COMPARATIVE STUDY INTO ROLLER VS TRACKS FOR FILL COMPACTION IN NZ FORESTRY

Forest Engineering Honours Project 2023
Supervised by: Dr Campbell Harvey
NZ School of Forestry, Christchurch, New Zealand

UC
UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Luke Veltman

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Executive summary:

Inadequate compaction can result in environmental and financial consequences. Within the New Zealand forest industry there are differing perspectives on the efficiency of track rolling versus purpose-built compaction rollers. This comparative study aims to provide clarity on achievable compaction levels and optimal number of passes for the predominant compaction methods employed in New Zealand's forests. The findings from this report are specific to the soil types and compositions encountered along with the machinery used. This study's findings aim to enhance the industry's understanding of the effectiveness of various compaction methods and the operational considerations involved in compaction processes. The results and findings of this study are split into 4 differing soil types across 3 different regions of New Zealand's North Island.

Site 1 in the Manawatu region was characterized by a Papa mudstone bedrock. Surface compaction samples showed that smooth drum rolling on average achieved 14.47 kN/m^3 dry density at a 18.1% Moisture content (MC). Overall achieving 7.24% greater level of compaction than track rolling when compared to the compaction curve derived from standard proctor results. Averaging the entire fill layer shows smooth drum performs 40% better than track rolling with depth and 16% greater when compared against number of complete passes completed.

Site 2 featured a clay soil in the Bay of Plenty region, where both track rolling and smooth drum rolling delivered comparable results. This soil showed particularly low strength once compacted and is attributed to the high MC along with it having allophanic properties. However, the higher moisture content in the clay soil led to the exclusion of the vibratory technology on the smooth drum roller to avoid liquefaction and maintain compaction efficiency. Site 2 testing also included testing of rhyolite-based soil with a sandy clay loam composition. Smooth drum rolling with vibratory technology achieved superior soil compaction compared to track rolling on this soil type. At the surface level track rolling achieved 3.79% poorer level of compaction than smooth drum, with it showing 33% poorer compaction than smooth drum rolling comparing pass for pass. When comparing compaction methods in respect to strength at depth it shows smooth drum rolling achieves 70% greater soil strength.

Site 3 featured sandy loam soil, where notably, padfoot rolling outperformed track rolling at the surface level with surface samples indicating padfoot rolling achieves 11.3% greater level of compaction. However, when comparing the averaged results for the two methods in respect to strength with number of passes there is little to no difference with both track-rolling and padfoot achieving on average 2 blows per 100mm once compacted. When considering the effect of depth on

strength, both compaction methods show similar values, with a notable peak at 200mm depth. For the 750mm lift thickness, it showed compression of approximately 33.3%.

Overall, the study underscores the impact of site conditions on the effectiveness of compaction techniques. Specialized compaction rollers demonstrated superior compaction results in soft fill material when given adequate compaction conditions such as soil at or below Optimal Moisture Content (OMC). The optimal number of passes tended to be around 6 with the initial passes having the most substantial impact on soil strength with subsequent passes demonstrating minimal further improvements. Moreover, for clay and sandy loam soils above OMC, track rolling proved to obtain comparable results to purpose-built rollers. The findings from both site 1 and the rhyolite at site 2 demonstrate that the utilization of smooth drum rolling leads to a general decrease in the necessary pavement thickness for compacted fill material used in constructing a forest road subgrade. This reduction is attributed to the higher CBR value. The potential cost-effectiveness of employing the smooth drum roller for compaction in comparison to this reduced pavement thickness remains uncertain. These findings emphasize the importance of aligning compaction methods with the soil characteristics and site conditions to achieve optimal results. Successful compaction strategies must be tailored to the specific soil types and MC of the soil at each site, maximizing the efficiency of compaction efforts. It is also noted that where there are inherent safety concerns around the utilisation of purpose-built rollers on undulating and unstable terrain it is advised to carry out track rolling due to compaction being able to be achieved at a reduced health and safety risk.

Introduction:

Adequate compaction during infrastructure construction is a key component in increasing the strength and bearing capacity of the soil. Across the New Zealand forest industry many forest managers and earthwork contractors employ various techniques for carrying out compaction on fill material. Track rolling is a common technique which utilises excavators or bulldozers for carrying out compaction through applying the force from their mass over the area of the tracks. The attractiveness for using tracked machinery for compaction originates from the machinery being readily available as it is already being on-site for carrying out the bulk earthworks. Tracked machinery is also preferred given the inherent safety concerns which purpose-built compaction rollers have on undulating and unstable terrain. With industry regulations assuming that fill material is to be under a strict compaction regime, there are no standards to be found specifying to what degree the fill must be compacted to and by which machinery. This is largely left up to the discretion of the manager or overseer.

Despite the lack of research and knowledge into the effectiveness of track-rolling in comparison to purpose-built rollers, it remains one of the most widely used compaction techniques within the forestry industry. This controversial topic of track-rolling has engineers, forest managers and earthwork contractors all taking varying opinions on the effectiveness of tracked machinery for carrying out compaction. Yet it remains one of the most widely used compaction techniques within the forestry industry.

Literature Review:

Oven-Drying of Soils:

Accurate measurement of the moisture content of a soil is an important step in characterizing a soils engineering behaviour. The equation for determining moisture content is shown in equation 1 with the mass of water (m_w) over the mass of the dry solid (m_s) particles.

$$Moisture\ content = \frac{m_w}{m_s} \times 100 \qquad (1)$$

Literature shows that drying of organic or peat soils is recommended to take place at lower temperatures around 80^{o}C to avoid the oxidation of particles and creating bias within results when weighed. This study conducted testing using 40g specimens over a period of 96 hours, and determined that the standard practise of drying soils at temperatures of 105 to 110^{o}C show the lowest required drying times with minimal to no inaccuracies in data collection while the mass is reaching equilibrium (O'Kelly, 2005).

Soil Dynamics and Compaction:

Compaction is an essential component across the forestry industry for strengthening and stabilising fill material during earthworks. Inadequate compaction presents a slope instability risk making it prone to failure and therefore causing both safety and environmental concerns. Compaction aids in soil stability by packing particles closer together and increasing the soil density. Compact soil is vital for increasing shear strength through decreased void ratio within the soil, consequently increasing resistance to the lateral movement (J. DeJong-Hughes, 2001). Decreased void ratio also reduces the ability of moisture to infiltrate and accumulate within the soil mass. As the water fills these voids, it elevates pore water pressure, subsequently diminishing effective stress and overall shear strength. Compaction also reduces differential settlement of fill material. Non-uniform settlement can lead to shear strains and stress concentrations, which can eventually cause slope failure (J. DeJong-Hughes, 2001) as well as allowing for uneven infrastructure which increases the depreciation of the road or landing quality.

A study investigated considerations and control methods for the potential of wetting-induced collapse in compacted fills. It concluded that the most critical conditions are the degree of saturation, dry density, and the total overburden pressure with regards to collapse potential. They determined the collapse potential is controlled by the change of MC within the soil. When the clay content is low, the ability for the soil to bind together decreases as clay functions as a binding agent between silt or sand particles. Upon wetting, the clay binders soften and create lubrication between the intergranular contacts, which facilitates collapse. Generally, the likelihood of collapse rises with excessive or low water content, decreased density, and increased vertical stress.

Compacted soils may also experience particle cementation over time. If compaction is followed by a prolonged period without wetting before experiencing repeated moderate precipitation events, collapse may occur (Lawton, Fragaszy, & Hetherington, 1992). Regarding fill material, loose fill may be stable when dry and first formed, however, the direct infiltration of rainwater on fill material can result in the saturation of the initial layers of fill. This saturation weakens soil strength and can lead to shallow slope failures. Proper compaction, characterized by sufficient density prior to saturation, enhances resistance to failure, particularly as volume expansion occurs during shearing rather than volume contraction (Lumb, 1993).

Compaction Curves:

Research indicates that for many soils dry density and moisture content follow similar correlations to the one shown below in Figure 1. Attempting to apply compaction to soil below optimal water content (OMC) will increase the potential for inefficient compaction and the formation of cracks. Whereas soil above OMC will exhibit improved workability but may become excessively saturated leading to loss in structural integrity and a tendency to become overly plastic, ultimately reducing its ability to compact. (Godwin, 2009).

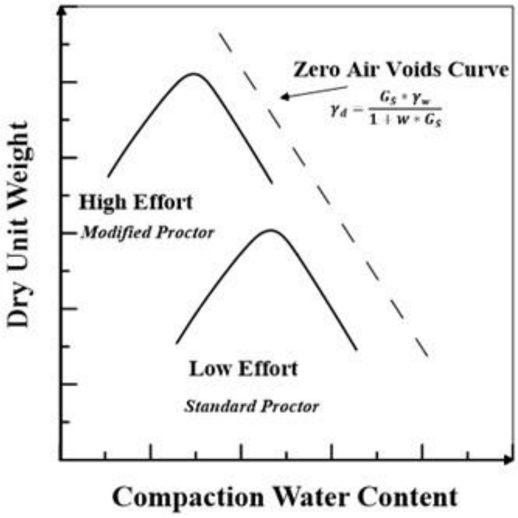


Figure 1: Compaction curves for proctor tests showing correlation between dry density and moisture content (Adams, 1981).

As moisture content is such an influential characteristic on compaction it can be optimised which is supported by Figure 1. This is due to water providing cohesion or lubrication to adjacent soil particles and aggregates (Adams, 1981). Moisture forms a thin film around each soil particle which aids with inter-particle contact.

Across several studies it was determined that OMC varies considerably with other soil characteristics and the level of compaction forces applied. The compaction effort is the primary external factor which influences the degree of compaction (Atkinson, 2000), therefore the compaction achieved has a strong corelation to the equipment used. With additional studies showing that the maximum strength of the soil is achieved just dry of optimum (Kitch, 2018).

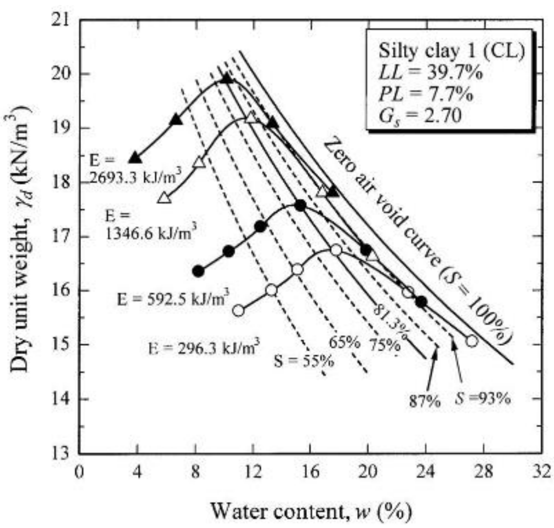


Figure 2: Compaction curves of silty clay, varying compaction energy (Horpibulsu, 2008).

The level of compaction is limited to the compaction energy available; this is shown above in Figure 2 where a study carried out tests on the same soil with differing compaction energies. Compaction curves of soils are essential for establishing what degree of compaction can be achieved given a certain compaction energy (Horpibulsu, 2008).

A study into developing a simplified method to predict compaction curves and characteristics of soils was conducted by Gurtug, Sridharan, & I'kizler (2018). As identified above, previous research has identified how the compaction curve with its associated OMC and dry density displays the level of achievable compaction for a given soil. However, the standard method for achieving this is through proctor tests where considerable time and effort is required (Gurtag, Sridharan, & I'lkizler, 2018). It was concluded that once the plastic limit of a soil is known it can be inputted into equation 2 below to arrive at the theoretical Maximum Dry Density (MDD) which can be achieved through standard proctor testing. This process can also be applied to determine the MDD from modified proctor results.

$$\gamma\_\max\left(\frac{kN}{m^3}\right) = 51.88\ OMC^{-0.4} = 51.88\left(0.943 w_p\right)^{-0.4} \qquad (2)$$

$$w_p = Plastic\ Limit$$

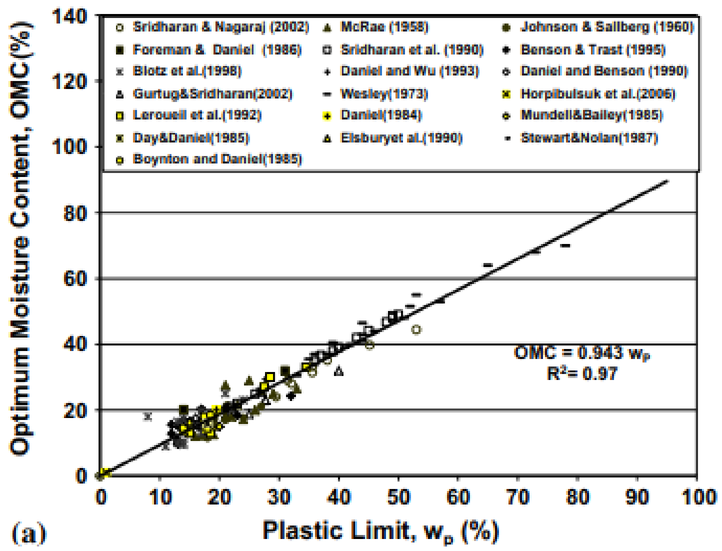


Figure 3: Correlation of OMC and Plastic limit using standard proctor.

Literature revealed that by carrying out a test to determine the plastic limit for a range of soil compositions, the OMC could be determined given the strong correlation illustrated by figure 3 above.

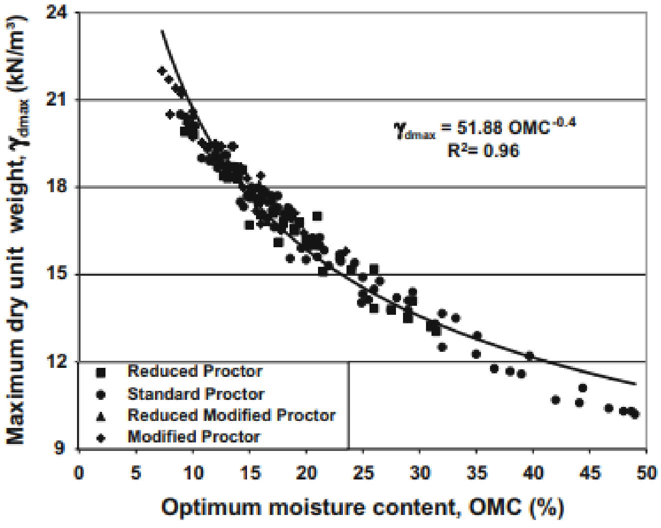


Figure 4: Correlation of maximum dry unit weight and OMC for differing soils

Figure 4 was developed from trialling 208 different soil types and shows that from the OMC the MDD can confidently be determined. A comparison between calculated dry density and a measured dry density on site can be made to determine the degree or level of compaction which is being achieved (Gurtag, Sridharan, & I'lkizler, 2018).

Compaction by Track-Rolling:

This literature review revealed that there is minimal existing research into the compaction ability of track rolling. This is presumably due to the civil and geotechnical industry largely implementing purpose-built rollers and other compaction machinery. A paper investigating the differing impact which tracks made on a 12 tonne combine harvest determined that soil deformation was reduced by 50% with the implementation of tracks. It was identified that tracks produce high penetration resistance near the surface of soil sample. However, in cases of uniform soil conditions, no notable increase in penetrometer resistance was observed below a depth of 400 mm. It was found that tracks decreased the pressure through distribution of mass over a greater area and achieved poor compaction (Ansorge, 2005).

Mounting tracks over the bogie wheels of forwarders is common practise within forestry to reduce ground pressure and improve traction. A study carried out on these found that the surface cone resistance within the ruts was approximately 10% lower compared to a wheeled version implying reduced soil compaction (Gunnar, Eliasson, & Wästerlund, 2003). Additional studies confirmed this finding such as one carried out by Ansorge (2005) determining that a wheeled machine with 24% greater mass delivered comparable cone penetrometer resistance to its tracked alternative. Overall, tracks deliver high surface compaction but have reduced effect with depth making the depth of fill a significant influencer on compaction results (Ansorge & Godwin, The effect of tyres and a rubber track at high axle loads on soil compaction, 2007).

Effect of Successive Passes:

The effect of successive passes on compaction showed that the first few passes delivered the most significant increases in penetrometer resistance compared to the later passes (Ansorge, 2005). This is supported by a study investigating the soil compaction of small-scaled mechanised forest equipment which found that the most significant changes occur at the surface level. Primary compaction occurred in the first few passes, while subsequent passes had lessened effects. (Tugrul, et al., 2020).

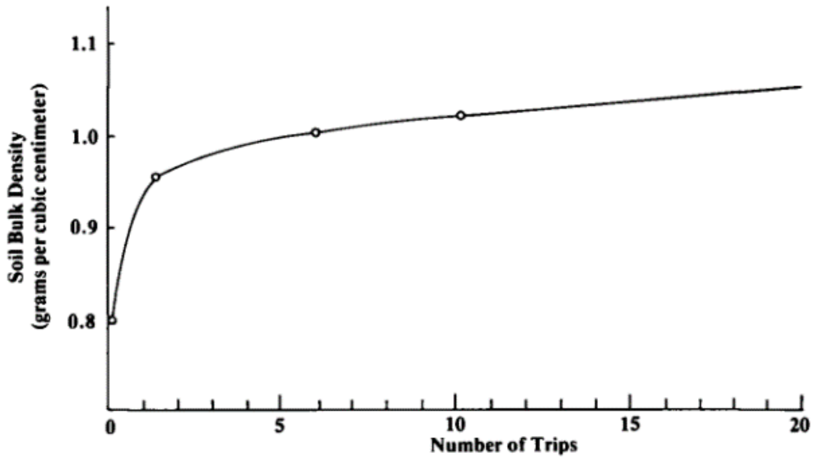


Figure 5: Effect of number of passes on soil bulk density (Tugrul, et al., 2020)

Figure 5 displays the effect of multiple passes on compaction. It is evident that the greatest density changes occur during the first few equipment passes, with progressively smaller increases thereafter.

The above findings were confirmed by a study which compared the effect which roller passes, vibration force, roller speed, and vibration acceleration had on compaction (Cao, Zhou, Li, Chen, & Dong, 2021). The most influential factor was found to be the number of passes, contributing to over 50% of the overall compaction. This would allow the number of passes to be the primary consideration and indicator for compaction quality control in construction. The study delivered similar results to previous studies finding primarily plastic deformation during the first three roller passes. Between four to seven roller passes, the soil particles are squeezed to achieve an increasing compaction, and stabilisation during the roller passes from eight to nine (Cao, Zhou, Li, Chen, & Dong, 2021).

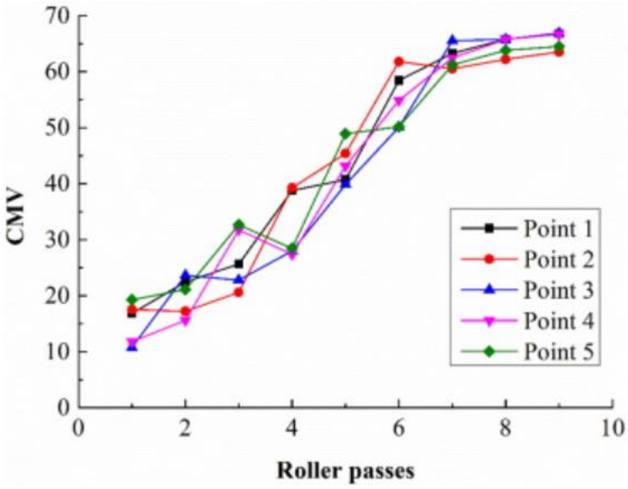


Figure 6: Correlation of roller passes and compaction meter value (CMV) (Cao, Zhou, Li, Chen, & Dong, 2021)

Overall, the analysis within this study showed that with the increase of roller passes, compaction meter value (CMV) has a slow growth at first followed with a fast increase, and eventually stabilizes. This is illustrated in figure 6. With the number of passes usually left up the discretion of the operators. This is primarily based on prior experience, rather than based on objective conditions this can lead to under or over-compaction (Cao, Zhou, Li, Chen, & Dong, 2021).

Table 1: Fill compaction requirements from the NZ Forest Road Engineering Manual (NZFOA, 2020)

Typical compaction requirements for fills				
Material type	Preferred type of compaction	Layer depth mm		Number of passes
		Subgrade	Fill	
Gravel/sand	Smooth drum	200	400	4 – 6
Clayey gravel/sand	Sheep-foot	150	300	4 – 6
	Pneumatic Tyred	150	300	6 – 8
Clay/silt	Sheep-foot	250	200	6 – 8
Crushed rock (pavements)	Heavy smooth drum	125		6

The New Zealand Forest Road Engineering Manual (NZFREM) includes table 1 which indicates the advised number of passes and lift thickness for differing soil types, based on the preferred type of compaction. This information concurs with the findings of above literature.

Purpose Built Rollers:

Purpose built rollers come in various shapes and sizes from impact rollers to smooth and padfoot. Table 2 is from a 1980's study which linked compactor type with soil it is best suited for, along with an advised fill lift thickness.

Table 2: Suitability for compacting soils (Peurifoy & Ladebetter, 1985)

Type of Compactor	Soil Best Suited For	Maximum Effect in Loose Lift, inches	Density Gained In Lift	Max. Weight Tons
Sheepsfoot	Clay, silty clay, gravel with clay binder	7-12	Nearly uniform	20
Steel tandem, two-axle	Sandy silts, most granular materials with some clay binder	4-8	Average*	16
Steel tandem three-axle	Sandy silts, most granular materials with some clay binder	4-8	Average*	20
Steel three-wheel	Granular or granular-plastic material	4-8	Average* to uniform	20
Pneumatic small-tire	Sandy silts, sandy clays, gravelly sand, and clays with few fines	4-8	Average* to uniform	12
Pneumatic large-tire	All types	3-6	Uniform	50
Vibratory	Sand, silty sands, silty gravel	Up to 24	Uniform	30
combinations	All	3-6	Uniform	20

Static rollers achieve compaction through the application of deadweight, exerting downward force on the soil surface encompassing kneading and pressure as its key technique to compress soil particles together, all without employing vibratory motion. Static rollers which are either smooth drum or sheepsfoot primarily deliver pressure, while pneumatic tire rollers combine pressure with a degree of kneading. Literature suggests that steel wheel rollers are employed for compacting various soil types in layers ranging from 4 to 12 inches in depth with clayey composition soils requiring this range to be reduced to 4 to 6 inches to prevent compaction of just the top layer (Rollins & Kim, 2010).

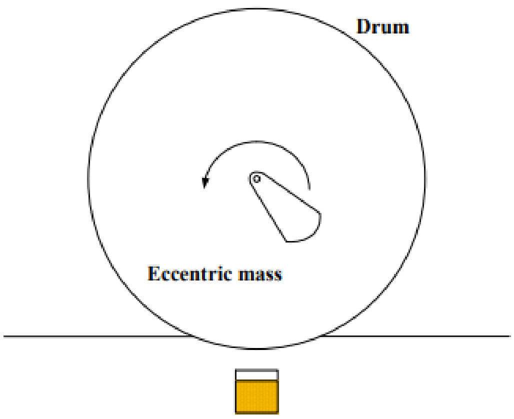


Figure 7: Drum of vibratory roller (Kim, 2010)

Some rollers employ a vibrating or oscillating system illustrated above in figure 7, working through at least one rotating eccentric weight which aids in generating additional downward force beyond that which can be achieved purely through the machine's mass alone. These vibratory rollers combine forces in a rapid series of impacts to overall increase the compaction ability of the machine. This technology can encourage liquefaction through this process so it is advised to avoid using vibration for soils which are past OMC where this additional moisture may decrease the ability to densify the soil in an efficient manner (Rollins & Kim, 2010).

Methodology Study:

Across the literature it is evident that there is a variety of methods in which to gather data. Further investigation into these alternative methods was conducted.

Density and Moisture Content:

The two common test methods used for measuring density and water content are the rubber balloon method and the nuclear densometer gauge. The rubber balloon method is a volume replacement technique which is applicable to both fine and coarse-grained materials. While it is relatively easy to perform, it is time-consuming and labour-intensive. One challenge lies in accurately measuring the volume of the test hole, particularly for coarse-grained and angular materials where the recorded volume may not be representative. Additionally, a deformation of the test hole during this procedure can lead to incorrect volume measurements, especially with softer and more deformable soils (Andraski, 1991). These tests are predominantly done in the top layer, with the test depth being limited to the hole dimensions.

Figure 8: Nuclear Densometer

Figure 9: Rubber Balloon Method

In contrast, nuclear gauges utilise nuclear radiation to determine density and water content, measuring the radiation which reaches the detector. The advantage of this method is its speed, providing immediate results after testing. Accuracy of the gauge depends heavily on accurate calibration, typically performed by the manufacturer. If the material being tested contains elements with significantly different interaction behaviours compared to the calibration standards, inaccuracies in density and MC can occur. Nuclear gauges are primarily for measurements up to depths of 300mm (Petrovic, 2019). To ensure reliability, it is recommended that users of the nuclear gauge validate the radiometrically measured densities and water contents by conducting comparison measurements with conventional methods like the rubber balloon method. This allows for potential discrepancies and any necessary corrections to be identified (Huber & Heyer, 2019).

Compaction:

Measuring differing levels of compaction was most commonly achieved within differing literature using a California Bearing Ratio (CBR) device such as a clegg hammer, or a form of penetrometer which delivers the penetration resistance of a soil at desired depths. Both handheld equipment delivered quick and easy in field tests for surveying and recording data.

Figure 10: Image of Clegg hammer

Figure 11: Scala Penetrometer

Although they are quick and easy to use, level of experience having little influence on the reliability of results, the primary disadvantage of using a Clegg hammer is the fact the results primarily concern the strength of the surface layer (Twomey, Otago, Ullah, & Finch, 2011). Whereas penetrometers allow for the penetration resistance down to depths well below the initial surface layer.

Moisture to soil:

Research found that when wetting was introduced to a soil sample there was a delay in the effect of the water as it flowed through the sample. As water moved throughout the sample it softens the interparticle bridges or bonds.

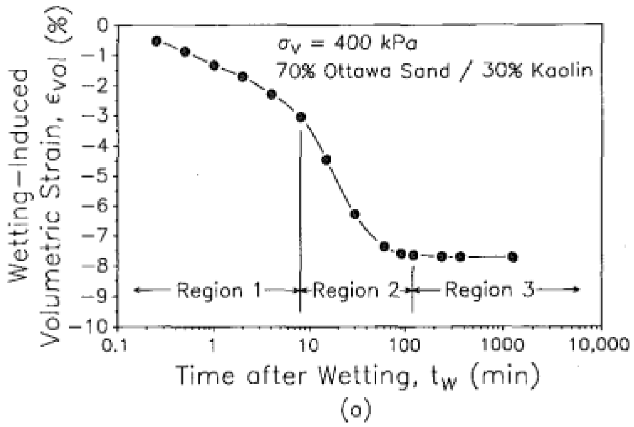


Figure 12: Volumetric strain associated with period after wetting (Lawton, Fragaszy, & Hetherington, 1992).

From figure 12 it is evident that during testing on-site for differing layers to be comparable with one another the moisture content must be similar otherwise the soil conditions and characteristics at the time of compaction will differ.

Oven Drying Soil Samples:

Literature on the drying behaviour of soils from various sources, stressed the importance of accurate moisture content measurement for engineering purposes. It highlights that soil composition, origin, and environmental factors affect drying rates and moisture retention. Overall, it was found that there is potential for chemical reactions during soil oven drying, with oxidation levels varying with temperature. It confirms that standard oven-drying practices at 110 ± 5°C to 105 ± 5°C for 24 hours provide accurate moisture content values for inorganic soils. For highly organic soils like peat, drying at 80°C for 24 hours gives accurate results, with oxidation starting between 80 and 90°C (O'Kelly, 2005). By consistent weighing of soil in 24 hour increments it should allow the mass to remain at a constant value indicating a MC of 0%.

Objectives:

The objective of this study is to determine the overall compaction which can be achieved along with the optimal number of passes for the primary compaction methods used in New Zealand forests for specific soil types and compositions. The results of the study aim to enhance the industry's understanding of the effectiveness of differing compaction methods along with operational aspects for executing compaction.

Methodology:

Site Locations:

Three sites were made available for this study, all being in the north island of New Zealand. Each site had its own distinctive geology and soils with site 2 having two discernible soil types.

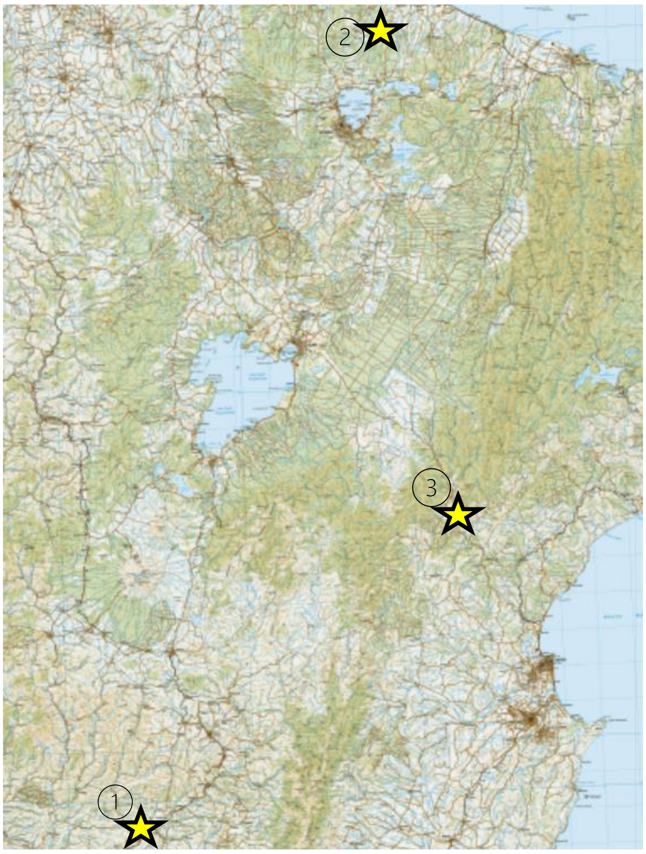


Figure 13: General test site locations

Locations of the testing sites are highlighted in figure 13. The compaction machinery used for each site was whatever was available and commonly used on-site.

Site 1: Craigdean Forest

Craigdean forest is situated 17 kilometres northwest from Huntersville in the Manawatu-Wanganui region. The site soil is composed of a thin loamy soil layer over-lying a hard mudstone known as Papa which is a formation of a blue-grey mudstone which is classified as a sedimentary rock. The majority of construction within this forest is cut and fill earthworks with this this Papa mudstone.

The machinery onsite which was utilised to gather track rolling data was a CAT D6T which is a 21-tonne bulldozer which is the primary machine which carried out track rolling compaction on site for infrastructure, this can be seen in figure 14.

Figure 14: CAT D6T which was used for compaction at site 1.

The track footprint of this machine has a 3.2m^2 ground contact area making the pressure exerted by this machine 64.2 kN/m^2.

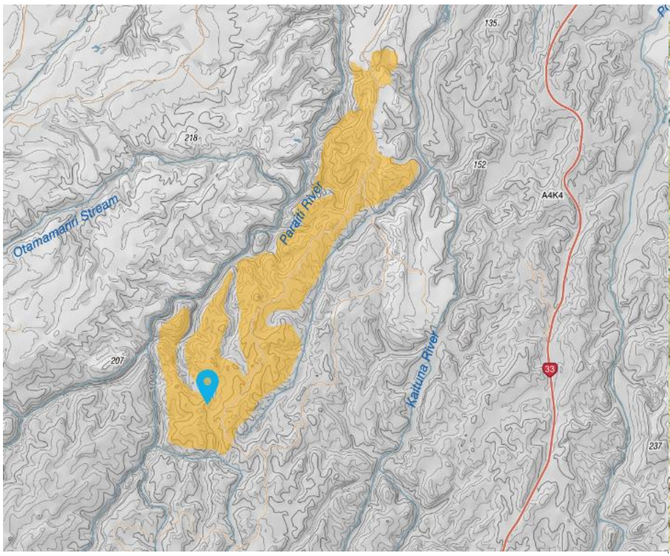
Figure 15: CAT CS-423E which was also used for compaction at site 1.

Onsite there was a CAT CS-423E smooth-drum roller (see figure 15) which is primarily used for compaction of aggregate on the pavement layer. This machine is purpose built for compaction, weighing 6.9 tonne with vibration ability. Specifications show the weight at the drum is 3410kg and a ground contact area of approximately 0.33 m^2. This equates to a ground pressure of 99.7 KN/m^2 for the drum when static, this figure increases when it is vibrating.

Figure 16: Craigdean skid 87 location

Testing within this forest took place on skid 87 (see figure 16), with fill material being sourced from the adjacent cut batter and broken up using the excavator bucket to simulate actual construction conditions of what the fill material would be. The cut batter on site was uniformly made up of Papa mudstone.

Site 2: Pinnacles Forest



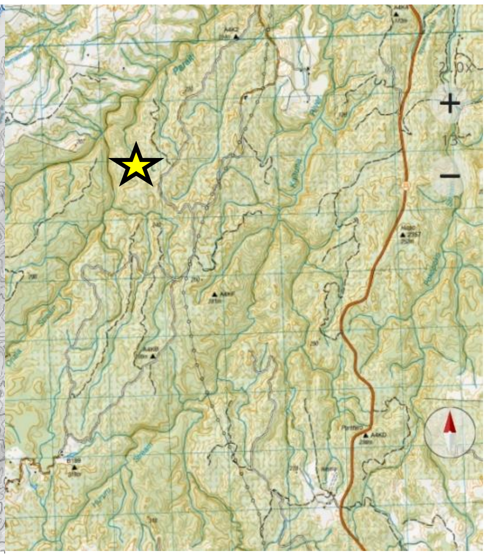


Figure 17: Smaps geology data of Site 2

Figure 18: Testing location of site 2 indicated.

Pinnacles forest is situated west of state highway 33 between Rotorua and Te Puke, the geology of the site according to Landcare research Smaps is predominantly comprised of allophanic soils and pumice.

Overall Smaps regional data suggested that the soil composition is a loamy to clay like material with parts of sandy loam.

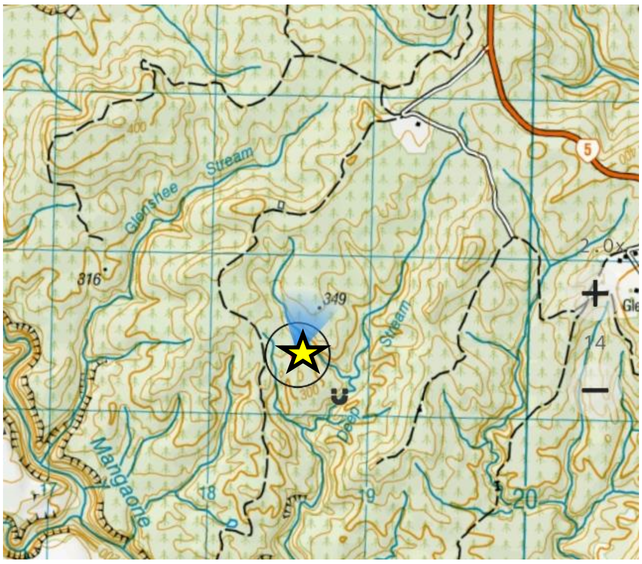
Figure 19: BOMAG BW 211 D smooth drum roller.

The smooth drum roller available onsite was a BOMAG BW 211D (figure 19). This roller like the one utilised at site 1 is primarily used for compaction of aggregate for the pavement layer and rarely used for compaction of fill material. The BW 211D vibratory roller has an operating weight of 10.6 tonne with two vibration frequencies being 30hz and 34hz for deep and shallow compaction. Considering the 5.67 tonne at the drum, an estimated static pressure of 153 kN/m^2 could be expected.

Figure 20: Hyundai 140LC-9 excavator.

Track rolling was tested using a Hyundai 140LC-9 pictured above in figure 20. This 14-tonne excavator given its track area produces 35.3 KN/m^2 of pressure.

Site 3: Glengarry Forest



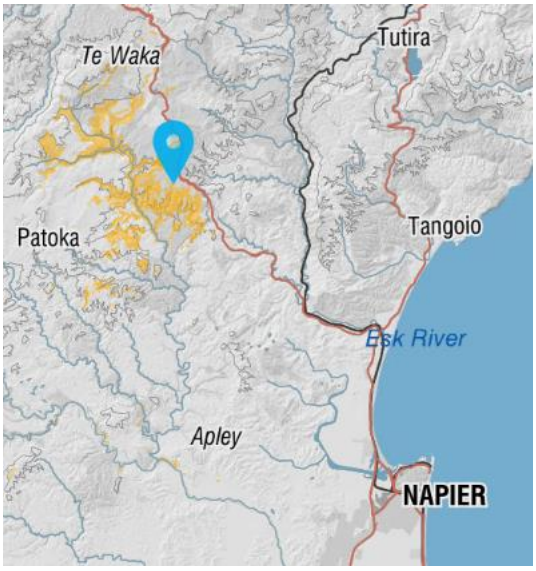


Figure 21: Glengarry Forest test site location

Figure 22: Site geology data according to Smaps

Glengarry Forest is located in the Hawkes Bay region west of state highway 5 approximately 40 minutes north of Napier shown in figures 21 and 22. The geology of the site based on Smaps collected data showed predominantly loamy to clayey soil composition situated above a rock layer with stone content being from 5% to 35%.

Figure 23: CAT CP-663E padfoot roller used on site 2

The Padfoot roller used in Glengarry Forest for site 2 was a CAT CP-663E pictured above in figure 23. This roller is utilised by the onsite earthwork's contractors for surface layer compaction of skids or landings. This 16.8 tonne vibratory compactor applies 11.3 tonnes of weight at the drum, an accurate estimation of the pressure exerted by this machine could not be achieved.

Figure 24: Kobelco SK210LC excavator

Track rolling was carried out using a Kobelco SK210LC seen above in figure 24. This 22-tonne excavator is used onsite predominantly for excavation and earthworks of cut and fills. This machines tracks enable it to have a ground contact area of 4.7m^2 allowing it to apply 47 KN/m^2.

Data Collection:

Procedure for Density, Moisture Content Assessment:

Despite the use of a nuclear gauge being preferred, it would require certified personal, exceeding the budget and making it unsuitable for this comparative study. Determining density and MC was achieved through collecting surface samples along the test layer as indicated in figure 33. Surface sampling was be completed after the final complete pass of each compaction method, with sampling consisting of digging a cone shaped hole into the compacted surface and retrieving everything from that hole into an airtight bag. After which a plastic liner was placed within the hole and filled up with water, recording the volume of the hole.

Figure 25: Example photo of taken surface sample

This process can be seen in figure 25 with the final recordings of volume, site location, layer number and sample number being recorded on the bag. An example of the data and results from this process is shown as appendix D.

Figure 26: Example image of surface samples in oven

Following the collection of soil samples, a laboratory analysis was undertaken at the University of Canterbury with the samples being put in the oven shown in figure 26. The analysis involved the following steps:

1. **Initial Recording**: The collected soil samples were carefully weighed, and their respective tin weights were recorded for accurate measurement.
2. **Drying Process**: The samples were placed within controlled-temperature ovens set at a constant temperature of 110°C as recommended by literature. This ensured the complete removal of all moisture content present within the samples.
3. **Periodic Mass Checks**: Mass checks were conducted at both 72 and the 96-hour interval to verify the stability of the sample masses which was also advised by literature. Consistent masses over this period indicated the elimination of all moisture from the samples.
4. **Calculation of Moisture Content**: By comparing the dry mass (obtained after the drying process) to the initial wet mass, the MC of the soil was determined. This calculation is fundamental to assessing compaction effectiveness and relating back to the site conditions.
5. **Dry Density Calculation:** The dry mass of the soil samples, in conjunction with the recorded volume measurements, allowed for the calculation of dry density, which is another critical parameter for compaction analysis. This calculation is shown in equation 3.

$$Dry\ Density\ \left(\frac{kN}{m^3}\right) = \left(\frac{mass\ of\ dry\ soil}{hole\ volume}\right) * 9.81 \quad (3)$$

Scala Penetrometer testing:

Figure 27: Example image of Scala penetrometer in use following machinery pass.

For this study the use of a Scala penetrometer was implemented due to the fact strength can be assessed in differing depth intervals. This equipment involves a standardised cone on an extension rod which is driven into the soil by dropping a standardized weight from a standardised height. Figure 27 above shows the Scala penetrometer in use following machinery passes. The methodology for using this equipment follows industry standards by recording the number of blows required for the cone and rod to penetrate through each 100mm depth range down to a depth of 800mm. The Scala penetrometer was employed to assess soil strength throughout the entire profile of the fill layer, offering a comprehensive analysis for beyond the surface measurements. This method facilitated the evaluation of soil strength variations with increasing depth, enabling direct comparisons between different compaction methods. By assessing the effect of successive passes on soil strength with depth, the study identified the optimal number of complete passes required for each compaction method based on the specific soil composition. Example results can be seen in appendix E and F.

Maximum Dry Density & Optimal Moisture Content:

Large bags of fill material were collected for each soil type for standard proctor tests to be conducted. Standard Proctor tests are regarded as foundational for their capacity to determine soil compaction characteristics with precision. The method involves the systematic filling of a mold in three distinct layers, each subjected to compaction through the controlled release of a 2.5 kg weight from a height of 30 centimetres 25 times per layer.

Figure 28: Process of carrying out standard proctor testing.

The compaction setup is shown in figure 28 for reference. This standardised procedure is carried out multiple times, initially beginning by adding water to an oven dried sample and progressively adding additional water to increase the MC. The density achieved through this compaction process is recorded and plotted against the MC, resulting in a characteristic compaction curve. Example test results from these tests can be seen in appendix A and B.

By plotting the MC and dry densities of the surface samples on the compaction curve, a visual representation of the compaction achieved by each method under specific site conditions emerges. This graphical approach provides a means of assessing compaction performance at the surface level. The MC of the surface samples, when averaged, serves as a key determinant in finding the theoretical MDD for the site conditions at time of compaction. This MDD, derived from the on-site MC allows for the level or degree of compaction to be found, when compared against the surface samples. This is shown below in equation 4.

$$Degree\ of\ compaction = \frac{Sample\ Dry\ density\ \times 100\%}{Theoretical\ Maximum\ dry\ density} \quad (4)$$

Soil type/composition:

The United States Department of Agriculture (USDA) Soil Texture Triangle was used to classify each soil based on physical composition which is a key factor which influences how soils act under compaction. The triangle features three axes representing the percentage of sand, silt, and clay in a soil sample. The USDA soil texture triangle is displayed in figure 29.

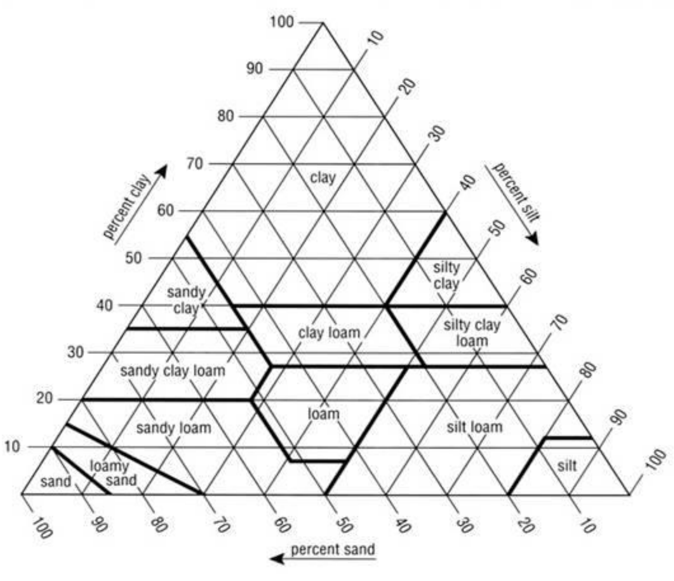


Figure 29: USDA soil texture classification triangle.

Oven dried soil samples are placed within a dry sieve and onto a vibratory sieve shaker for three hours to break up the soil into the separate sizes, then weighing each sieve allowed the percentage sand, silt, clay particles to be determined. Once these values are obtained, they are plotted on the texture triangle. The intersection of the three percentages on the triangle identifies the specific soil texture class, such as sandy loam, clay, or silty. An example for the results achieved from the dry sieve analysis is show as appendix C.

Site Layout:

Site layout for each compaction method was kept consistant with fill being sourced from virgin subgrade, broken up with an excavator and placed in a layer of 750mm ± 50mm thickness to simulate a representative lift. Locations of these layers were on pre constrcuted skids to best avoid interuption to the current earthworks operations.

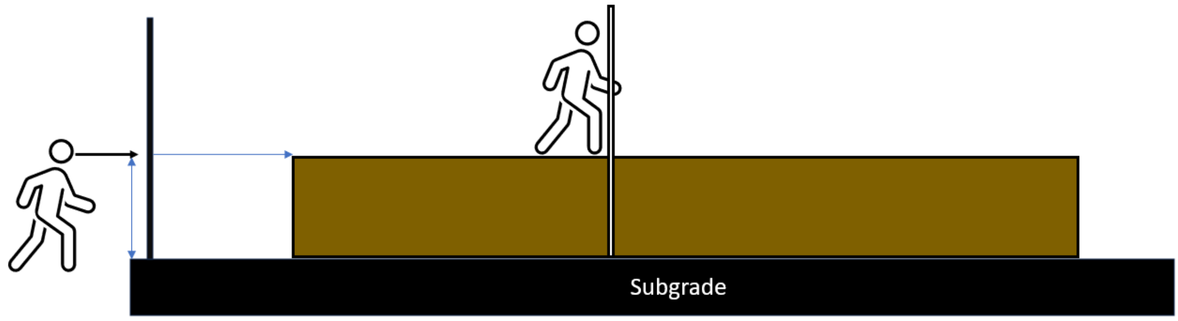


Figure 30: Depth measuring methodology.

Depth was determined with a marked pole which was pushed into the fill layer at points along the length of the test layer visulised above in figure 30. By utalising the marker pole as a probe and plunging it into the soft fill untill the firmer subgrade below was reached it allowed the determination of depth.

Layer depth was additionally controlled by placing a vertical marker pole adajent to the test area with marked heights on it and the use of a clinometer, shown in figure 30. By looking through the clinometer at the horzontal, peaks and troughs can be found and fixed by the operator or marked out and avoided when testing commenced.

Figure 31 & 32: Image displaying how desired 750mm layer thickness was achieved.

In addition to this the marker pole was placed beside the fill layer during its construction acting as a guide for the excavcator operator. This is methedology can be seen being carried out in images 31 and 32.

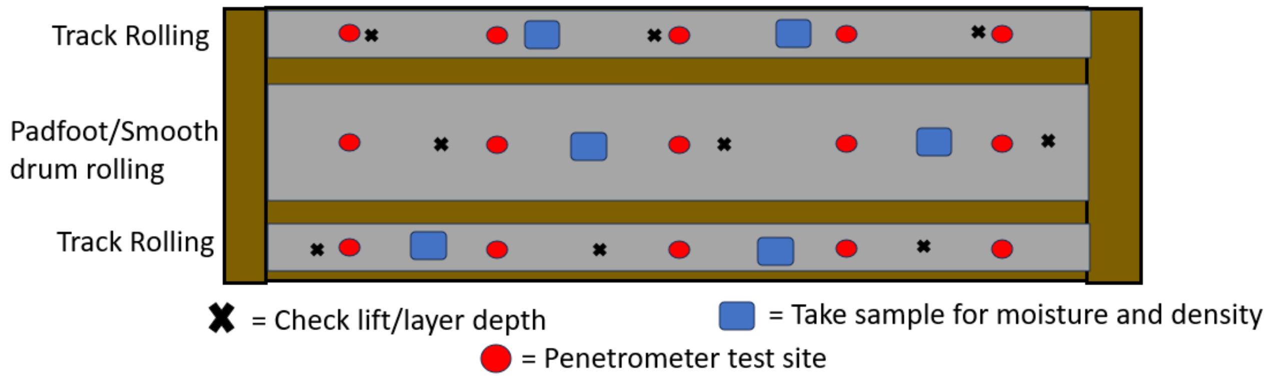


Figure 33: Testing layout diagram

Each test layer was constructed to a test length of roughly 1.5 times the effective surface track length as well as a width greater than that of the tracked machinery to allow for testing of both track-rolling and purpose-built rolling on the same fill layer. Rollers were instructed to compact the section of the layer inbetween the track-rolling marks, as seen in figure 33. It was completed this way to avoid differences in layer and fill characteristics between the track-rolling and padfoot testing. Scala penetrometer test locations as well as sample locations are across the length of the layer, with testing of track-rolling being completed on both track marks.

Data was be collected after each successive pass for the initial 4 passes, with additional tests on the 6^{th}, 8^{th}, and 10^{th} pass as well as initial tests prior to compaction to determine the conditions of the soft fill layer. A complete pass was classified as a full forward and backward pass over the fill layer, with testing being completed only on parts which either the roller or tracks completely went back and forwards over. It was decided that for all sites the purpose built compaction rollers had vibe on at the operators preferred setting, unless it appeared the soil had high MC and implementing the vibration would induce liquefaction in which case the vibe was turned off.

Results:

Site 1, Papa mudstone:

Soil samples from the Papa at Craigdean forest were collected to determine soil characteristics and correlate the results back to the conditions at the time of compaction for Papa mudstone.

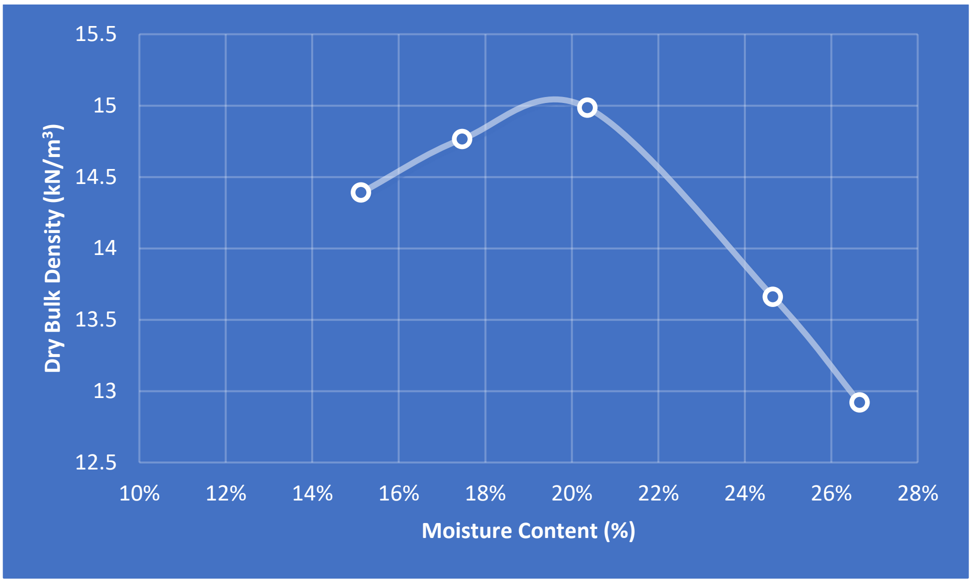


Figure 34: Compaction curve for Papa soil found at Site 1.

Standard proctor testing on the site 1 soil samples yielded a compaction curve (figure 34) indicating that a OMC at 19.5%, corresponding to a MDD of approximately 15.1 kN/m^3 for the compaction effort associated with the standard proctor test.

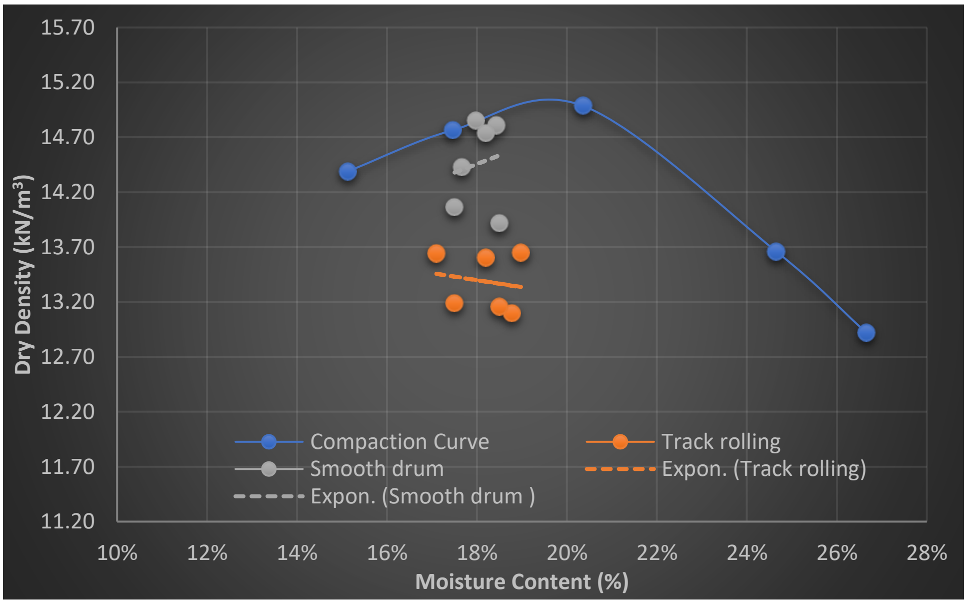


Figure 35: Site 1 compaction curve with track-rolling and smooth-drum compaction data

Testing allowed the dry densities and MC of the on-site surface compaction samples to be recorded and plotted against the compaction curve, seen in figure 35. Track-rolling samples averaged a 18.2% MC (standard deviation of 0.67%), while smooth-drum samples averaged 18.0% MC (standard deviation of 0.37%). Showing the conditions for both compaction methods to be comparable.

Figure 35 visualizes dry densities of both compaction methods against the compaction curve for Papa mudstone. Track-rolling achieved an average of 13.39 kN/m^3 (standard deviation of 0.245 kN/m^3), and smooth drum compaction averaging 14.47 kN/m^3 (standard deviation of 0.366 kN/m^3). With an overall average of 18.11% MC, from the compaction curve the MDD given the site conditions is approximately 14.9 kN/m^3. From this the level of compaction at the surface given the site conditions which the CAT D6T delivered track-rolling is 89.86% (standard deviation of 1.64%) of the MDD whereas the CAT CS-423E smooth-drum roller was 97.10% of the MDD (standard deviation of 2.45%).

Site 1 Track-Rolling results:

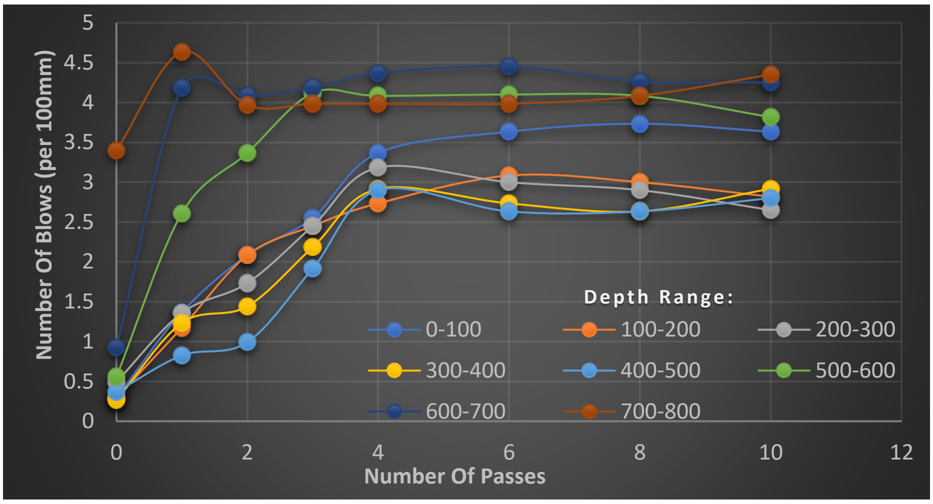


Figure 36: Averaged penetrometer results for site 1 tracking-rolling

Figure 36 provides a graphical representation of the averaged Scala penetrometer results for the layers subjected to track rolling. Notably, the initial spike in the number of blows within the 700-800mm depth range, suggests that the layer thickness was appropriately established given that the high results are attributed to subgrade contact. The figure further demonstrates that with each successive pass, the tested layer undergoes progressive consolidation, resulting in a reduction in volume. This consolidation is evident as the number of blows required for the 600-700mm depth range stabilizes after a single complete pass, while the 500-600mm depth range achieves a similar stability after three complete passes. Both at levels comparable to the 700-800mm layer, meaning the fill layer which initially began at 750 compressed to 500mm after the 3rd complete pass.

Results reveal a distinct pattern in the number of blows necessary to penetrate the surface layer (0-100mm depth) during compaction with a substantial increase in the number of blows during the initial four passes. Progressive passes had diminishing effects and eventually plateaued after eight passes at a value just below the strength of the original subgrade of 3.5 to 3.75 blows per 100mm. Within the depth range of 100-500mm, a similar trend is observed, with compaction tending to plateau after four to six complete passes, reaching a value slightly greater than half of the subgrade strength of around 2.75 blows per 100mm.

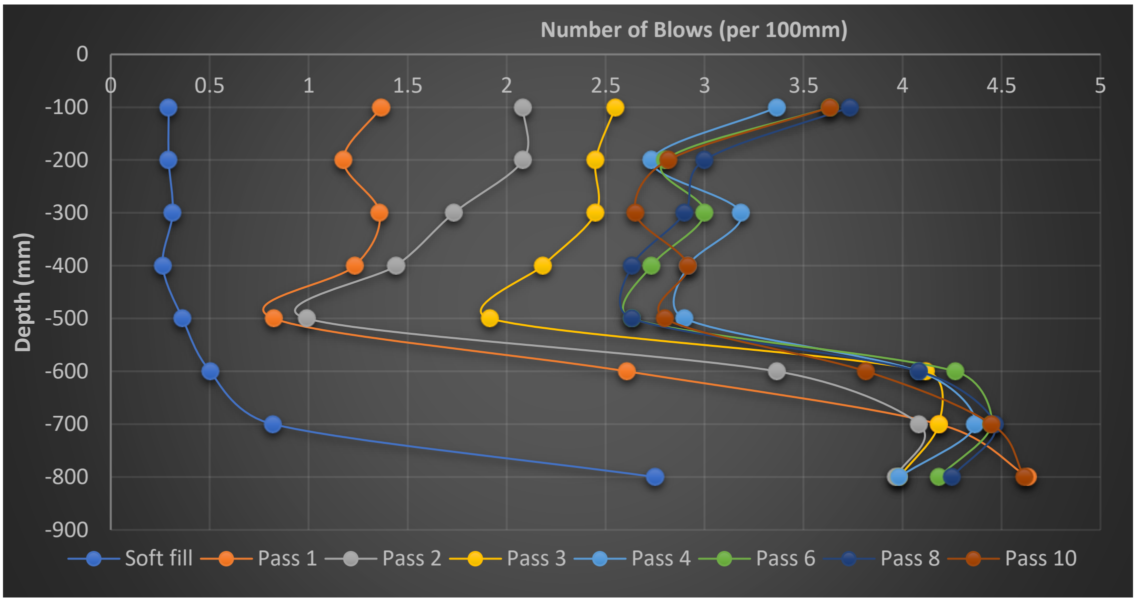


Figure 37: Averaged track-rolling data showing relationship between depth and number of blows for each pass.

Figure 37 provides a visual representation of the evolving strength characteristics within the compacted layer across varying depths and successive passes. Results are similar to figure 36 how a progressive increase in strength can be seen with each consecutive pass, until the 4^{th} to 6^{th} pass where after which results remain relatively constant. Furthermore, the track-rolling data reveals a discernible pattern of declining soil strength from the surface to a depth of 500mm for all passes. Followed by a notable spike in strength within the depth range of 500mm to 800mm where the subgrade is contacted.

Site 1 Smooth-Drum rolling results:

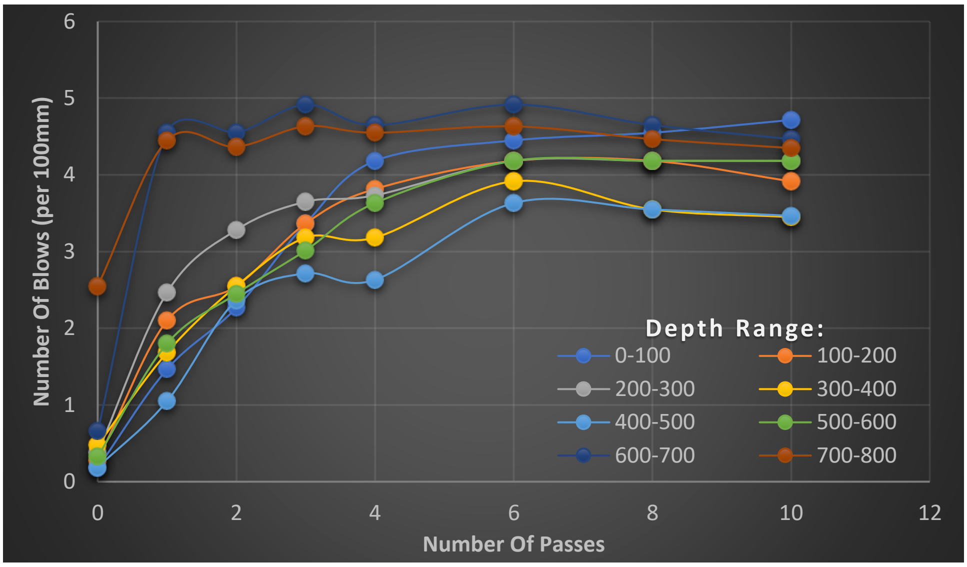


Figure 38: Site 2 smooth-drum roller averaged results

Figure 38 shows the averaged Scala penetrometer results for the layers subjected to smooth drum rolling. The 200mm to 600mm depth range shows a notable and consistent upward trend in strength with successive passes. Reaching a peak by the sixth pass followed by a plateau, and in certain instances a decline is observed.

For the depth range of 700mm to 800mm, the dataset shows an initial increase showing the lift thickness of 750mm was achieved. The depth range of 600mm to 800mm maintains relatively consistent values at approximately 4.5 blows per 100mm after the initial pass, albeit with some minor fluctuations. In contrast, the surface layer (0 – 100mm) demonstrates substantial strength growth with each successive pass. Although the rate of increase reduces after the 4th pass, there is a steady rise in strength, extending through the tenth pass.

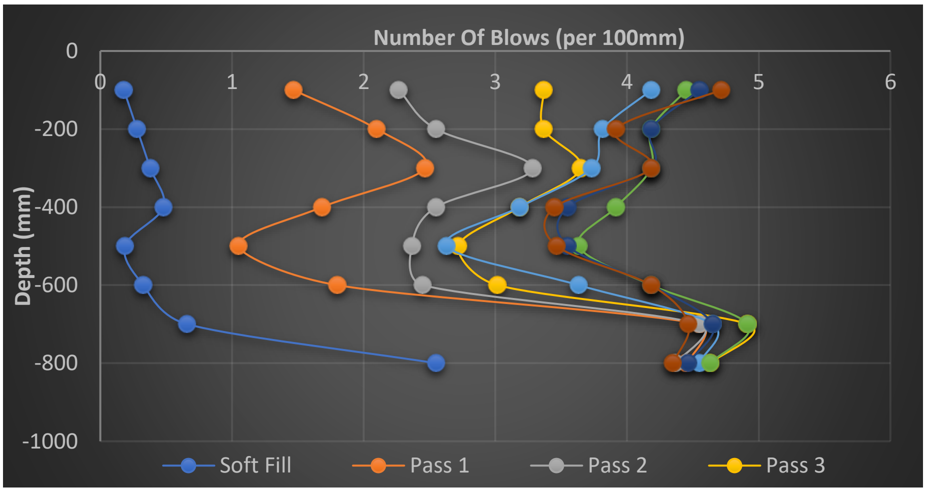


Figure 39: Averaged smooth-drum Scala data showing relationship between depth and number of blows for each pass.

In Figure 39, the smooth-drum roller compaction conducted at site 1 reveals a consistent trend that after the 6th pass, subsequent passes show comparable strength across the profile of the layer. During the initial three complete passes (passes 1 to 3), there is an observable upward trend in strength from the surface down to a depth of 300mm. However, beyond this depth, all data series (excluding the soft fill) demonstrated a declining trend, reaching its lowest point at 500mm depth. Following this decline, there is a clear upward trend in strength, peaking at around 4.5 blows per 100mm at a depth of 700mm, after which it stabilizes.

Site 1: Comparison between compaction methods:

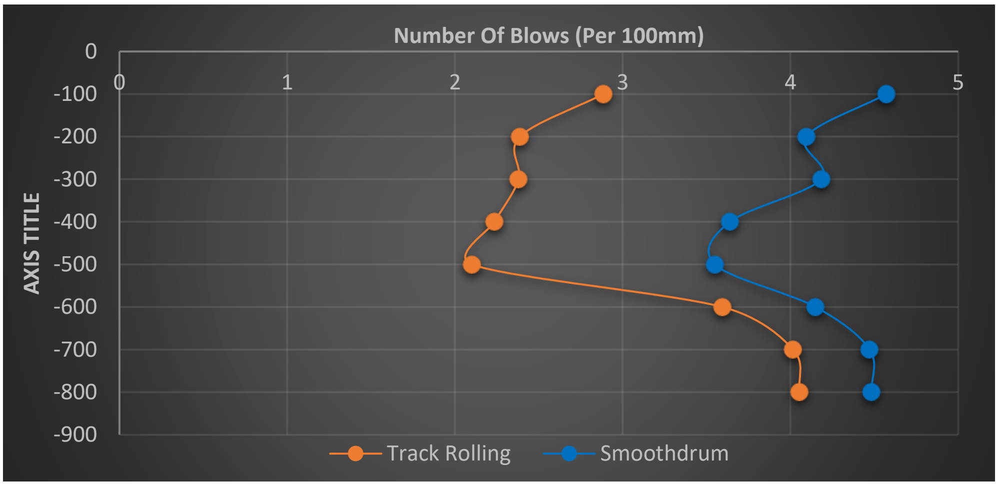


Figure 40: Site 1 comparison between track-rolling and smooth-drum averaged results.

When conducting a comparative analysis of the results between track-rolling and smooth-drum roller compaction, as depicted in Figure 40, a discernible pattern emerges. The smooth-drum compaction achieved 4.57 blows per 100mmm which is 36.9% greater compaction at 100mm depth then track rolling, this progressively increases to 43% difference at 300mm depth. On average, the smooth-drum roller demonstrates 25% greater compaction than track-rolling within the 500mm depth range. Beyond this depth, both compaction methods converge, yielding similar results.

It's noteworthy that both methods exhibit similar trends, characterized by a decreasing number of Scala penetrometer blows at 500mm depth. Figure 40 further illustrates that depths exceeding 500mm, show a notable upward trend in soil strength, down to a depth of 700mm where it stabilizes. This is due to the fill layer being compressed over the course of compaction to a thickness of 500mm.

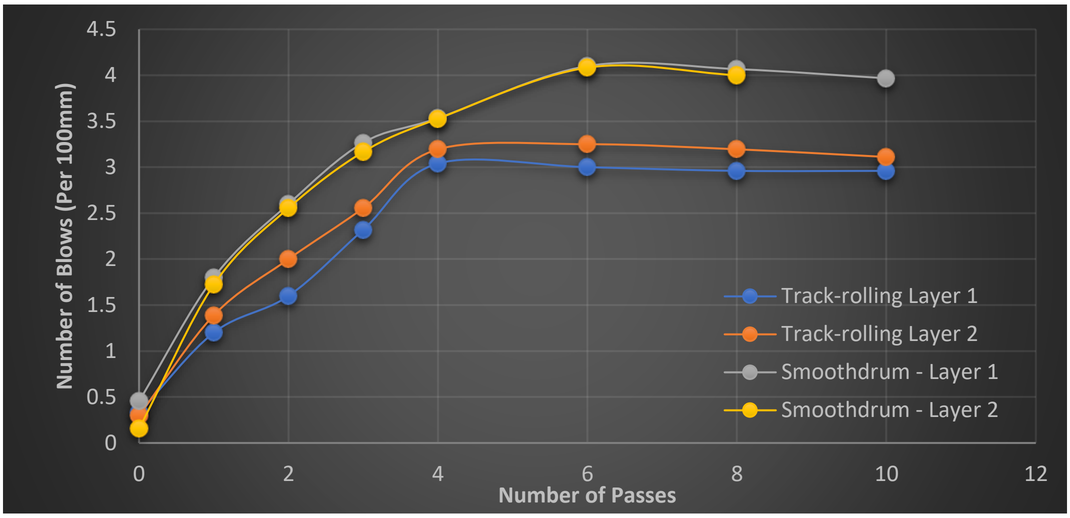


Figure 41: Site 1 track-rolling & smooth-drum comparison with averaged results.

Figure 41 provides a comprehensive comparison of the results for track-rolling and smooth-drum roller compaction at site 1. This data is only considering the initial 500mm of the layer as this is what it compressed to due to compaction. On average, track-rolling yields results approximately 12% lower results than those obtained through smooth-drum rolling.

Both compaction methods exhibit similar trends. Specifically, the track-rolling data which stabilizes after the fourth complete pass, registering around 3 to 3.25 blows per 100mm. Whereas the smooth-drum roller method reaches its peak of around 4 blows per 100mm, by the 6th pass and then plateauing. Additionally, it is important to highlight that both methods demonstrate significant increases in soil strength compared to the initial results obtained from the soft fill, particularly after the first pass.

Site 2, Clay soil:

It was observed that the composition of the soil varied between locations on site 2 within Pinnacles Forest. Consequently, for the sake of clarity and precision, the results have been segregated into two distinct sections corresponding to these differing soil types.

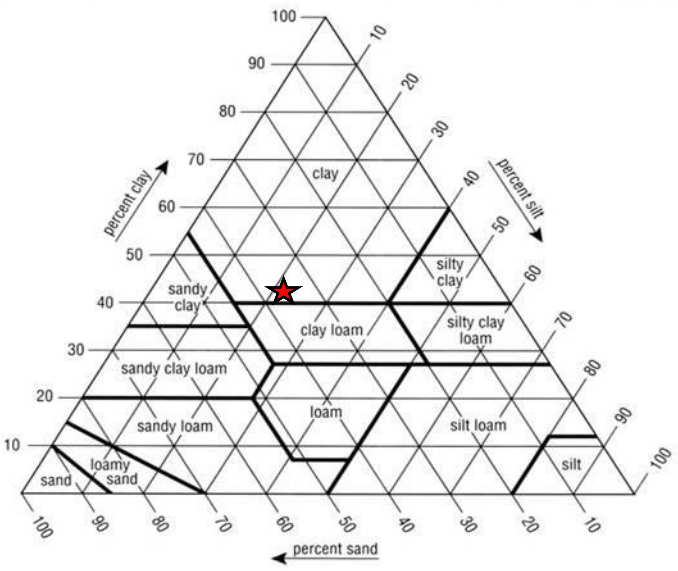


Figure 42: Soil classification chart identifying site 2 clay soil.

Figure 42 presents a soil classification chart identifying the characteristics of the initial soil type encountered at site 2. The dry sieve analysis revealed this soil comprised of 36.63% sand, 22.86% silt, and the remaining being clay. This composition positions the soil within the clay classification near the threshold for a clay loam.

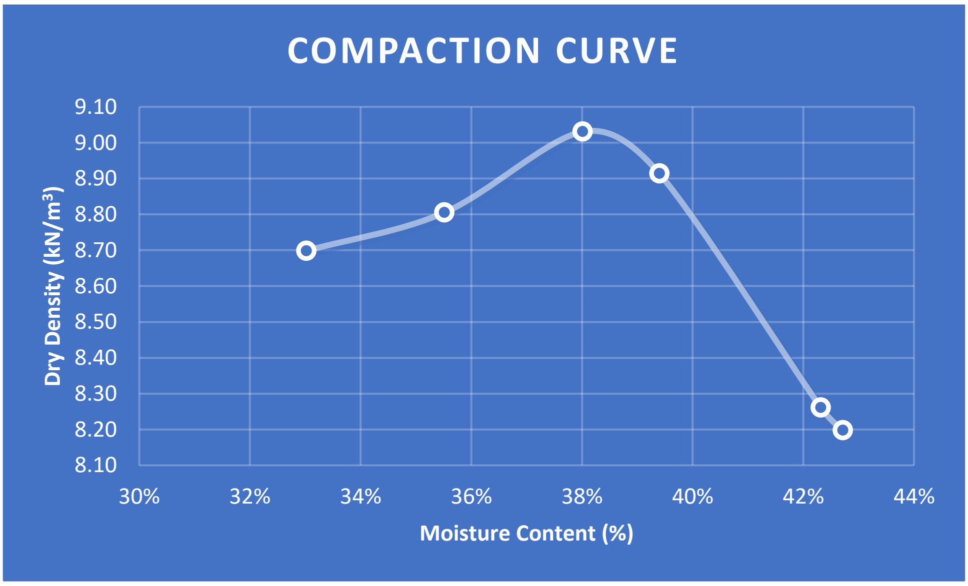


Figure 43: Site 2 day1 soil compaction curve from standard proctor test results

Standard Proctor tests were conducted on clay soil samples from site 2. The results, as illustrated in Figure 43, provide an indication of the soil's compaction characteristics. The OMC can be derived from the compaction curve to be 38.2% for the clay soil, corresponding to a MDD of 9.04 kN/m3.

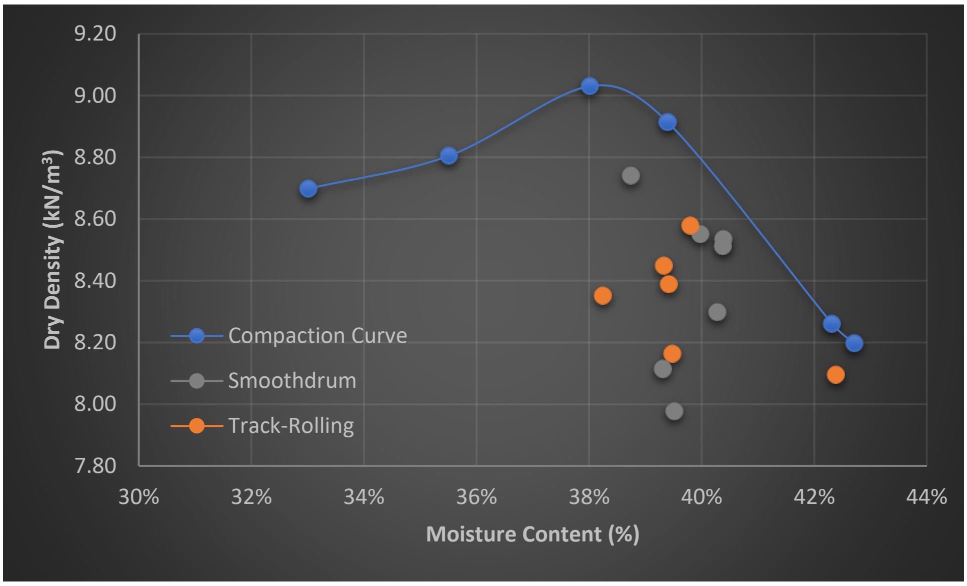


Figure 44: Site 2 clay soil compaction curve with track-rolling and smooth-drum compaction data

Figure 44 presents the data derived from both track-rolling and smooth drum surface compaction samples. The track-rolling samples indicate a MC of 39.78% (standard deviation of 1.4%), while the smooth-drum samples exhibit a MC of 39.97% (standard deviation of 0.5%). Both compaction methods show that on the day of compaction, the soil condition was on the wet side of the compaction curve. The data further shows that both track-rolling and smooth-drum compaction techniques yield comparable results, with average dry densities of the surface samples measuring 8.34 kN/m^3 and 8.33 kN/m^3, respectively.

The averaged MC of both compaction methods was 39.79%. This MC corresponds to an estimated MDD of 8.87 kN/m3, derived from the compaction curve. The level of compaction achieved by smooth drum rolling was 93.92%, falling within a range of 91.18% to 96.67% with one standard deviation. Track-rolling, on the other hand, achieved an average compaction level of 94%, with one standard deviation ranging between 91.97% and 96.02%. These area relative to the MDD at the MC at time of compaction.

Site 2, clay soil track-rolling results:

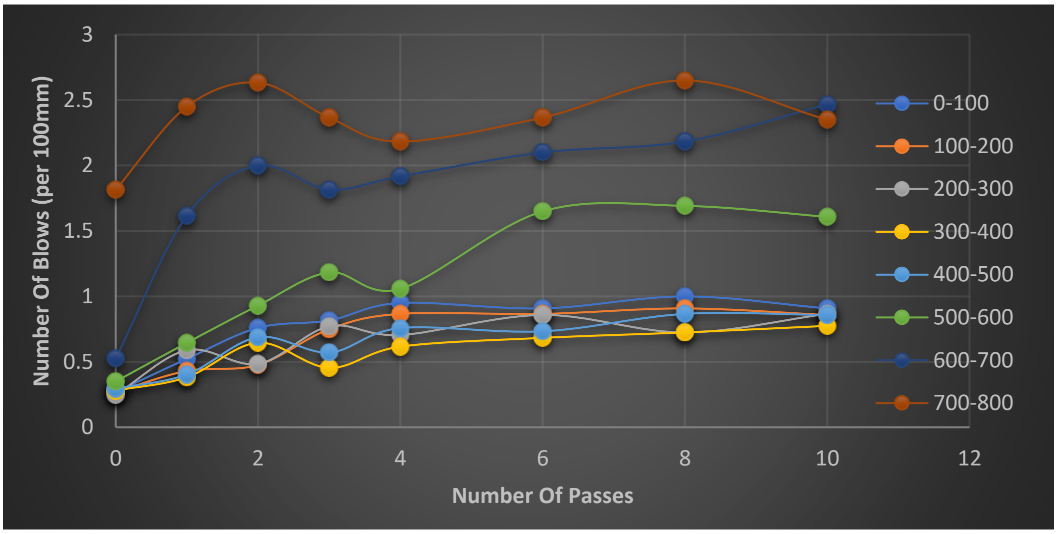


Figure 45: Site 2, clay soil, averaged track-rolling results

Figure 45 shows the averaged results obtained from the test layers subjected to track-rolling compaction for site 2's clay soil. Following the initial machine pass, the 600mm to 800mm depth range displays notably higher results compared to other depths, maintaining relative consistency at approximately 2.25 blows per 100mm with moderate fluctuations. This shows the desired 750mm lift thickness was achieved. Within depth ranges from the surface down to 500mm, the results exhibit a similar trend with gradual increases in strength with successive passes up till the 4th pass where it plateaus around 0.85 blows per 100mm.

The depth range of 500mm to 600mm shows a steady increasing trend, with the exception of a dip observed at the 4th pass. This trend continues until the 6th pass, at which point it peaks and follows a slightly negative trend. It overall shows standalone results with no similarities in the values to other depth ranges.

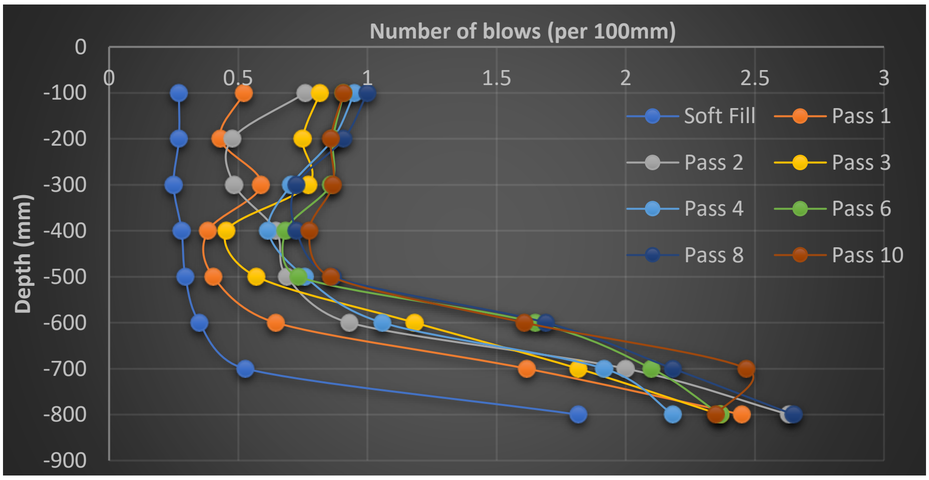


Figure 46: Site 2, clay soil track-rolling results showing strength correlated to depth of differing passes.

Figure 46 shows the track-rolling data obtained from clay soil at site 2 and the relationship between soil strength and depth during successive passes. In all passes, soil strength maintains relatively stable with moderate fluctuations until a depth of 500mm. Beyond which a discernible upward trend is observed extending to the 700mm to 800mm depth range. With each subsequent pass of the excavator, the upward trend in strength for the fill persists until the 4th to 6th pass, at which point soil strength reaches a comparatively consistent level around 0.82 blows per 100mm.

The soft fill prior to any passes shows readings averaging around 0.28 blows per 100mm down to 0.5 blows at 700mm, this is followed by a notable increase in strength to 800mm depth, reaching approximately 1.8 blows per 100mm. Therefore, also showing the depth of the layer was around the desired 750mm depth.

Site 2, clay soil smooth-drum roller results:

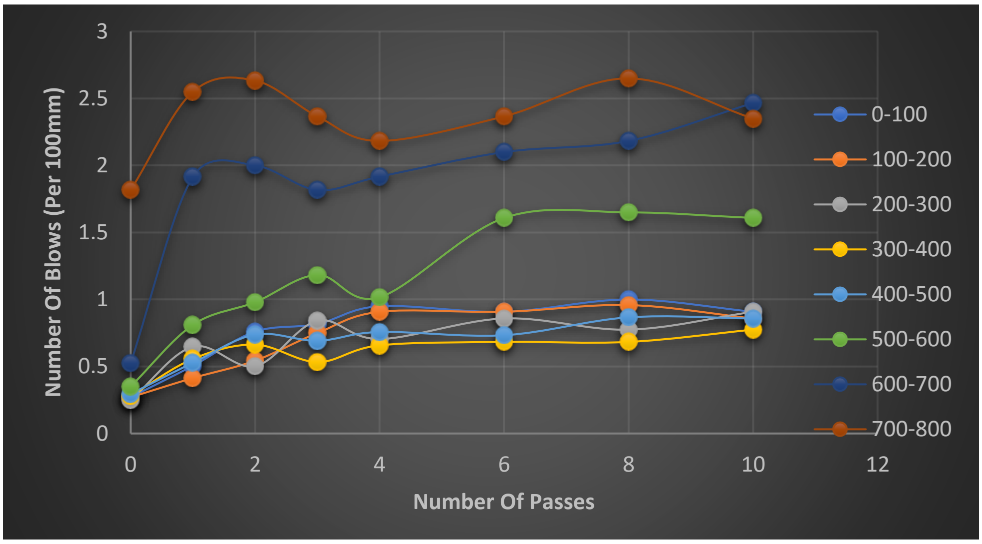


Figure 47: Site 2, soil 1, averaged smooth-drum roller results.

Figure 47 shows the averaged results obtained through smooth drum Scala penetrometer testing, highlighting the relationship between soil strength and number of passes across various soil depths. For depth ranges spanning from the surface down to 500mm, there is a increasing trend shown up till the 4th pass, where soil strength stabilizes at approximately 0.75 blows per 100mm. Depth ranges spanning 600mm to 800mm show considerably higher soil strength compared to other depths. After the first pass the 600mm to 700mm range records strength readings ranging from 1.8 to 2.65 blows per 100mm, while the 700mm to 800mm depth range starts with an initially high value.

Figure 47 shows similar trend that track rolling did with the depth range of 500mm to 600mm having standalone values, reaching 1.65 blows per 100mm after the 6th pass. Beyond which it plateaus at a strength level between the results observed in the depth ranges above and below it.

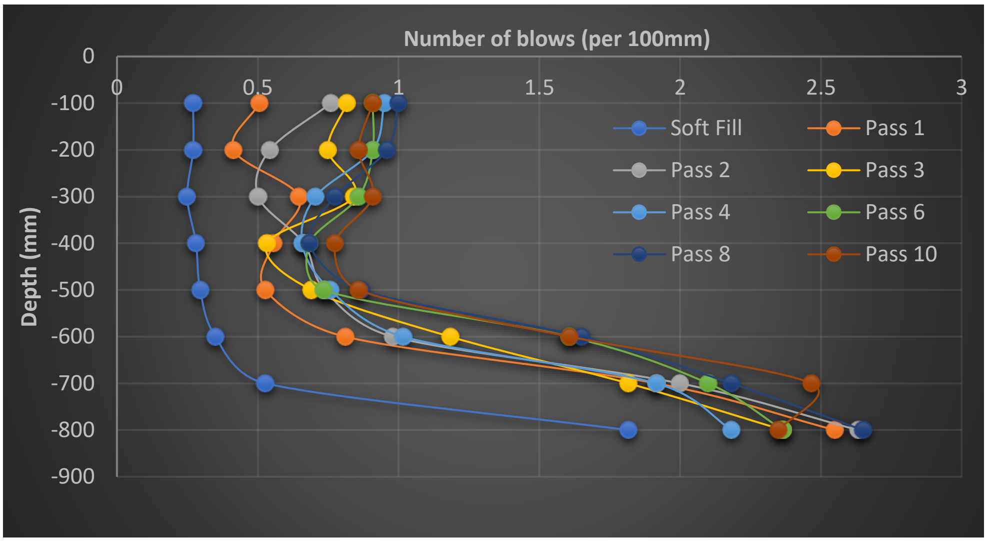


Figure 48: Site 2, clay soil smooth-drum roller results showing strength correlated to depth of differing passes.

The data presented in Figure 48 is a result of averaging Scala penetrometer findings from layers subjected to smooth drum rolling compaction in clay soil at site 2. There are notable increases in strength after each successive pass up to the 3rd pass, after which the increases in strength reduce to the 6th pass where after which the strength remains relatively constant. Passes 4 to 10 exhibit strength levels just below 1 blow per 100mm at the initial depths, with a slight decreasing trend observed down to 0.75 blows at 500mm depth. However, beyond this depth, all results except for the soft fill, exhibit an upward trend from 600mm depth to either 700mm or 800mm. The data gathered for the soft fill is identical to that in the track rolling results given that the test layer of fill was the same for both.

Site 2, Clay soil: Comparison between compaction methods:

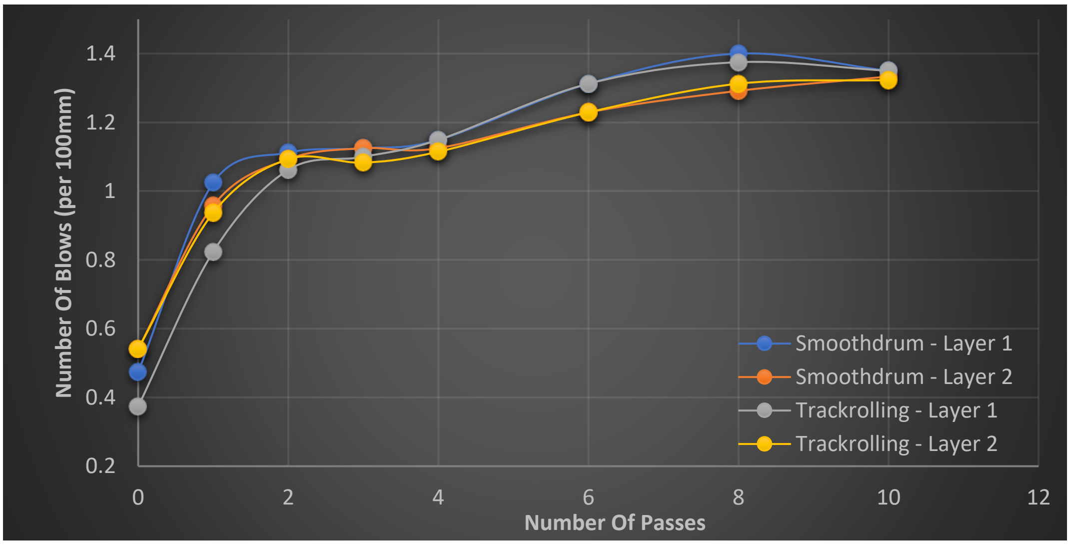


Figure 49: Site 2 track-rolling & smooth-drum comparison with averaged results.

Figure 49 shows the averaged data for smooth drum and track-rolling data for each layer tested for depths down to 500mm to avoid the results from the subgrade. The common trend across all data taken on the clay soil at site 2 is that the initial 2 passes of the compaction machinery show the largest increases in strength up to 1.1 blows per 100mm followed by a plateau with a slight increasing trend till the 4th pass, after gradual increases with each pass are observed up until the 8th pass where a second plateau is shown at around 1.3 to 1.4 blows per 100mm. After the 4th pass there emerges a difference in strength between layers with minimal difference between machinery results for either layer. However, after the initial pass on layer one the track-rolling results are 19.6% lower than that of the smooth drum, however this difference soon diminishes with the following pass.

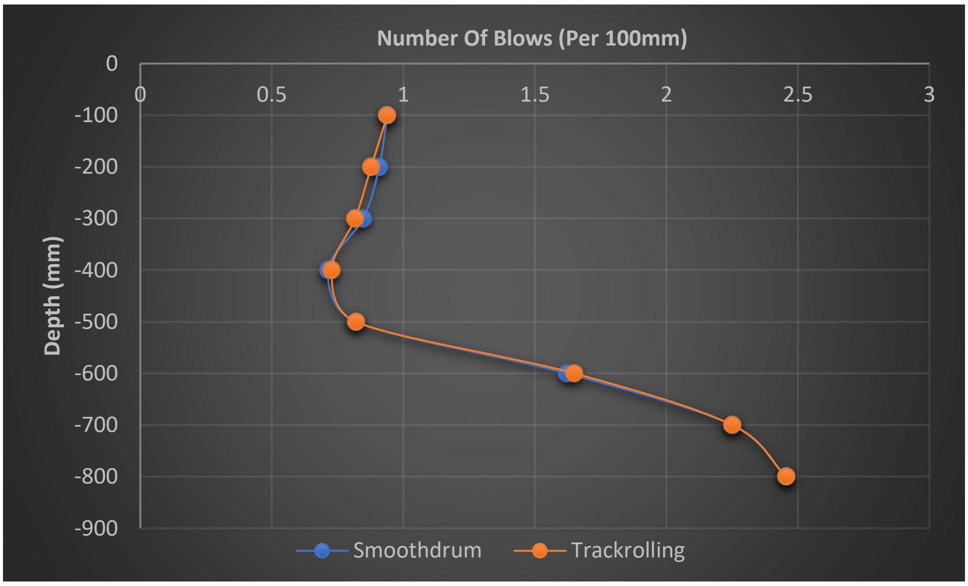


Figure 50: Site 2 comparison between track-rolling and smooth-drum averaged results.

Figure 50 shows the averaged overall results for both track rolling and smooth drum rolling compaction considering strength in number of blows per 100mm and depth. It shows that both compaction methods follow nearly identical trends. Both methods show that the weakest part of the compacted layer is at 400mm in depth, which was the depth of the fill layer after compaction.

Site 2: Rhyolite soil

Within Pinnacles Forest (site 2), it became evident that on site there was an on-site rhyolite deposit which was regularly utilised by earthworks contractors for subgrade material. Further testing was conducted exclusively on these rhyolite-based soil layers.

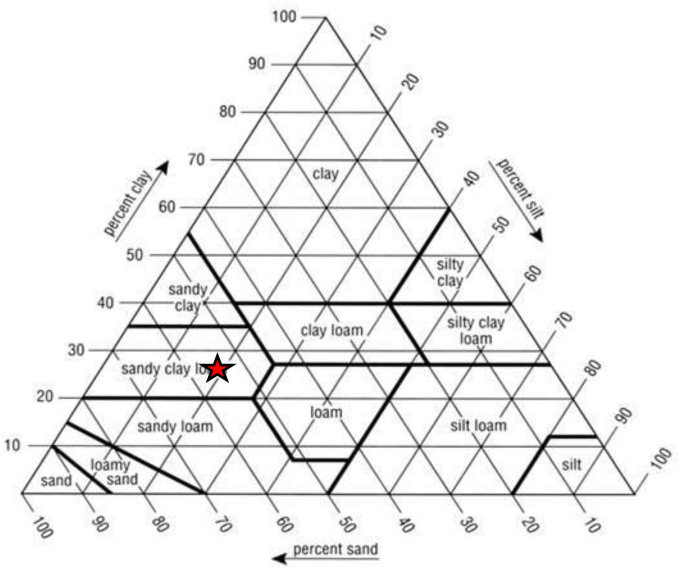


Figure 51: Soil classification chart identifying site 2 soil 2.

Conducting a sieve analysis on the rhyolite-based soil found at site 2 revealed its composition: 55.09% sand, 19.92% silt, with the remaining fraction being clay. This analysis, as depicted in Figure 51, classifies the rhyolite soil as a sandy clay loam.

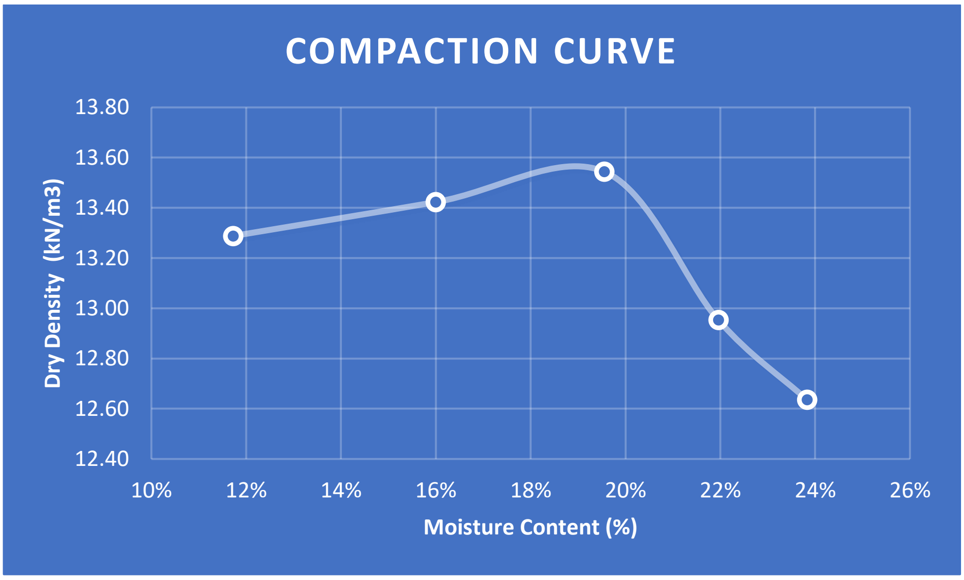


Figure 52: Site 2, soil 2 compaction curve from standard proctor test results

The rhyolite samples obtained from site 2 underwent standard proctor testing, with the results presented in figure 52. The OMC revealed by the standard proctor test was 19% with a corresponding MDD of 13.55 kN/m^3.

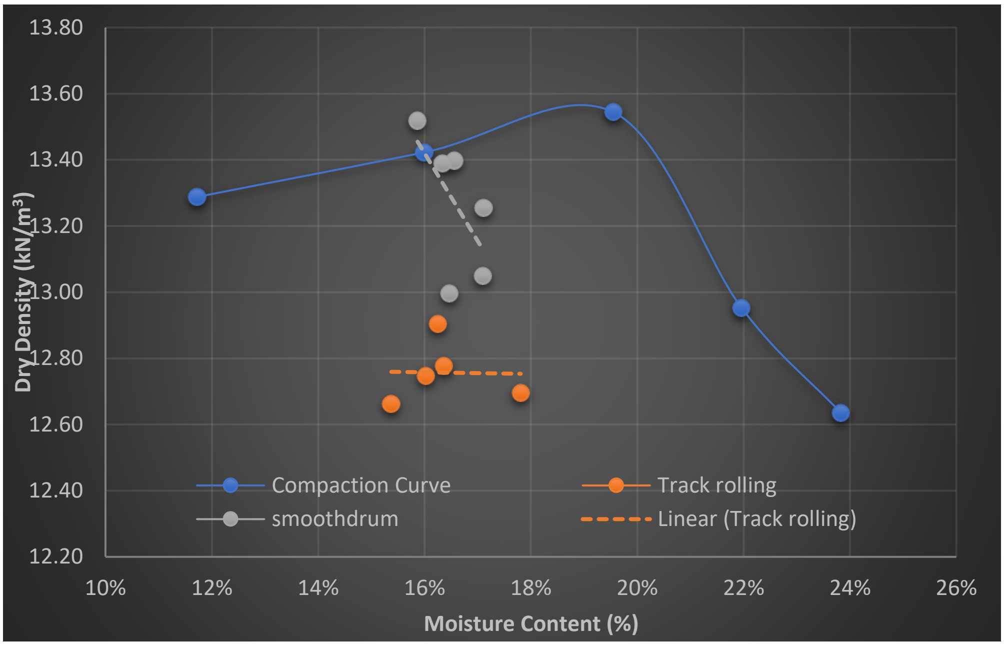


Figure 53: Site 2 rhyolite compaction curve with track-rolling and smooth drum surface compaction sample results.

Inputting the data gathered from the surface samples of both track-rolling and smooth drum rolling in with the compaction curve, enables a comparative analysis to be done as shown in figure 53. Track-rolling samples had an average MC of 16.37% (standard deviation of 0.89%) while smooth drum rolling samples had an average MC of 16.57% (standard deviation of 0.43%). In terms of average surface dry density, track-rolling achieved 12.76 kN/m^3 (standard variation of 0.09), whereas the smooth drum had an average dry density of 13.27 kN/m^3 (standard variation of 0.19). Considering the average MC for both compaction methods arrive at an overall average MC of 16.48%. Considering this MC on the compaction curve, it corresponds to a MDD of approximately 13.45 kN/m^3.

Comparing this MDD for the on-site conditions to the average dry density of both track-rolling and smooth drum roller surfaces provides insights into the level of compaction achieved—94.85% and 98.64%, respectively. Examining the results within one standard deviation, track rolling achieved compaction levels ranging from 94.15% to 95.54%, while smooth drum rolling achieved levels between 97.23% and 100.05%.

Site 2 rhyolite track-rolling results:

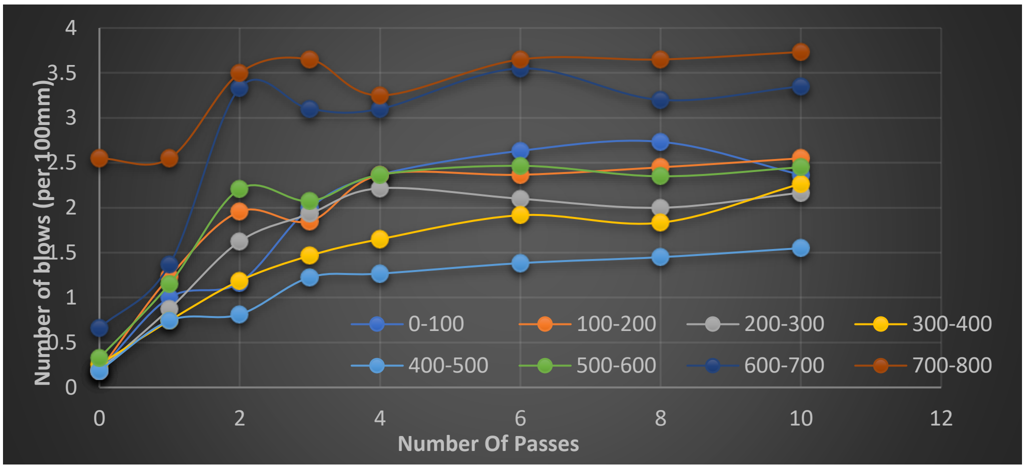


Figure 54: Pinnacle Forest, rhyolite Scala penetrometer results for track rolling

Figure 54 takes averaged Scala penetrometer data and shows the relationship between the number of passes and number of blows per 100mm for track-rolling. The 700mm to 800mm depth range is the only depth range which shows and initially high strength being 2.5 blows per 100mm, increasing to 3.5 after 2 passes with the 600mm to 700mm depth range slightly below. These two depth ranges remain around this value with moderate variations. Depths from the surface to 600mm, except for the 400-500mm range, converge to a final value around 2.45 blows per 100mm after the 10th pass. The initial 4 to 6 passes show the greatest increases in strength followed by either more gradual growth or a plateau. The depth range 400-500mm shows notable weaker results than the other layers with it increasing to 1.23 blows after the 3rd pass with more gradual increases till a value of 1.55 blows per 100mm at the final pass.

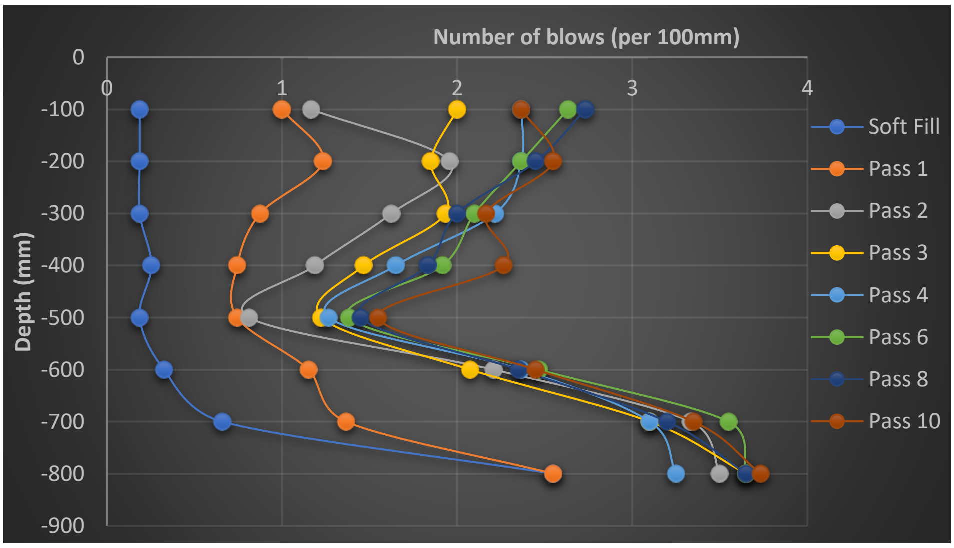


Figure 55: Site 2, rhyolite track-rolling results showing strength correlated to depth of differing passes.

Figure 55 displays the data created through averaging the Scala penetrometer results of the layers tested under the compaction efforts from track-rolling rhyolite soil at site 2.

It shows that there are notable increases in strength after each successive pass up till the 4th pass, after which the increases in strength mellow with successive passes and follow similar strength values and trends. It is evident that the initial 2 passes show the greatest increases in strength. All data series barring the soft fill indicate a decreasing trend in strength with depth down to 500mm, from which they show a sharp increasing trend to 700mm depth. The data gathered for the soft fill is identical to that in the smooth drum rolling results given that the test layer of fill was the same for both. It shows consistently slow strength of around 0.18 blows per 100mm down to 600mm where it shows a slight increase at 700mm followed by a larger increase at 800mm depth.

Site 2 rhyolite smooth drum roller results:

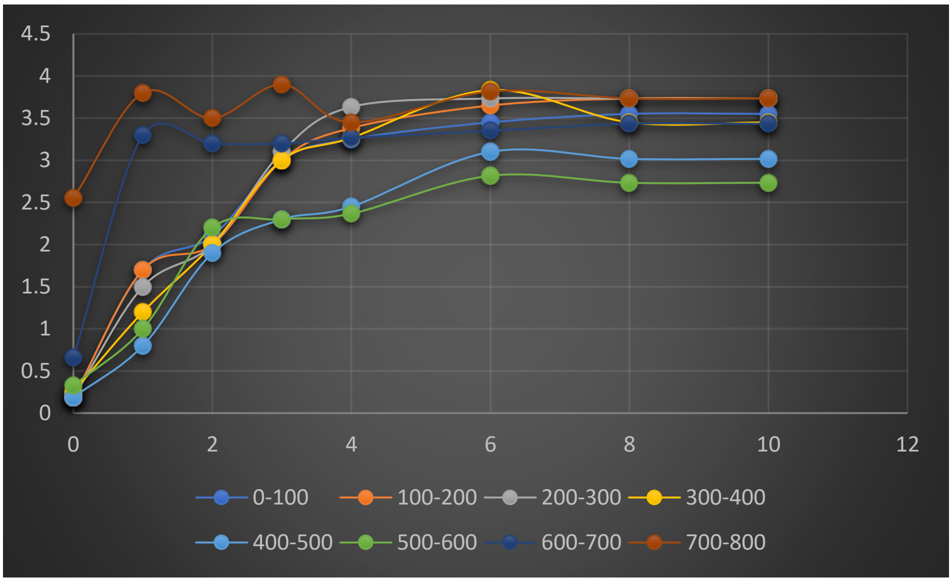


Figure 56: Pinnacle Forest, rhyolite Scala penetrometer results for smooth drum rolling.

Figure 56 presents the averaged Scala penetrometer data of the relationship between the number of passes and number of blows per 100mm for smooth drum rolling on rhyolite soils. The 700mm to 800mm depth range is the only range which shows an initially high strength of 2.5, increasing to 3.8 blows per 100mm after the first pass and evening out to around 3.7 with mild fluctuations. After the initial pass of the roller, the 600mm-700mm depth range also shows significant increase in strength followed by a plateau around 3.3 blows per 100mm. The figure shows that for depths from the surface to 400mm show increases in strength with each continual pass up till the 4th to 6th pass where they plateau around 3.5 blows per 100mm. With depths 400mm to 600mm showing a plateau after the 6th pass of the roller with 400-500mm settling around 3 blows and 500-600mm around 2.73 blows per 100mm.

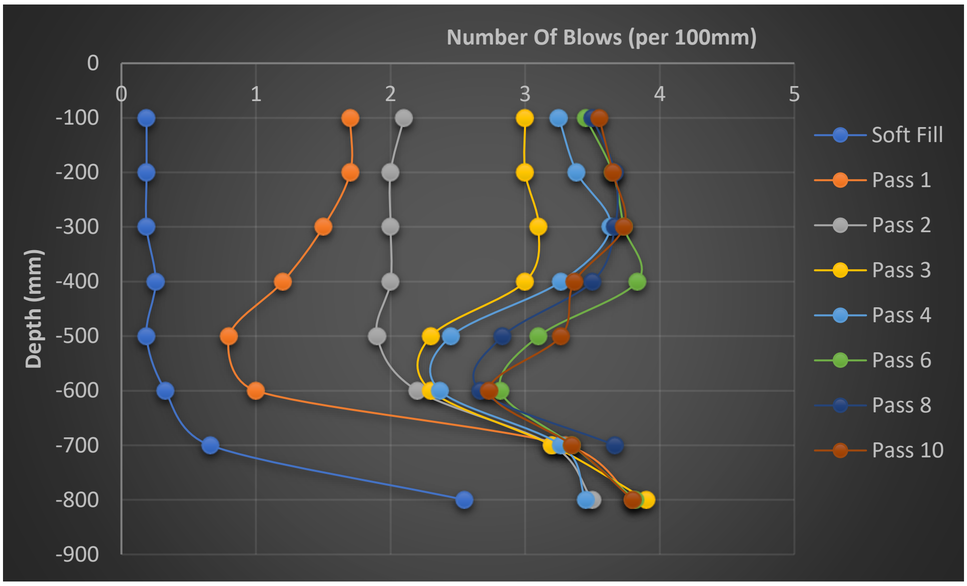


Figure 57: Site 2, rhyolite soil smooth-drum roller results showing strength correlated to depth of differing passes.

Averaging the Scala penetrometer results under the compaction efforts from smooth drum rolling of the rhyolite soil at site 2 can be seen in figure 57. It is evident that the initial 6 passes of the roller show the most significant increases in strength for the depths down to 500mm, with succeeding passes showing little to no improvement in strength but following the same trend. All data series barring the soft fill and the 2nd pass show a trend of a slight increase in the first 100 to 200mm of depth followed by a decreasing trend in strength with increased depth down to the 500mm to 600mm range, where all results exhibit a sharp increasing trend in strength at 700mm and 800mm depth.

Site 2: Comparison between compaction methods for rhyolite:

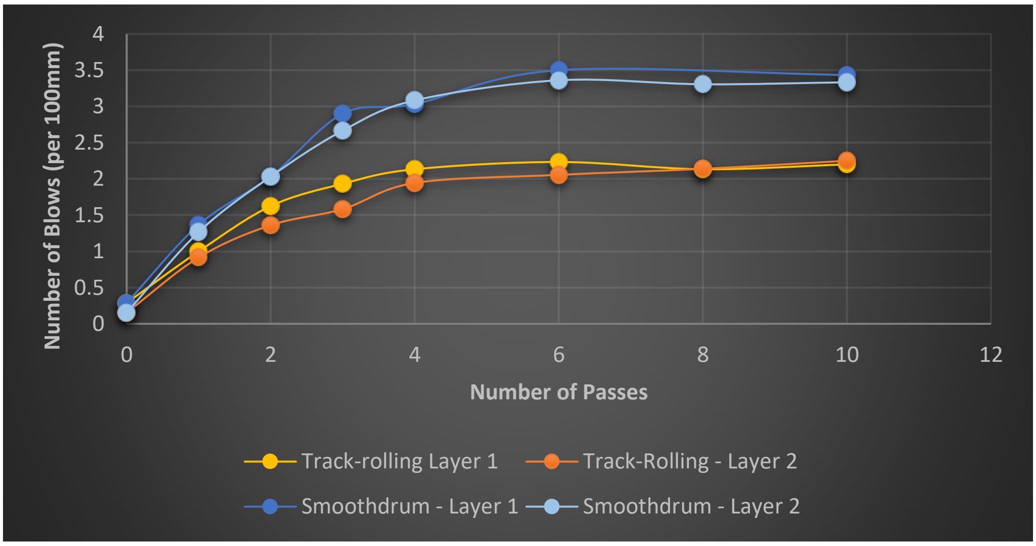


Figure 58: Site 2 rhyolite soil, track & smooth drum rolling comparison with averaged results.

Figure 58 above shows a comparison between the averaged track-rolling and smooth drum rolling results at site 2 on rhyolite soils, only depths down to 600mm were considered due to the compression of the layer and the deeper results showing data of the subgrade. It shows that track-rolling achieves its greatest improvements in strength in the first 2 complete passes with slight improvement seen to the 4th pass. Following this the results show minimal increases in strength with succeeding passes. Results from the smooth drum roller show notable improvements up till the 6th pass following which a plateau can be seen. When comparing the results, track-rolling results on average are 26.6% less than the smooth drum roller.

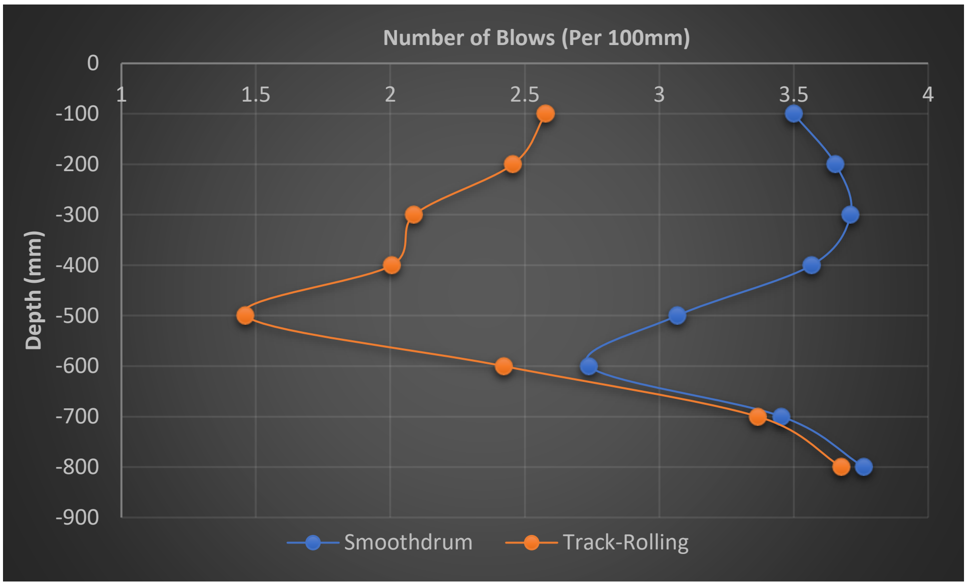


Figure 59: Site 2 rhyolite soil, Comparison between track-rolling and smooth-drum rolling results.

Figure 59 shows a comparison between the averaged data gather from Scala penetrometer testing of both smooth drum and track-rolling of rhyolite soil in Pinnacle's Forest in the Bay of Plenty. Smooth drum rolling results show a trend to have an initial increase in soil strength from 100mm to 300mm depth followed by a decreasing trend with depth, down to 600mm. Track-rolling shows a constant decreasing trend in soil strength from the surface down to 500mm. Both methods show a sharp increasing trend in soil strength with depth to 800mm depth. Smooth drum results show greater than 3.5 blows per 100mm down to 400mm where track rolling has results from around 2.5 to 2 blows per 100mm from the surface down to 400mm.

Overall, smooth-drum rolling achieves 35.7% greater compaction than track-rolling, this incrementally increases with depth to 109.9% greater results at 500mm. Depths 600mm to 800mm have minimal difference in results for compaction methods.

Site 3, Sandy Loam:

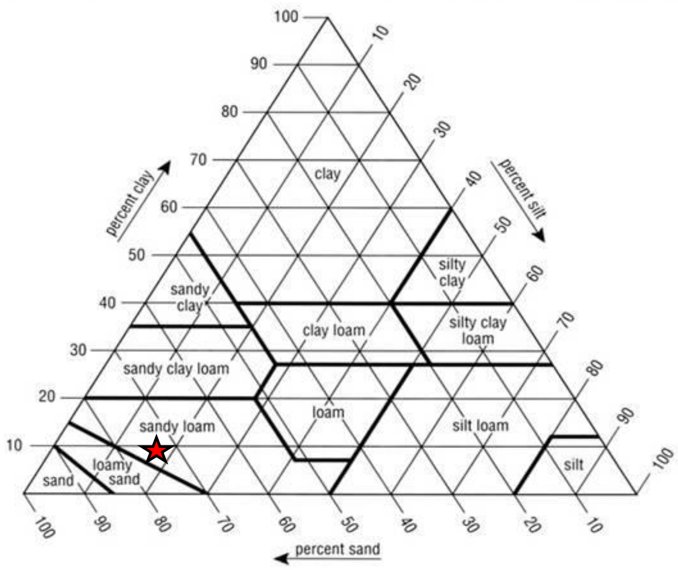


Figure 60: Soil classification chart identifying soil present at site 3.

Conducting a sieve analysis on the rhyolite-type soil found at site 3 revealed a composition comprising 74.61% sand, 15.77% silt, with the remaining portion consisting of clay. This analysis, as depicted in figure 60, categorizes the soil within the sandy loam soil classification.

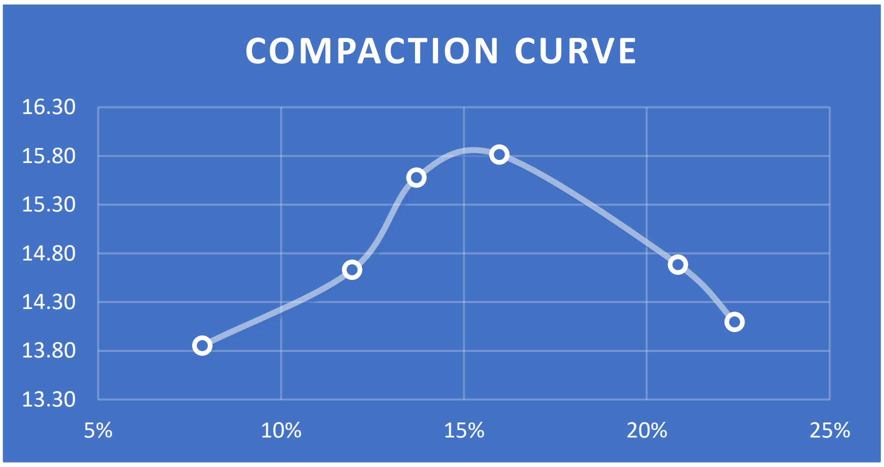


Figure 61: Standard proctor results for sandy loam soil at site 3 in the Hawkes Bay

Sandy loam soil samples collected from site 3 in the Hawkes Bay underwent standard proctor tests to assess its compaction characteristics. The results, displayed in figure 61, indicate that the OMC for the sandy loam soil at site 3 was determined to be 15.1%, with a corresponding MDD of 15.85 kN/m³.

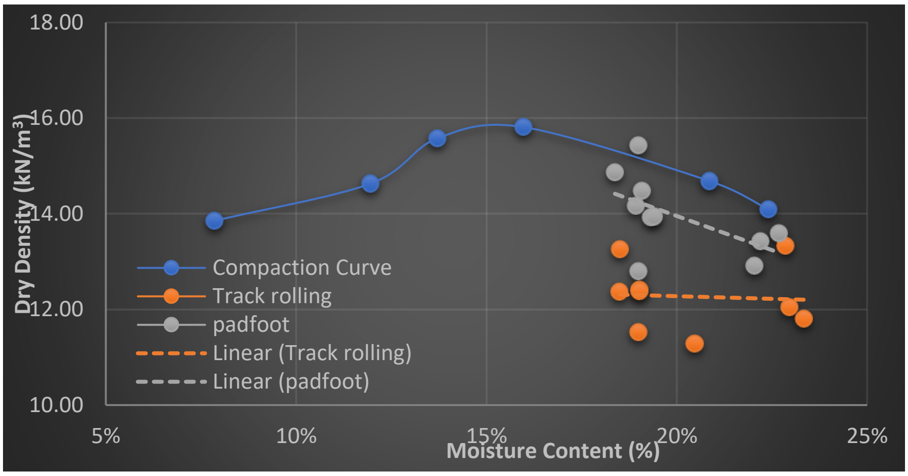


Figure 62: Site 3 sandy loam soil compaction curve with track-rolling and padfoot roller surface compaction results.

Figure 62 presents the results from surface compaction samples comparing both track-rolling and padfoot rolling with the compaction curve. Track-rolling samples exhibited an average MC of 20.41% (standard variation of 2.07%), and an average dry density of 12.27 kN/m³ (standard deviation of 0.7 kN/m³). On the other hand, padfoot rolling yielded an average MC of 20.0% (standard deviation of 1.62%), and an average dry density of 13.95 kN/m³ (standard deviation of 0.83 kN/m³).

Overall, averaging all samples collected at site 3, sandy loam soil had an average moisture content of 20.19%. When compared to the compaction curve this MC corresponds to an ODD of approximately 14.9 kN/m³ for the on-site conditions. Track-rolling and padfoot rolling attained a compaction level of 82.34% and 93.65% respectively, and a range from 77.64% to 87.03% and 88.09% to 99.21% within one standard deviation.

Site 3, Sandy loam soil track-rolling results:

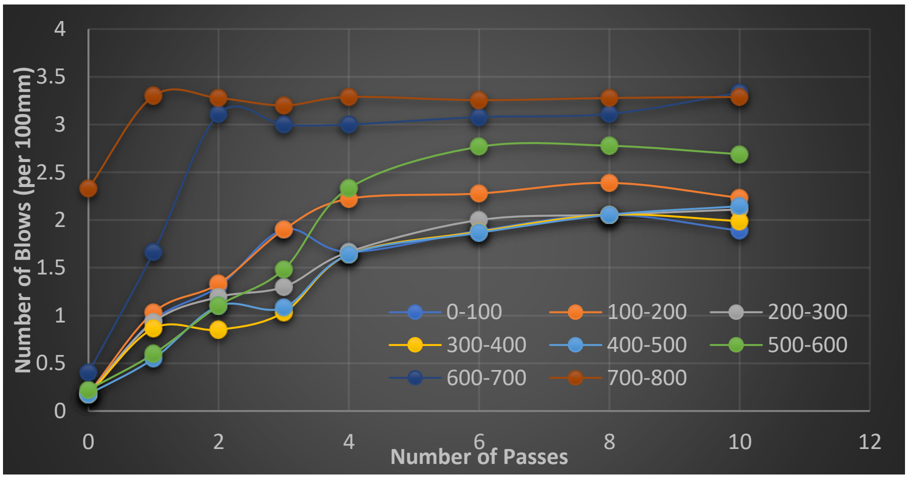


Figure 63: Glengarry Forest, sandy loam soil Scala penetrometer results for track rolling

Averages of the Scala penetrometer test results for tracking rolling at site 3 can be seen in figure 63 above. The depth range from 700mm to 800mm has an initial soil strength of 2.33 blows per 100mm, growing to 3.3 blows where it remains relatively constant. The depth range from 600mm to 700mm show similar results with a rapid increasing trend in soil strength with the initial 2 passes then levelling out around 3 blows per 100mm.

Depths from the surface layer down to 600mm in depth show steady increases in blows per 100mm up to the 6th pass with the depth range 100mm to 200mm plateauing after the 4th pass around 2.27 blows per 100mm. The depth range between 500mm to 600mm shows a plateau after the 6th pass of around 2.75 blows per 100mm whereas all depths above it show a plateau from 2 blows to 2.3 blows per 100mm.

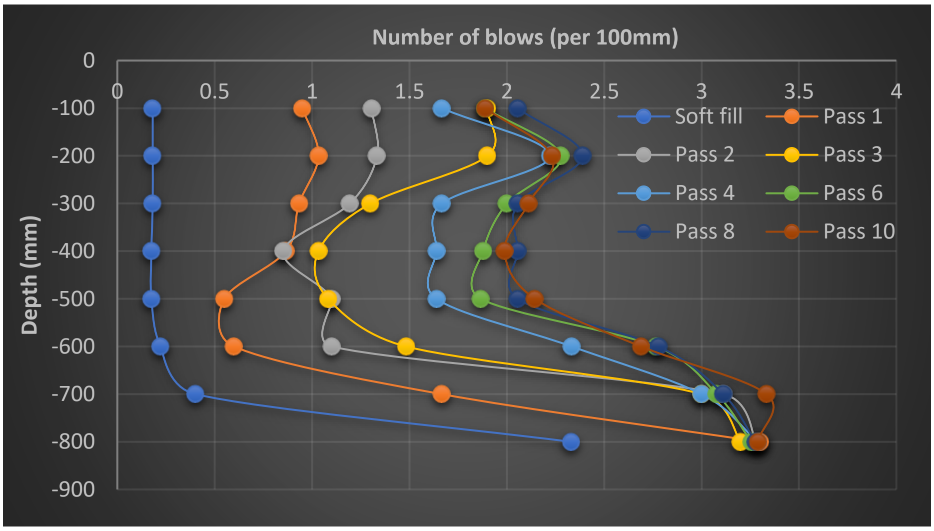


Figure 64: Site 3, sandy loam soil track-rolling results showing strength correlated to depth for differing passes.

Averaged Scala penetrometer results of the layers tested under the compaction efforts from track-rolling of the sandy loam soil at site 3 are shown in figure 64. The soft fill layer remains consistent around 0.17 blows with a slight increase at 700mm and an extensive increase at 800mm to 2.33 blows per 100mm. This shows the desired lift thickness of 750mm was achieved.

Data shows that with each consecutive pass of the excavator for depths higher than 600mm the soil layer becomes stronger up till the 6th pass, after which minimal improvement can be seen. At all passes it was seen that there was a decrease in strength after 200mm to around 500mm to 600mm in depth. Followed by a sharp increase down to the deeper depths around 700mm to 800mm, arriving at a value of around 3.2 to 3.3 blows per 100mm assumed to be the subgrade and not the fill layer.

Site 3, Sandy Loam soil Padfoot results:

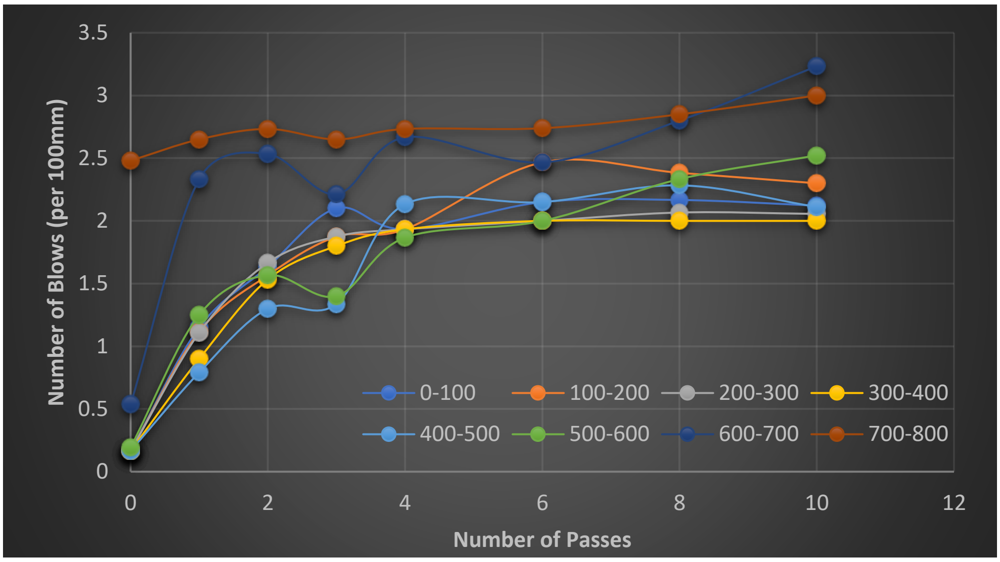


Figure 65: Glengarry Forest, Sandy loam soil Scala penetrometer results for Padfoot rolling.

Figure 65 shows the averaged Scala penetrometer results for padfoot rolling in Glengarry Forest on sandy loam soil fill layers. It shows that the deepest depth ranges measured started with an initially high value of 2.5 blows per 100mm which remained relatively constant with a slight increase towards the later passes. The 600mm to 700mm depth range shows a sharp increase following the initial pass of the padfoot and follows a similar trend and values to the layer below barring a dip after the 3rd pass.

Predominantly all the depths from the surface to 500mm depth show similar trends with strength increasing with successive passes until the 4th to 6th pass where they plateau between 2 and 2.5 blows per 100mm. The 500mm to 600mm depth range shows a similar trend to that described above, however proceeds to begin an upwards trend in strength following the 6th pass.

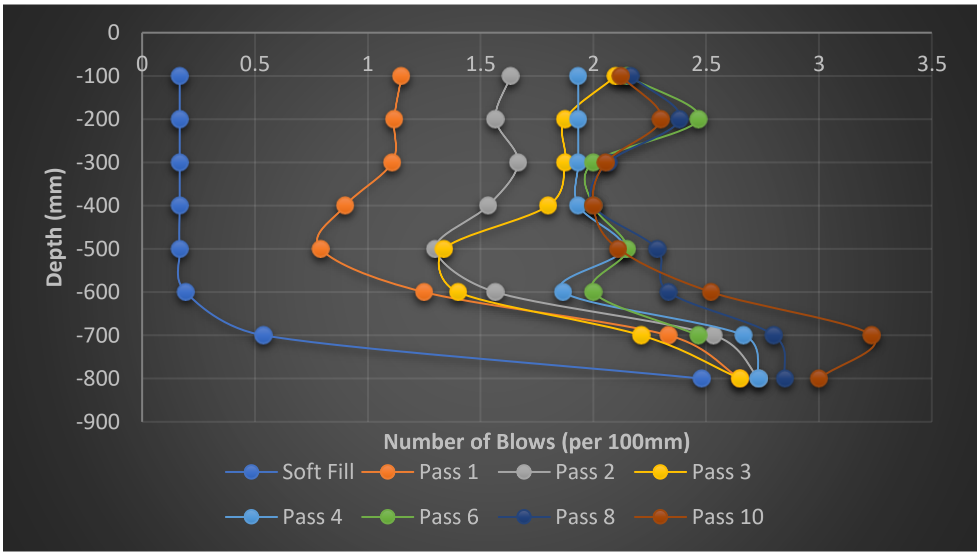


Figure 66: Site 3, Sandy loam soil Padfoot roller results showing strength correlated to depth of differing passes.

Figure 66 shows the averaged data of Scala penetrometer results for the layers tested under padfoot rolling on sandy loam soil found at site 3. The data for the soft fill is the same as that recorded for track-rolling due to the test layers being the same. It is seen that with each successive pass the values incrementally increase with the initial passes having the greatest increases, up till the 6th pass where the following passes of the padfoot have little to no improvement. The initial three passes show that the top 300mm of the test layer remain consistent with following depths showing a decreasing trend in strength with depth down to 500mm. Whereas the data for the 4th to 10th pass indicate that down to a depth of 500mm the strength remains relatively constant with a peak at a depth of 200mm.

Site 3: Comparison between compaction methods for sandy loam soil at site 3

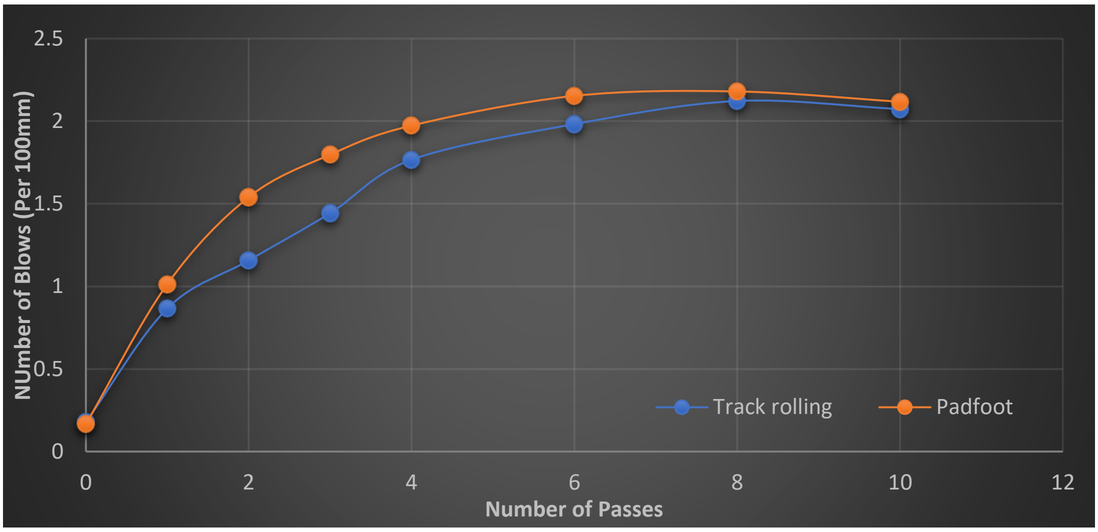


Figure 67: Site 3 sandy loam, Track-rolling and Padfoot averaged data

Figure 67 shows the averaged data for smooth drum and track-rolling data for each layer tested down to a depth of 500mm to avoid data from the subgrade below the layers. Both compaction methods show that the most substantial improvement in soil strength during the initial 2 passes with subsequent passes showing further increases up till the 6th pass where after which little improvement can be seen. Both padfoot rolling and track rolling yield similar average strength values for the tested layers, however, padfoot shows to have somewhat greater results over the course of the compaction.

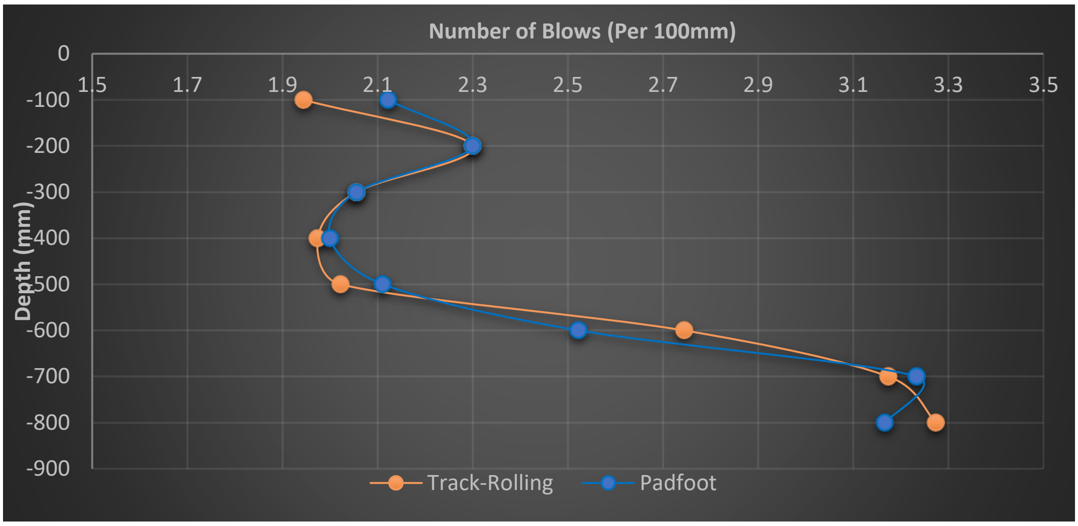


Figure 68: Site 3 sandy loam, Comparison between Track-rolling and Padfoot averaged data

Figure 68 presents the averaged overall results for both compaction methods, considering strength with increasing depth. It shows that both compaction methods follow similar trends, both indicate a peak at 200mm depth followed by a decreasing trend with depth down to 450 – 500mm. Beyond this depth, both methods show a sharp increasing trend where the denser subgrade is picked up after consolidation.

Discussion:

Site1 Papa:

It can be assumed that the results and conclusions made from the data gathered at site 1 are representative of Papa mudstone which exhibits the same characteristics as that at Craigdean Forest in the Manawatu when compacted using the machinery tested.

Given the results for both compaction methods, it could be seen that on average the desired lift thickness of 750mm was achieved. The results associated with the 600mm - 700mm depth range for both compaction methods show that the Papa mudstone onsite compacted by 150mm to 200mm during the first pass, with subsequent passes having minimal impact on size reduction, the layer over the course of testing decreased by 20% to 25% in volume. Track rolling revealed that the initial 4 complete passes achieved the greatest compaction, with later passes only minimally affecting the top 200mm of the layer.

Smooth drum rolling showed that for depths from 100mm to 600mm, compaction improves with each pass up to the 6th pass, beyond which strength improvement plateaus. The top 100mm showed significant strength gains in the first 4 complete passes, with diminishing returns in subsequent passes. Furthermore, smooth drum rolling can restore material down to a depth of 300mm to a similar strength level to the subgrade, with material deeper than this in the layer exhibited a decline in strength.

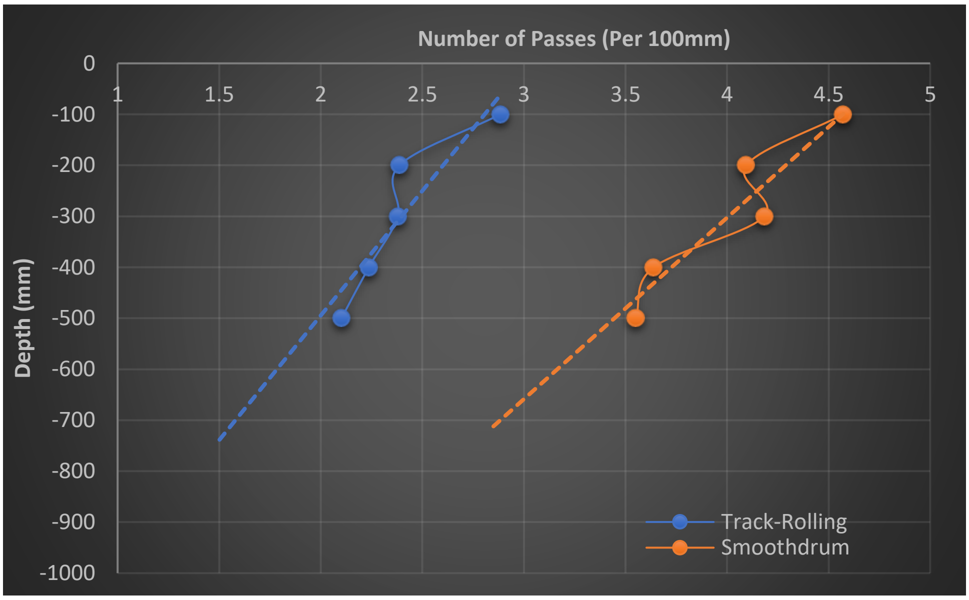


Figure 69: Extrapolated strength correlating with depth of Track-rolling and Smooth drum rolling.

Comparison of the two compaction methods indicate that smooth drum rolling delivers better compaction down to a depth of approximately 550mm. This is limited by the initial layer thickness meaning that if greater lift thicknesses were implemented the trends shown above in figure 69 could potentially be expected for Papa mudstone. It shows that with greater fill thicknesses the difference in effectiveness of compaction methods decreases along with overall strength with depth. However, greater lift thicknesses than the 750mm which was tested is not recommended.

Comparing the results of the two compaction methods on Papa mudstone, it's evident that track rolling reaches maximum compaction after 4 passes, while smooth drum rolling achieves its highest strength after 6 complete machine passes. On average, track rolling results in 16% lower compaction compared to smooth drum rolling with each pass, where with depth smooth drum rolling performs 40% greater. When the layer is averaged and converted to an approximate CBR value, track rolling yields a CBR of 5.5, while smooth drum rolling averages a CBR of 7.5. Carrying out double population t test analysis on the data, it can confidently be said that for Papa mudstone, a 6.9 tonne vibrating smooth drum roller delivers greater overall compaction when compared to a 21-tonne bulldozer.

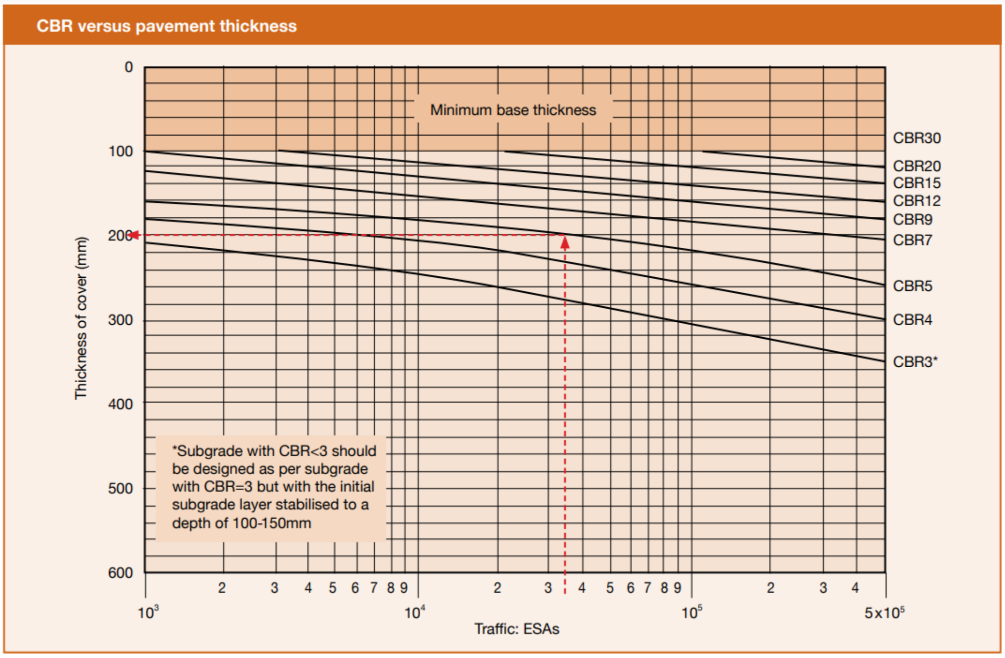


Figure 70: Guide to pavement design given CBR & ESAs, retrieved from (FOA, 2020)

Following the guide for pavement deign chart in the NZFREM (figure 70), from a CBR value as well as an Equivalent Standard Axles (ESA) value, the advised pavement thickness required can be determined. If the Papa fill material at site 1 was compacted using either track-rolling and smooth drum rolling, over a range of ESA values, smooth-drum rolling requires 35mm less pavement material.

back to a required pavement thickness using figure 70 shows that depending on the expected Equivalent Standard Axles (ESA)

Site 2 clay soil:

Clay soil which was tested exhibited characteristics of having a higher MC than the OMC making it on the wetter side of the compaction curve derived from standard proctor results. While testing, this became apparent causing the roller operator to opt out of using the vibratory technology as this would cause additional liquefaction causing a poorer final compaction. The surface compaction samples taken for both compaction methods had a t test conducted and it indicated that there was not enough difference between the two to say one was greater than the other. Typically compaction curves for allophanic soils are difficult to define given the tendency for differing MC to return the same dry density (Kett, Ingham, & Evans, 2010).

Results showed that for both track rolling and smooth drum rolling testing the initial soft fill layer fell within the desired lift thickness. Results for both compaction methods show similar trends in volume reductions for clay soil compacting it by roughly 150mm to 200mm. Results for the 500 – 600mm depth range of both compaction methods had similar trends being in between the two main sections of data meaning this range must have been on the edge of the original terrain, making this soil have an overall size reduction of 20% to 25% in volume for this lift thickness.

Track rolling revealed that the initial 4 complete passes yield the most significant compaction with depths to 500mm showing similar strengths. With following passes only affecting the 500mm to 600mm depth range. Smooth drum compaction showed similar trends with the greatest improvement across the initial 500mm being in the first 4 complete passes with the following two passes only showing improvement in the 500-600mm layer, after which strength improvement plateaus. Both compaction machinery had similar overall trends with t tests confirming this by determining that there is no significant difference in the overall compaction of clay fill material.

Given that the clay soil was identified to be allophanic, it adds additional explanation for the poor strength which was achieved during compaction (Hewitt, Balks, & Lowe, 2021). Allophanic soils are efficient at absorbing and retaining water. This water remains bound until the remoulding which happens during compaction, overall reducing the bearing strength of the soil. This can be seen in the results of this study for the clay soil at site 2.

Site 2 Rhyolite fill material:

Evaluating the results from the surface samples of both track and smooth drum rolling showed both methods were tested under the equivalent MC conditions and t test analysis showed that smooth drum rolling does deliver greater surface compaction. After the 2nd pass of track rolling, it showed it had been compacted by up to 150mm whereas the smooth drum achieved this after the initial pass.

Track rolling compaction indicated that the surface depths down to 400mm achieved around 2 to 2.5 blows per 100mm after the 4th to 6th pass. Whereas smooth drum rolling showed that from the surface down to 400mm depth showed greatest increases in strength during the initial 4 passes with following passes only showing improvement in the 400mm to 600mm depth range till the 6th pass. It showed that smooth drum rolling with vibratory technology allows fill material of this rhyolite makeup to return to similar strength that it originally was when naturally consolidated at around 3.5 blows per 100mm.

Both compaction methods show similar trends when comparing strength to depth for successive passes. Both show relative uniformity in strength down to 300mm depth after which it shows a decreasing trend in strength with depth down to 500mm where it is assumed it hits the subgrade, causeing the results to start increasing again. Comparing the results of the two compaction methods on the rhyolite fill soil at site 2 show on average, track rolling results in 33% lower compaction when pass for pass strength is compared. Comparing strength with respect to depth, smooth drum rolling achieved 70% higher soil strength for the tested layers. When the layer is averaged and converted to an approximate CBR value, track rolling yields a CBR of 3.5, while smooth drum rolling averages a CBR of 6. Due to t test results it can confidently be said that for rhyolite fill material Papa, a 10.6 tonne vibrating smooth drum roller delivers greater overall compaction when compared to a 14-tonne excavator.

Rhyolite fill material at site 2, if compacted for road construction would require between 60mm and 90mm reduced pavement thickness depending on designed ESA, when smooth drum rolled. This was determined from figure 70 above. The reduced volume of the required pavement would result in financial benefits, however, whether or not this out weighs the cost of utalising the machinery.

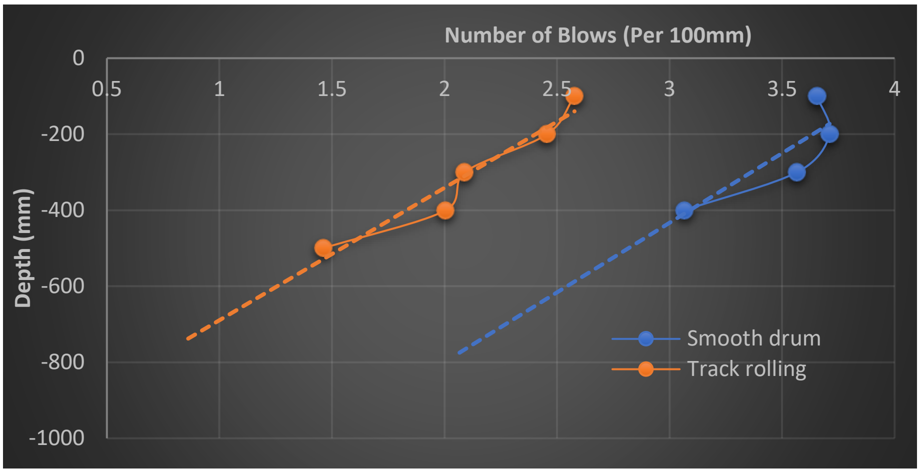


Figure 71: Extrapolated strength correlating with depth of Track-rolling and Smooth drum rolling.

It was seen that during testing the compaction of the soft fill could not be tested beyond 500mm depth given the compaction of the 750mm layer. Figure 71 above shows a prediction of what could be expected if greater lift thicknesses of the fill layers are tested on the same material using the machinery present at site 2. However, greater lift thicknesses than the 750mm which was tested is not recommended.

Site 3 Sandy Loam:

Site 3 at Glengarry Forest was concluded to have a soil composition falling within the sandy loam classification. When considering the surface samples received from both compaction methods it shows that padfoot rolling achieves a higher compaction at the surface layer in comparison to track rolling with this being confirmed by a t test analysis. Both methods showed that the sandy loam material could be compacted by around 250mm for a 750mm initial lift thickness.

When comparing track and padfoot rolling it shows that track rolling and padfoot rolling compaction begins to plateau after the 6th pass. Both methods showed that the initial passes had the most significant improvements on compaction of the fill material with minimal difference with the 8th to 10th passes. When comparing the averaged strength for the entire depth with successive passes of both methods it shows minimal differences with a t test confirming that it could not be said with confidence that one is better than the other. When comparing averaged strength achieved with differing depths it shows similar results with no distinguishable, meaning it cannot be said with confidence that padfoot rolling achieved better compaction when considering depth.

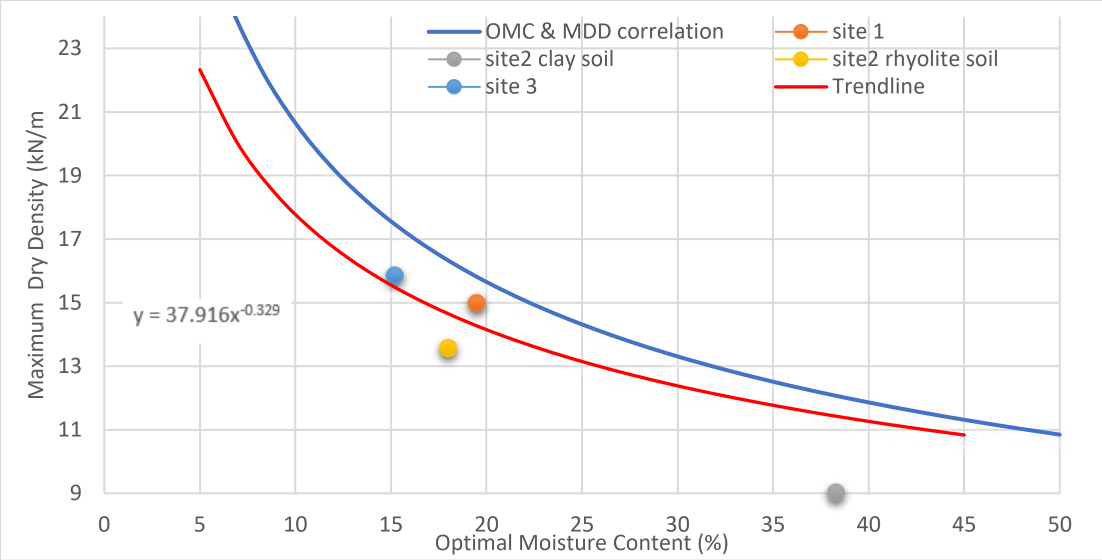


Figure 72: Comparing study findings to literature correlation for OMC and MDD

Figure 72 above illiterates how the findings in this study relate to those found in another. The study conducted by Gurtug et al. (2018) carried out numerous standard and modified proctor tests as well as gathering data from multiple previous studies. When plotting the findings from this study against this correlation it shows that there are definite similarities. However, the correlation in literature would not return accurate results for MDD. When a trendline is created from the data in this study (excluding the clay soil) it shows very similar trend with an equation of $y=37.916x^{-0.329}$ compared to the equation of correlation being $y = 51.88x^{-0.4}$.

The comparative study conducted in this report had standard proctor tests conducted to determine these soil variables to eliminate any possible inaccuracies. In future, the calculation process using the plastic limit would be valuable if there are time constraints. However, it would be advised to carry out initial proctor tests to validate this process.

Referring to literature, the findings from this study indicate similar behaviour to that shown in table 1. Both literature and this study found that the optimal number of passes for differing fill material was between the 4th to 8th pass, predominantly being the 6th complete pass.

Conclusion:

It is concluded that the effectiveness of compaction techniques is, as expected, highly dependent on the specific site conditions. Across the three test sites there were four distinctive soil compositions, each yielding differing results. Notably, site 1 and the rhyolite soil at site 2 demonstrated that purpose-built rollers achieved superior compaction at the surface level. The other two sites showed that there was not a distinguishable difference between the two compaction methods. Although, site 3 data did show greater surface compaction was achieved using the padfoot.

At site 1, where Papa mudstone was prevalent, findings indicated that the optimal number of complete passes for both track rolling and smooth drum rolling is approximately four. Subsequent passes showed minimal to no further improvements in soil compaction within the fill layer.

The clay soil at site 2 returned results where both track rolling and smooth drum delivered similar compaction with t tests confirming that there is not enough evidence to suggest there is a notable difference between the two compaction methods. At this site, both methods exhibited the greatest enhancement in soil strength within the initial four complete passes, with the impact extending to greater depths up to the 6^{th} pass. However, it's worth noting that due to the elevated moisture content in the clay soil, the vibration feature of the smooth drum roller was not utilised. This decision was made to avoid increasing soil moisture through liquefaction, which could have compromised overall compaction efficiency. Had the soil possessed lower moisture levels, the vibratory technology of the roller might have set it apart from track rolling. Compaction of this study showed overall poor results, this can both be attributed to the high MC at time of compaction as well as the soil showing allophanic properties.

Site 2's rhyolite-based soil displayed trends suggested that both compaction methods reached their optimal performance after six complete passes. Overall, the data revealed that for rhyolite soil with a sandy clay loam composition, smooth drum rolling with vibratory technology achieved superior soil compaction compared to track rolling.

Site 3, which consisted of sandy loam soil, indicated that both padfoot and track rolling on this soil demonstrated optimal compaction results after six passes. Notably, padfoot rolling only outperformed track rolling at the surface level with overall layer compaction of the two compaction methods being similar.

Testing conducted at site 1 and site 2's rhyolite soil revealed that the uppermost 300mm layer of the fill material regained the strength of the originally consolidated virgin ground. These findings underscore the critical importance of aligning compaction methods with the unique soil characteristics and site conditions to achieve optimal results. Notably, for clay and sandy loam soils above the OPM, track rolling demonstrated a comparable level of compaction to that achieved by a purpose-built roller.

The results from both site 1 and the rhyolite at site 2 showed that when smooth drum rolling is implemented, there is an overall reduction in the required pavement thickness if the fill material was compacted for a forest road subgrade. This is due to the greater CBR value. It is undetermined whether this reduction in pavement outweighs the cost of implementing the smooth drum roller for compaction. Despite purpose-built rollers achieving better compaction for some of the soils tests it is recommended that in situations where operator health and safety is of concern around rollers on rough unstable terrain than it is advised that a tracked piece of machinery is implemented for compaction. Given that governing regulations have broad statements concerning compaction of fill material the use of substandard compaction techniques such as track rolling will remain to be utilised due to its inherent financial and operator health and safety benefits for difficult situations.

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Appendix:

Appendix A: Example results from standard proctor testing.

Test	1	2	3	4	5	6
	Proctor Test					
Mass of Mould PRIOR to Filling & Levelling	3844.87	3845.34	3845.21	3845.19	3845.23	
Mass of Soil & mould after compacting &	5568.01	5663.61	5757.59	5687.68	5635.46	
Mass of Wet Soil in Mould, M_w	1723.14	1818.27	1912.38	1842.49	1790.23	0
Mould Volume, V (cm^3)	997	997	997	997	997	
Dry Bulk Density, $\rho_{Bulk(d)}$	**14.39**	**14.77**	**14.99**	**13.66**	**12.92**	
	Cpa	CPb	CPc	CPd	CPe	CPf
	141.1646308	144.8518274	147.0090507	134.0009254	126.7372084	

Appendix B: Example results pre and post oven drying of standard proctor samples.

Test	1	2	3	4	5	6
Mass of Wet Soil + Tin	104.17	109.11	136.10	165.93	179.27	
Mass of Dry Soil + Tin	93.27	95.63	114.88	132.79	140.08	
Mass of Tin	32.12	31.94	31.88	31.51	32.26	
Mass of Wet Soil , M_w	72.05	77.17	104.22	134.42	147.01	
Mass of Dry Soil , M_D	61.15	63.69	83.00	101.28	107.82	
Mass of Water	10.90	13.48	21.22	33.14	39.19	
Moisture Content, MC	15%	17%	20%	25%	27%	
	Cpa	CPb	CPc	CPd	CPe	CPf

Appendix C: Example results from dry sieve analysis.

DRY SIEVING for PARTICLE SIZE DISTRIBUTION

n	Sieve Size (mm)	A: Mass of Sieve (g)	B: Mass of Sieve & Soil (g)	B - A = Mass Retained (g)	% Passing See Equation below
1	36				
2	26.5				
3	19				
4	9.5				
5	6.7				100%
6	2	423.7	776.17	352.5	72%
7	1	385.31	668.21	282.9	50%
8	0.5	338.58	529.88	191.3	35%
9	0.25	314.63	431.83	117.2	25%
10	0.075	279.22	478.69	199.5	10%
11	<0.075	271.9	393.59	121.7	0%
	SUM	2013.34	3278.37	1265.0	

	Size Range	
Gravel %	(>4.75mm)	0
Sand %	(0.075 < x < 4.75)	74.61%
Silt %	(0.002 < x < 0.075)	15.77%
Clay %	(<0.002mm)	9.62%
		Sandy Loam

Appendix D: Example results from surface compaction samples.

padfoot	Layer 1				Layer 2				Layer 3			
	Sample 1	Sample 2	Sample 3		Sample 1	Sample 2	Sample 3		Sample 1	Sample 2	Sample 3	Sample 4
volume	120	110	50		85	60	130		75	110	100	120
Tin	31.6	31.75	32.5		31.69	31.78	32.25		31.87	32.01	29.71	31.62
Wet soil + tin	246.55	227.69	120.48		168.57	148.33	260.82		171.08	232.64	198.6	243.22
dry soil + tin	197.8	190.62	103.48		142.58	126.19	210.1		145.5	194.35	161.37	202.16
mass of dry soil	166.2	158.87	70.98		110.89	94.41	177.85		113.63	162.34	131.66	170.54
mass of wet soil	214.95	195.94	87.98		136.88	116.55	228.57		139.21	200.63	168.89	211.6
Mass of water	48.75	37.07	17		25.99	22.14	50.72		25.58	38.29	37.23	41.06
MC	23%	19%	19%		19%	19%	22%		18%	19%	22%	19%
Dry density	13.5869	14.1683	13.9263		12.7980	15.4360	13.4208		14.8628	14.4778	12.9158	13.9416

Appendix E: Example results from Scala penetrometer on soft fill layer.

1 craigdean track

	average # of Blows/						
Depth (	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Average
0 - 50							
50 - 100	0.5	0.2	0.2	0.25	0.5		0.33
100 - 150							
150 - 20	0.5	0.2	0.2	0.25	0.5		0.33
200 - 25							
250 - 30	1	0.2	0.2	0.25	0.2		0.37
300 - 35							
350 - 40	0.33	0.2	0.2	0.25	0.2		0.236
400 - 45							
450 - 50	0.33	0.2	0.2	1	0.2		0.386
500 - 55							
550 - 60	0.33	1	0.5	1	0.2		0.606
600 - 65							
650 - 70	0.5	1	0.5	1	0.2		0.64
700 - 75							
750 - 80	0.5	4	2	4	3		2.7

2 craigdean track

Appendix F: Example results from Scala penetrometer after final pass.

Pass #10

	average # of Blows/						
Depth (	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Average
0 - 50							
50 - 100	4	3	5	3	3	4	3.6667
100 - 150							
150 - 20	3	3	3	2	3	3	2.8333
200 - 25							
250 - 30	2	2	3	3	3	2	2.5
300 - 35							
350 - 40	3	3	3	3	3	2	2.8333
400 - 45							
450 - 50	3	2	4	3	3	3	3
500 - 55							
550 - 60	4	3	4	4	4	4	3.8333
600 - 65							
650 - 70	5	5	4	4	4	5	4.5
700 - 75							
750 - 80	5	5	5	4	3	5	4.5