but towards the end of the site a red/orange clay soil was noted and can be seen on the cut batter in the first image below. The two photos below once again compare the road pre and post stabilisation.

Figure 47: Site 6 pre and post stabilisation

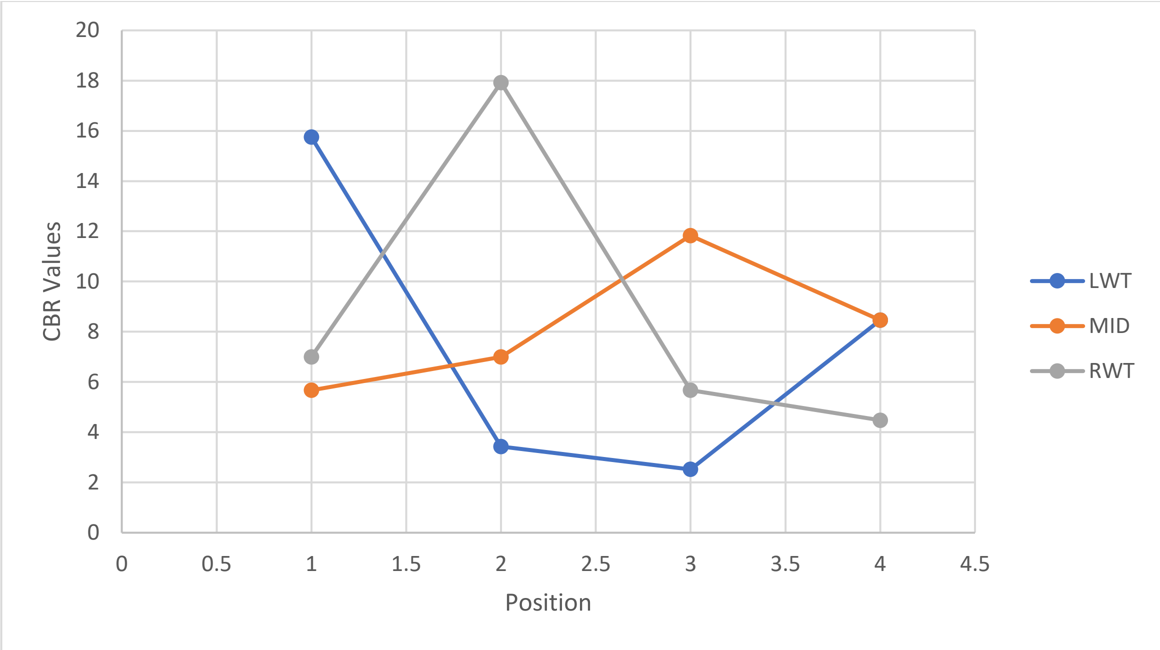

Figure 48: Site 6 pre-stabilisation results

The average CBR for Site 6 before stabilisation was determined to be 8 with a SD of 5. These values are like those found on the other sites on this road. The graph shows that there are large fluctuations between values especially between positions on the same line for example at P1 the LWT value is 15.75 and then at P2 it is only 3.43. This is due to the rock content and changing soil types along the site which can be seen below in three pictures which were taken at P1, P2 and P3.

Figure 49: Site 6 pre-stabilisation P1, P2 and P3

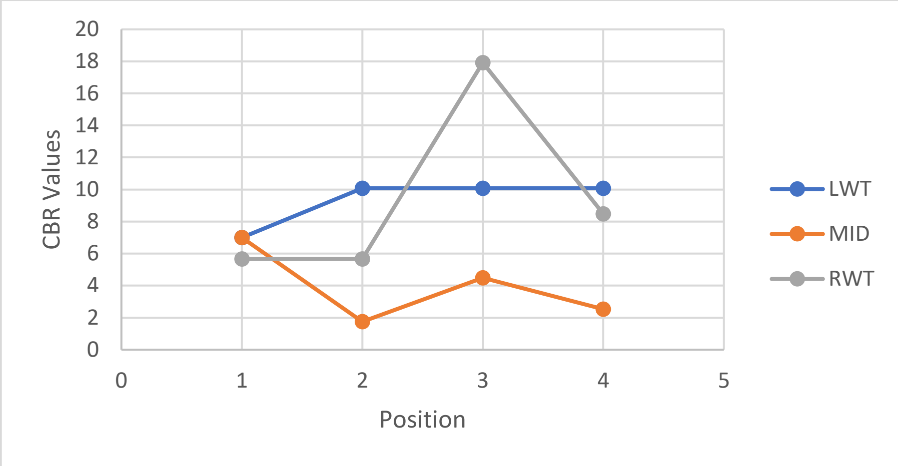

Figure 50: Site 6 post-stabilisation results

The average CBR for Site 6 after stabilisation was 8 this showing no improvement, the SD value was 4, this shows that the data has reduced in variation but has not increased in strength. With the lower amount of gravel and sand present in the soil, the cement was unable to create strong and effective bonds. This effectively not increasing the average CBR value. The joined values for pre and post stabilisation can be found below in *Figure 51*.

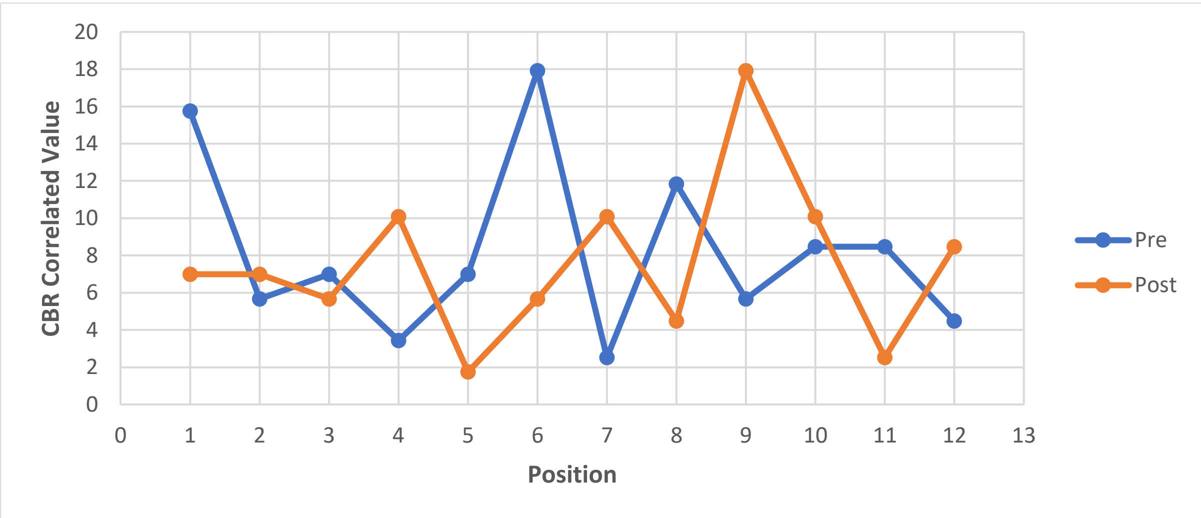

Figure 51: Site 6 pre and post stabilisation results

Like the lime treated section in Site 5 the pre and post stabilisation values fluctuate between being high and low. The graph shows that there is no improvement when treated with a mixture of lime and cement. The higher values on this site (CBR of 17) are in the lower range of site 4 which had comparable properties (soil, slope, and water control) but was treated with PolyCom this shows that for this site PolyCom is better suited.

Costs

Base case

The second objective of this study was to investigate the cost benefits of stabilising. To determine these costs an aggregate depth was needed. This was calculated using the AUSTROADS graph below. The design traffic load was different for each forest due to the Omataroa being a stub road and Waerenga being an arterial road. Omataroa had a design traffic of 13,694 and Waerenga had a value of 116,973. Using this and the CBR values found on site an aggregate depth for the un-stabilised and stabilised sections could be calculated.

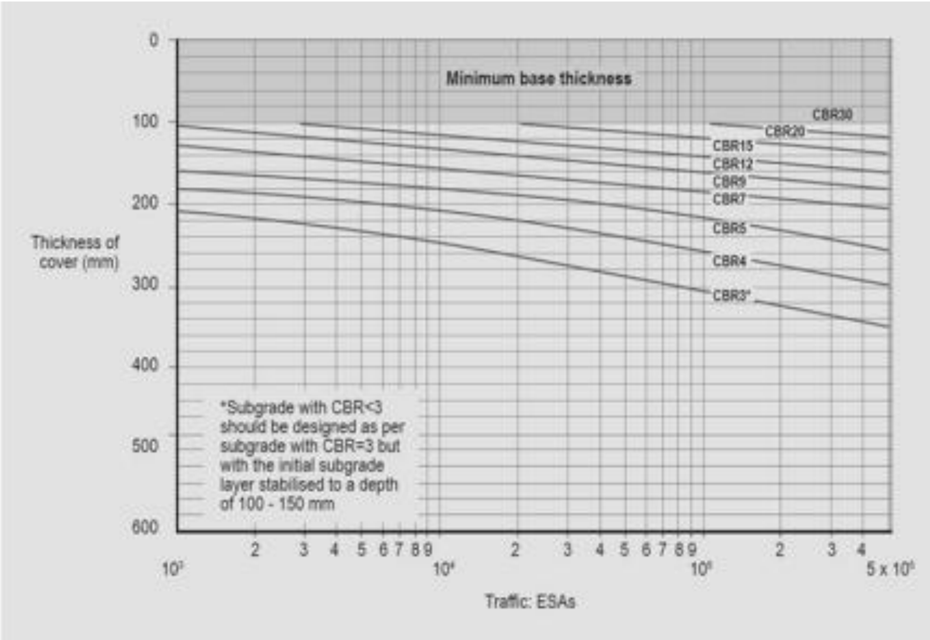

Figure 52: AUSTROADS graph used to determine aggregate depth

The aggregate depths for Omataroa were low due to having a high initial CBR. However, in Waerenga the CBR values were a lot lower, so more aggregate was required to withstand the loads applied to the road. The aggregate depths for the two roads can be seen below.

Omataroa		
Pre-stabilisation	**CBR**	**Aggregate thickness (mm)**
S1	15	110
S2	23	100
S3	30	100
Stabilised	**CBR**	**Aggregate thickness (mm)**
Polycom S1	21	100
Lime S2	14	110
Cement S3	37	100

Figure 53: Omataroa Aggregate depth

Waerenga		
Pre-stabilisation	**CBR**	**Aggregate thickness (mm)**
S1	9	165
S2	6	205
S3	8	108
Stabilised	**CBR**	**Aggregate thickness (mm)**
Polycom S1	28	100
Lime S2	6	205
Cement S3	8	180

Figure 54: Waerenga Aggregate depth

To determine the overall cost of construction the aggregate and machine costs were supplied by Rayonier Matariki Forests. Costs varied between forests for aggregate because it was supplied from different quarries. The machine hours also varied due to different machines being used for certain stabilisers. For example, the running costs of an excavator was not included for PolyCom but was included for the Burnt lime sections. The stabiliser costs were PolyCom - $900, Burnt lime - $1092.50, Burnt lime and Portland cement $1852.50. With all the costs included the final per/metre cost was calculated and can be seen below in *Figures 55 and 56.*

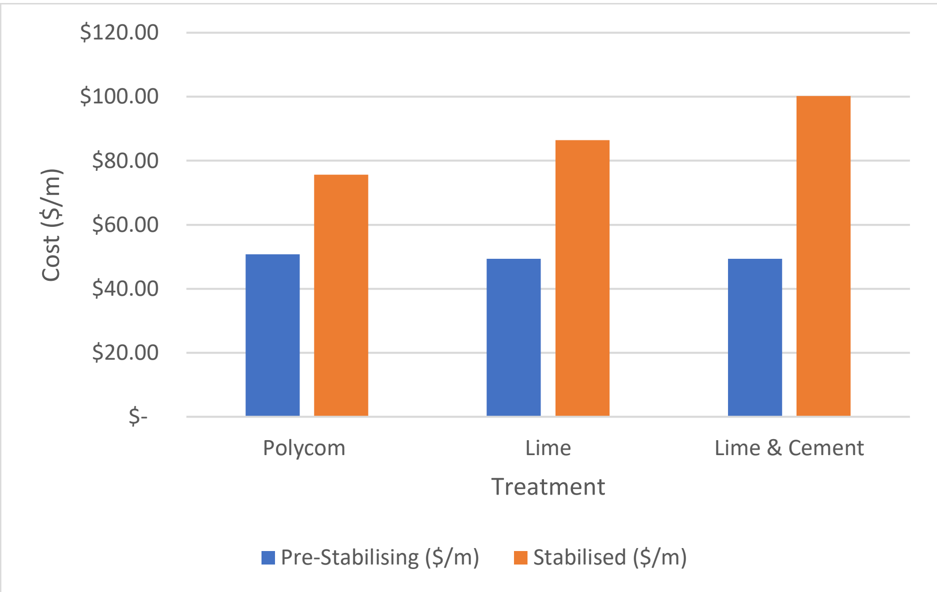

Figure 55: Costs in Omataroa

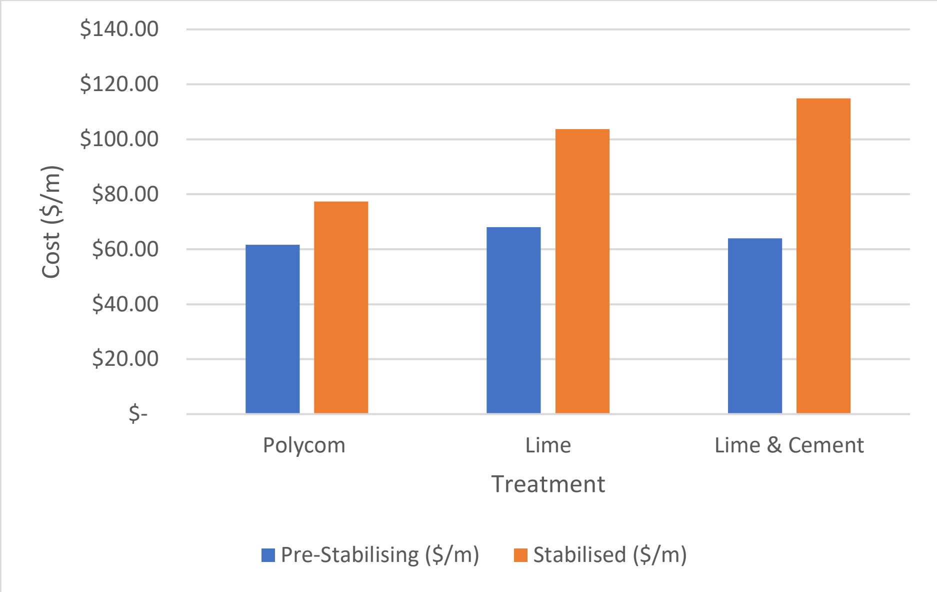

Figure 56: Costs in Waerenga

As seen in the figures in all cases it is more expensive to apply a stabiliser and aggregate compared to adding more aggregate to get the road. A considerable difference can be found in the Omataroa results. The results show that if the initial CBR is high there is no need to stabilise and if you do it is going to make the roading costs a lot more. The PolyCom results in Waerenga provide the closet results with stabilising being $15.82/m more. This is because the CBR values in Waerenga were low before stabilising and high after stabilisation with PolyCom.

With the varying costs and depths of aggregate used around New Zealand a break-even analysis was conducted to see the point where stabilising would be cheaper. The analysis was based on results from the PolyCom in Waerenga. These results showed a saving in aggregate of 39%. Different aggregate depths were used, and the results can be found in *Figure 57* below.

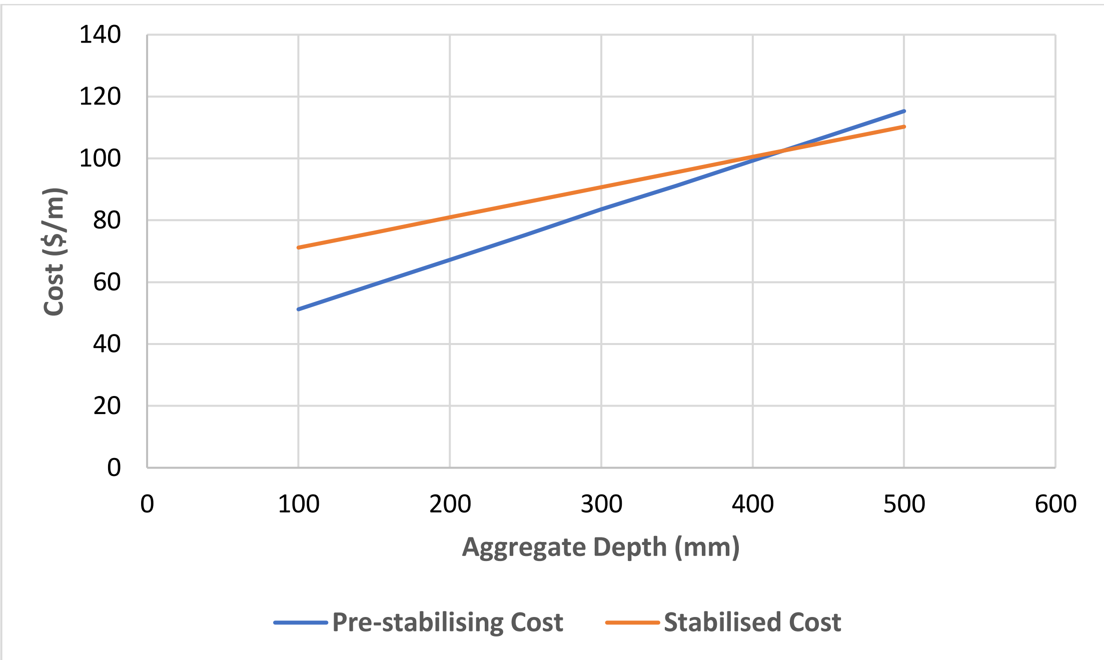

Figure 57: PolyCom break even analysis

As seen, it is cheaper to apply a stabiliser when more than 400 mm of aggregate is required. This is quite a high aggregate depth for forestry roads around New Zealand, but some roads being built are going through swamps or soft soils, so this depth is required. Meaning that there is a market for these stabilisers. Another analysis was done by changing the aggregate costs. It was found that when aggregate costs were increased to $20/t for rotten rock and $30/t gap 60mm that the required depth for stabilising to be cheaper was only 300mm. So, the trend shows that at higher aggregate prices and depths that it would be cheaper to apply a stabiliser. These levels may not be met yet but with forests being harvested on marginal land and further away from rock suppliers there is an opportunity for stabilising subgrade to be cheaper.

Discussion

All three stabilisers showed mixed results across both forests, these results showed which stabiliser may be suitable for the site and how they perform in different soil types and weather events. The stabiliser which showed the best performance across both roads was PolyCom. This product increased the average CBR in Omataroa by 6 and in Waerenga by 19. It was applied at approximately 20% less than recommended by the supplier and still showed satisfactory results. It worked well in sandy loam soils but better in the clay loam soil with more sunlight hours which was the conditions in Waerenga. This shows it suits roads with comparable properties to Waerenga.

In terms of Standard Deviation for PolyCom, it decreased in Omataroa after treatment but was increased in Waerenga. In Omataroa the difference was only 1 this showing no significant improvement but because the CBR has increased, and the deviation has decreased it is a big positive. In Waerenga SD increased by 11 this showing a significant increase in variation for this site. These increases and decreases can be explained through the varying soil types within each site and the inconsistent spread of granules. The PolyCom reacted within minutes and created webs between the broken soil. So, to make sure all areas are stabilised it is recommended to walk the treated area to see if the webbing has formed.

The Burnt lime (mix rate of 4%) & Portland cement (mix rate of 3%) stabilisation mix improved the Omataroa road but showed no improvement in Waerenga. In Omataroa the CBR value increased from 30 to 37, the soil already had a high value, so the improvement shows that this stabiliser suits the site. In reality this site would not be stabilised due to having such a high average CBR value. However, because the stabilisers improved the soils strength it can be recommended as an effective stabiliser for sand and gravel soils. Another factor leading to its effectiveness was the 6-7 sunlight hours that this section got per day. This allowed the stabiliser to set and harden. It is hard to comment on how effective the Burnt lime was in this stabilisation section as it performed poorly in the other sections.

In the Waerenga forest cement and lime made no improvement to the soil properties, this could be due to the low gravels and sand content found in the soil. This meant that cement was not able to create effective bonds. What is unexplained is why the lime did not react with the clay found in the soil. The Standard Deviation was highest in Omataroa with a value of 25 in both the pre and post-stabilisation tests. This shows that the data was highly variable and the addition of the cement and lime did not reduce the variably of the soil's strength. A large problem for this forest road was the amount of organic soil present on the road and neither of these stabilisers work well with this soil type.

Lime stabilisation had the worst performance in each forest which was surprising as it has been a proven method for hundreds of years. In Omataroa the CBR value decreased from 23 to 14, on this site there was high organic content with low clay content. This makes it hard for the lime to create any strong bonds and the amount of bonds made would have been small. Another factor leading to the decrease in CBR was the poor compaction after stabilisation compared to the compaction before stabilisation. This shows the importance of making sure the compaction of the soil is maximised. In Waerenga the CBR value before and after stabilisation was 6 showing no change. This was the most unexpected result from the study as the road had considerable amounts of clay. Reasons for no improvement could be due to the implementation method, the high rainfall and poor weather or if the concentration of the lime was too low.

In terms of costing, it was found that for both forests it would be cheaper to not stabilise. The closest price difference was in Waerenga for an area treated with PolyCom. It was still \$15.82/m more expensive so is not a viable option at the prices provided. A break-even analysis found that it would be cheaper to apply PolyCom if the depth of aggregate required was more than 400mm with the base case prices and if the prices were increased to \$20/t for base material and \$30/t for gap 60mm then the required depth was only 300mm. This gave a benchmark for where stabiliser should be applied and provided a trend that shows with increasing costs and aggregate depths that it is cheaper to apply a stabiliser.

Future research

An option for future research could be to find out the optimum mixture ratio of PolyCom. In this study 1kg of PolyCom was used to stabilise 30m^3 which is more than the recommended 25m^3. With the results showing good improvement the rate could be lowered more, this will also decrease the cost due to the same amount of product stabilising more soil. This study could also be done for the other stabilisers but because PolyCom showed the best results this stabiliser is recommended. It also has limited information on its use in New Zealand.

Conclusion

In conclusion it was found that PolyCom was the best performing stabiliser across both forests. It showed increased CBR results in different soil types and climate. It excelled in the Waerenga forest increasing the CBR by 19 showing that it is suited to clay soils that get plenty of day light hours. It was evident that the other stabiliser struggled in soils that did not suit their reaction type, with lime not increasing the road in either forest and the lime & cement mix only increasing Omataroa which had a higher granular content in the soil.

References

Bhandakkar, K. (2020, September). *The constructor* . Retrieved from https://theconstructor.org/question/what-is-the-purpose-of-soil-sample-soaked-in-water-7days-in-cbr-test/

Clegg. (n.d.). Retrieved from https://www.clegg.com.au/products.html#:~:text=The%20Clegg%20Hammer%20was%20developed,Western%20Australia%20in%20the%201970s.

Dhir, R. K. (2017). *Science direct*. Retrieved from Geotechnical applications : https://reader.elsevier.com/reader/sd/pii/B9780128044919000021?token=1E9FF2FB4F6072185F1691F32F529D338000CA4DB8ABA184F6BFB94D1C421244A4729C5B766AEAFD0E6A68D7BF34BADC&originRegion=us-east-1&originCreation=20220606023115

Efthymiou, D. P. (1996, June). Retrieved from ALTERNATIVE STABILIZATION METHODS OF FOREST ROADS FOR AN EFFICIENT AND GENTLE MECHANIZATION OF WOOD HARVESTING SYSTEMS: http://users.auth.gr/~pxeskio/papers/22.pdf

Groundtest equipment . (n.d.). Retrieved from https://www.groundtest.co.nz/impact-soil-tester-clegg.html#:~:text=The%20tester%20measures%20the%20deceleration,performed%20in%20a%20half%2Dday.

Inc, N. F. (2020). *NZ Forest Road Engineering Manual*. Retrieved from https://docs.nzfoa.org.nz/live/nz-forest-road-engineering-manual/

Mahamedi, M. K. (2014). *Cement and lime mixture stabilization of an expansive overconsolidated clay*. Retrieved from https://www.sciencedirect.com/science/article/pii/S0169131714000957

Padmavathi, M. P. (2021, April 2021). Retrieved from Stabilization of Clays and Clayey Soils Using Polycom-A Polyacrylamide Additive: https://link.springer.com/chapter/10.1007/978-981-33-6444-8_72#citeas

Rajapakse, R. (2016). *Science Direct* . Retrieved from https://www.sciencedirect.com/book/9780128046982/geotechnical-engineering-calculations-and-rules-of-thumb

Georgees, R. N., Hassan, R. A., Evans, R. P., & Jegatheesan, P. (2015). Effect of the Use of a Polymeric Stabilizing Additive on Unconfined Compressive Strength of Soils. *Transportation Research Record: Journal of the Transportation Research Board*, *2473*(1), 200–208. https://doi.org/10.3141/2473-23

Mesfun, R. T., Quezon, E. T., & Geremew, A. (2019). EXPERIMENTAL STUDY OF STABILIZED EXPANSIVE SOIL USING PUMICE MIXED WITH LIME FOR SUBGRADE ROAD CONSTRUCTION. *International Journal of Research -GRANTHAALAYAH*, *7*(7), 118–124. https://doi.org/10.29121/granthaalayah.v7.i7.2019.736

Taha Jawad, I., Raihan Taha, M., Hameed Majeed, Z., & A. Khan, T. (2014). Soil Stabilization Using Lime: Advantages, Disadvantages and Proposing a Potential Alternative. *Research Journal of Applied Sciences, Engineering and Technology*, *8*(4), 510–520. https://doi.org/10.19026/rjaset.8.1000