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Spatial Variability in Subgrade Properties:

A Forest Road Case Study

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October 2011

Abstract:

The variation of mechanical properties in forest road subgrades is not well understood. Significant variability may necessitate compromises between insufficient or conservative designs in an effort to minimise the costs of road rehabilitation or needlessly thick pavements. The goal of this study is to quantify the spatial variation of subgrade bearing strength and dry density.

Field trials were performed on a 100m section of a road subgrade. Variation in bearing strength was measured using a Clegg Impact Soil Tester (CIST). A sampling tube was used to extract subgrade core samples for laboratory determination of density. Additional laboratory assessments were performed to contextualise these results.

This research shows that the subgrade tested had considerable variation in bearing strength (COV = 75%) as well as dry density (COV = 7.8%). In practical terms both of these parameters ranged from very poor to very good. Both these variations pose practical difficulties for implementing design choices.

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1. INTRODUCTION

Forest roads in New Zealand utilise a two layer design comprising an aggregate running course overlying a formed soil subgrade. The aggregate layer, often termed an ‘improved layer’ should be of sufficient thickness and strength to dissipate axle loads, thereby avoiding permanent deformation of the underlying subgrade. Vehicle loading during a forest roads design life is easily characterised in terms of forecasted timber volumes and known truck configurations. Hence subgrade bearing strength is often the key determinate of aggregate thickness in forest road design (Australian Road Research Board 2009).

Variation in subgrade properties is an area of not well explored by the New Zealand forest industry. A significant variation in subgrade properties could mean that assumed design values are either insufficient or conservative. Consequentially, costs may be incurred as a result of premature road failure or needlessly thick pavements. It is not evident whether the widely used design methods account for variation to some extent in determining pavement thickness. The goal of this study is to quantify and discuss the variation in subgrade properties of a forest road. In particular this study investigates the spatial variation in bearing strength and compaction.

2. LITERATURE REVIEW

Research in the area of subgrade variation is predominately focused upon large scale civil engineering projects. Such studies have considered different types of variation. Existing literature is largely focussed upon the effects and extent of seasonal variations in cold climates, although other studies have considered spatial variation (Lee 2010, Wasniak 1999, White, Harrington, Ceylan & Rupnow, 2005). Saha (2008) showed that subgrade variation across roughly 100km of US highway was very high and demonstrated that using a single subgrade design strength yielded an inefficient design. White *et al* conclude that “pavement performance is adversely affected by non-uniform subgrade support” – and that this must be overcome with better construction methods and field quality control techniques.

Existing literature has considered spatial variation in both physical and mechanical properties. Subgrade bearing strength and stiffness are fundamentally important mechanical properties for road design. Many methods of measuring strength and stiffness have resulted from varying regulations and design methods. Existing research has compared R-values (Saha 2008), Resilient Modulus (Wasniak, 1999) and Clegg Impact Value (CIV) or Dynamic Cone Resistance (White *et al.* 2005). Wasniak (1999) and Saha (2008) extensively compare physical properties such as soil density, moisture content, soil type/gradation and plasticity. It is important to note that studies have concerned highways with both flexible and rigid pavement designs and testing is typically performed over many kilometres. While the findings of these studies are fundamentally relevant, the test subjects are very different to relatively short unpaved forest roads.

The design of unpaved roads in New Zealand predominantly follows the APRG Report 21 method (Fairbrother 2011). Both the ARPG 21 report the New Zealand forest road engineering manual (NZ Forest Owners Assoc. 2012) incorporate the Austroads figure 8.4 design chart (Austroads, 2004) for evaluation of pavement thickness. A necessary input for the figure 8.4 design chart is the Californian Bearing Ratio (CBR) of the subgrade. The NZFOA roads manual (2012) describes two ways of determined CBR i*n situ* using either a dynamic cone penetrometer or a Clegg Impact Soil Tester (CIST).

3. METHOD

3.1 Study Design

The purpose of the study is to examine the variability of forest road subgrade properties. From a road building perspective bearing strength is the most important attribute of a subgrade. This study will measure subgrade CBR using a Clegg Impact Soil Tester (CIST). The CIST measures the deceleration of a calibrated weight in free fall and reports the measurements as Clegg Impact Value (CIV). The value CIV can then be correlated to CBR. Fairbrother, McGregor & Aleksandrov (2009) studied correlations between CIV and CBR and found that correlations worked reasonably well despite over predicting low CBR soils.

It is well known that water has a negative effect upon the bearing strength of soil, hence strength measured *in situ* will only reflect the condition of the soil at the time of measurement. For this reason the study will also measure soil dry density. Increased density results in increased bearing strength, reduced water absorption and minimises settlement due to loading (ARRB 2009). It was chosen to compare variation of *in situ* dry density with compaction achieved by lab testing as a second measure of physical subgrade properties.

The study required an unpaved forest road subgrade for testing. The road selected for the study was located in Waieke forest on Banks Peninsula of Canterbury New Zealand. The road is roughly 1.3km long, located on moderate terrain and appears to be of side cast construction. It was likely built as a farm track and predates the current forest. In 2013 the road will be used to extract wood from 34ha of *Pinus radiata* forest. Full length trees will be extracted by stem truck to a processing yard. Currently the subgrade has rutting caused by groundbased log extraction. Prior to the commencement of stem trucking the subgrade will require grading, minor widening and reinstating of drains before the application of aggregate. The road is typical of many ‘farm tracks’ that will require upgrading in the future, and was selected due to availability and time constraints.

3.2 Field Sampling

Sample sites were established at 10m intervals along the unpaved roadway. Three sample plots were established at each site, one in each wheel rut and the third in the centre. The decision to sample only 100m of road was made to minimising confounding factors caused by changes in soil type or composition. Each plot was lightly excavated until the exposed subgrade was both consolidated and level. The following procedures were performed at each of the 30 sample plots:

Clegg impact tests (three) were performed using a standard Clegg Impact Soil Tester (CIST). The manufacturer's recommended best practises were adhered to. The hammer of the CIST was raised and dropped four times and the value displayed by the devices readout, the CIV was recorded after the fourth blow.

A soil core sample was cut using a soil cutting tube. The procedure used was identical to that in NZS 4402:1986 Test 5.1.3 – 'Sampling tube method for determination of *in situ* density' except that the cutting tube had a non standard internal diameter of 38mm and was removed using a hammer apparatus as used in NZS4402:1988 – Test 6.5.2 (Standards NZ 1986). Samples were airtight bagged for transport to the lab.

Lastly, large representative soil samples were collected at 0m, 50m and 100m along the roadway for laboratory soil classification and compaction testing.

Figure 1. Three sample plots with the Clegg tester (rear) and core cutter (front).

3.3 Lab Testing

This section describes the range of tests used to determine soil properties. Wherever applicable this study used tests specified in NZS 4402:1986 – 'Methods of Testing Soils for Civil Engineering Purposes' (Standards NZ 1986).

Moisture Contenst of the core samples were determined by oven drying in accordance with NZS4402 Test 2.1 – 'Determination of the Water Content'. All the following tests used this Test 2.1 in their specific procedures.

Dry Densities of the core samples were determined as calculated in NZS4402 5.1.3 – 'Sampling tube method for determination of *in situ* density'. In summary, the content of each core sample was weighed to the nearest 0.1g. The volume the soil occupied was calculated from the occupied dimensions of the sampling tube.

The wet density is calculated as:

$$\text{Wet density} = [\text{soil mass (g)} / \text{volume (mm}^3)] \times 10^6 \qquad (\text{kg/m}^3)$$

The dry density of the sample is:

$$\text{Dry density} = \text{wet density} / [1 + \text{moisture content (\%)}] \ (\text{kg/m}^3)$$

Proctor Curves were determined using NZS4402 Test 4.1.1 – 'Standard Compaction Test' and Test 4.1.2 - 'Heavy Compaction Test'. The large soil samples collected from 0m, 50m and 100m along the roadway were compacted at a range of moisture contents to determine the relationship between moisture content and compaction, and the optimum moisture content (OMC).

Plastic Limit of the subgrade soil was determined using NZS4402 Test 2.3 – 'Determination of the Plastic Limit'. This test is required for classifying the soil according to the unified soil classification system (USCS). Tested soil was from the large sample taken at 50m.

Liquid Limit of the subgrade soil was determined using NZS4402 Test 2.5 – 'Determination of the Cone Penetration Limit', as required for soil classification according to the USCS. Soil taken at 50m was penetrated by a drop cone at various prepared moisture contents and the moisture content at 20mm penetration (the liquid limit) was interpolated.

Wet Sieving was used to determine the particle size distribution of representative portion of the three large soil samples. A coarse test was made on roughly 800g of soil using only 4.75mm and 75µm sieves to determine the percent fines (passing 75µm), percent sand (retained on 75µm) and percent gravel (retained on 4.75mm).

4. RESULTS

The results of field and laboratory testing are shown below in Tables 1 to 3 and Figure 2.

Table 1. Clegg impact values measured along and across the studied subgrade.

Position	Inside			Middle			Outside		
10	11	12	13	11	11	11	8	9	10
20	4	6	6	12	12	12	20	21	22
30	20	18	19	8	9	9	7	8	8
40	17	18	18	10	11	13	6	7	7
50	12	12	11	11	11	12	8	7	7
60	22	26	25	11	12	11	5	6	5
70	13	13	14	11	12	12	15	13	10
80	12	13	12	13	14	13	18	19	21
90	13	14	13	15	16	17	14	15	16
100	12	12	13	10	10	11	8	8	8
Mean	14.1			11.7			11.2	**Total:**	**12.3**
COV	35.4%			16.7%			48.5%	**Total:**	**36.8%**

Table 2. Results from lab testing of core samples taken along and across the studied subgrade.

Position	Moisture Content (%)			Wet Density (kg/m^3)			Dry Density (kg/m^3)		
	Inside	Mid	Outside	Inside	Mid	Outside	Inside	Mid	Outside
10	17.9	17.0	20.7	1950	1970	1900	1650	1690	1580
20	15.7	15.9	21.5	2130	1870	1960	1840	1620	1610
30	14.1	21.3		2120	1840		1860	1520	
40	15.4	17.1	14.7	2130	2010	2090	1840	1720	1820
50	24.2	19.6	19.7	1920	1870	1840	1550	1570	1540
60	17.7	16.8	15.0	2060	2060	2060	1750	1760	1790
70	11.7	12.9	19.5	2140	1950	1990	1910	1730	1670
80	12.2	15.1	17.0	2120	1870	2050	1890	1620	1760
90	16.1	14.6	23.6	2050	2010	1870	1770	1750	1510
100	18.8	22.7	19.1	1810	1750	1910	1520	1430	1600
Mean	**16.4**	**17.3**	**19.0**	**2040**	**1920**	**1960**	**1760**	**1640**	**1650**
COV	**22.0%**	**17.7%**	**15.5%**	**5.6%**	**5.0%**	**4.6%**	**8.0%**	**6.8%**	**6.9%**

Sample plot 30-outside has been omitted because it was not possible to collect a reliable sample. Further excavation of the plot showed this was a result of an abundance of fractured rock material.

Table 3. Average physical properties of the subgrade soil as determined by laboratory testing.

Position	% Gravel	% Sand	% Fines	Plastic Limit	Liquid Limit	Plasticity Index	USC Group	USC Name
0m	0.5	10.7	88.8	20.9%	29.4%	8.6%	CL	Lean Clay
50m	0.8	12.9	86.3					
100m	0.2	11.4	88.4					
Average	**0.5**	**11.7**	**87.8**					

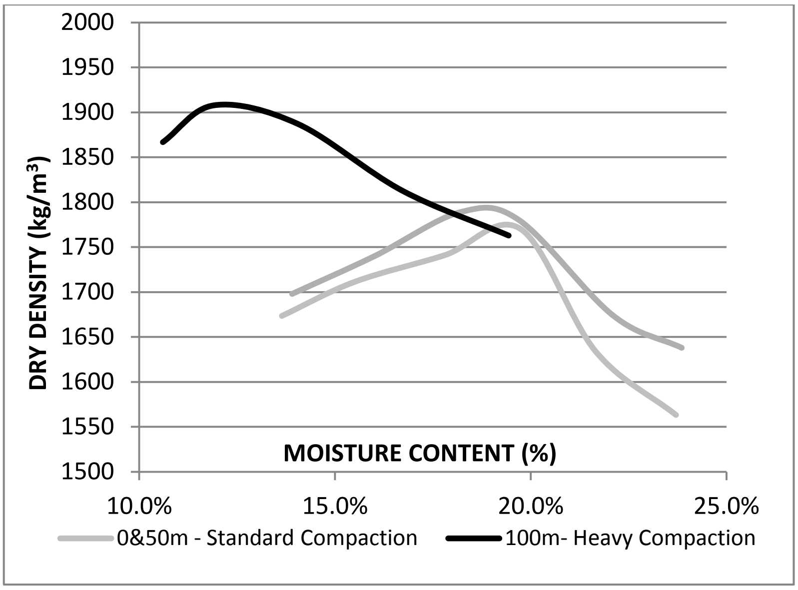

Figure 2. Proctor curves showing the optimum moisture content and maximum dry density for both standard and heavy compaction effort.

Figure 2 demonstrates that the standard compaction test produced a maximum dry density of approximately 1780kg/m^3 at a moisture content of 19.5%. Heavy compaction produced 1910kg/m^3 at 12% moisture content.

5. ANALYSIS AND DISCUSSION

Observation of the core samples showed that a number of them predominantly consisted of dark coloured, fragrant organic soils. A visual assessment was made and the eight darkest soils were categorised as organic. The remaining the samples were assumed to consist of mineral soil.

Figure 3. Core samples ordered by colour. Eight samples (left) consist of predominantly organic material.

Best practises guideless instruct the removal of all organic material when constructing the subgrade (Austroads 2009, NZFAO 2012). The presence of organic material might be the result of less rigorous construction practises owing to its origins as a farm track. Five of the eight organic samples came from the fill slope, this might indicate mixing (and subsequent degradation) of plant material during the placement of fill.

Wet sieving of three soil samples collected at 0m, 50m and 100m along the roadway established that the soil was predominantly fines (87.8%) with 11.7% sand and 0.5% gravel. The soil particle size distribution did not change significantly throughout the length on the road. With the exception of organic soil, the soil type is assumed to remain largely the same (Table 3). The plasticity index was relatively low at 9% (Austroads 2007). Categorised according to the Unified Soil Classification System this subgrade consists of a lean clay. The Unsealed Roads Manual (ARRB 2008) suggests a low presumptive design CBR of between three and six for clays.

5.1 Clegg Testing

The results of Clegg testing show considerable variation throughout the 100m of roadway sampled. Individual CIV values range from 4 to 26 with a coefficient of variance (COV) of 36.7% for the entire sample. There are a number of correlations that can be used for converting CIV to CBR. The New Zealand Forest Road Engineering Manual recommends using:

$$CBR = 0.07CIV^2 \qquad \text{(Clegg 1980)}$$

Table 4. Conversion of average sample plot CIV to CBR.

Position	CBR (%)			
	Inside	Middle	Outside	Mean
10	10.1	8.5	5.7	8.1
20	2.0	10.1	30.9	14.3
30	25.3	5.3	4.1	11.5
40	21.8	9.0	3.1	11.3
50	9.5	9.0	3.8	7.4
60	41.4	9.0	2.0	17.5
70	12.4	9.5	11.2	11.1
80	10.6	12.4	26.2	16.4
90	12.4	17.9	15.8	15.4
100	10.6	7.5	4.5	7.5
Mean	**12.05**	**Max**	**41**	
COV	**75%**	**Min**	**2.0**	

Total variation is high (COV of 75%) however areas of low CBR are typically localised. Four of the five samples with very low CBR were located adjacent to each other on the outside section of the subgrade. Collectively these soils were drier than average and had a greater than average density, both of which should improve mechanical properties. Linear regressions show that neither CIV nor CBR correlates with either moisture content or dry density. The average CBRs for the inside, middle and outside of the subgrade are 15.6%, 9.8% and 10.7% respectively. Results from an independent t-test (Table 5) show that there is no evidence to suggest a significant difference in the means of the three lateral positions across the road.

Table 5. Independent t-tests comparing the Californian Bearing Ratio across the subgrade.

Comparison	Levene's Test	t-test for Equality of Means			95% CI of the Difference of Means	
	Sig.	t	df	Sig.	Lower	Upper
In - Mid	0.016	1.571	10.6	0.146	-2.36	13.94
In - Out	0.973	1.014	18	0.324	-5.23	14.99
Mid - Out	0.060	-0.265	10.8	0.796	-8.49	6.67

When converting CIV to CBR the quadratic relationship has the effect of increasing the variation. Although the mean CBR is adequate for forest road construction the large variation means the bearing strengths of roughly five out of the thirty sample plots are inadequate or very marginally adequate. These sections of road would likely have to be excavated and replaced with a more substantial material (Austroads 2009). These results also raise the question of selecting a suitable design CBR. Without subgrade improvement this significant variability in bearing strength necessitates tradeoffs between high construction costs or the increased probability of road failure. Furthermore it shows that limited testing of subgrade strength is likely to be highly misleading and testing of CBR in this manner should be treated cautiously.

5.2 Compaction Testing

The mean dry density for the entire sample is 1685kg/m^3 with a COV of 7.8%. When considering only the mineral soils this becomes 1735kg/m^{3}and 6.6% COV. Compared to the variation in either CIV or CBR this is quite modest. The range of dry densities observed is likely to be significant to yield inadequate performance with regards to settlement under load.

The large disparity between the levels of compaction may be a result of the subgrades origins as a farm track. Long term weathering and poor drainage may have altered the soil. White *et al* indentify some of the largest contributors to poor subgrade uniformity as expansive soils, variable soil type, the presence of voids and cut fill transitions. The extremely high density shown by some of the samples is highly unlikely to be the result of construction and is not explained adequately by other parameters measured in this study.

The Austroads (2008) and ARRB (2009) road manuals both specify relative target relative compactions of about 100% of standard compaction at OMC. It is uncertain whether this level of compaction is cost effective or practical for forest roads. Despite this, the majority of mineral samples fall short of this target as do all organic samples.

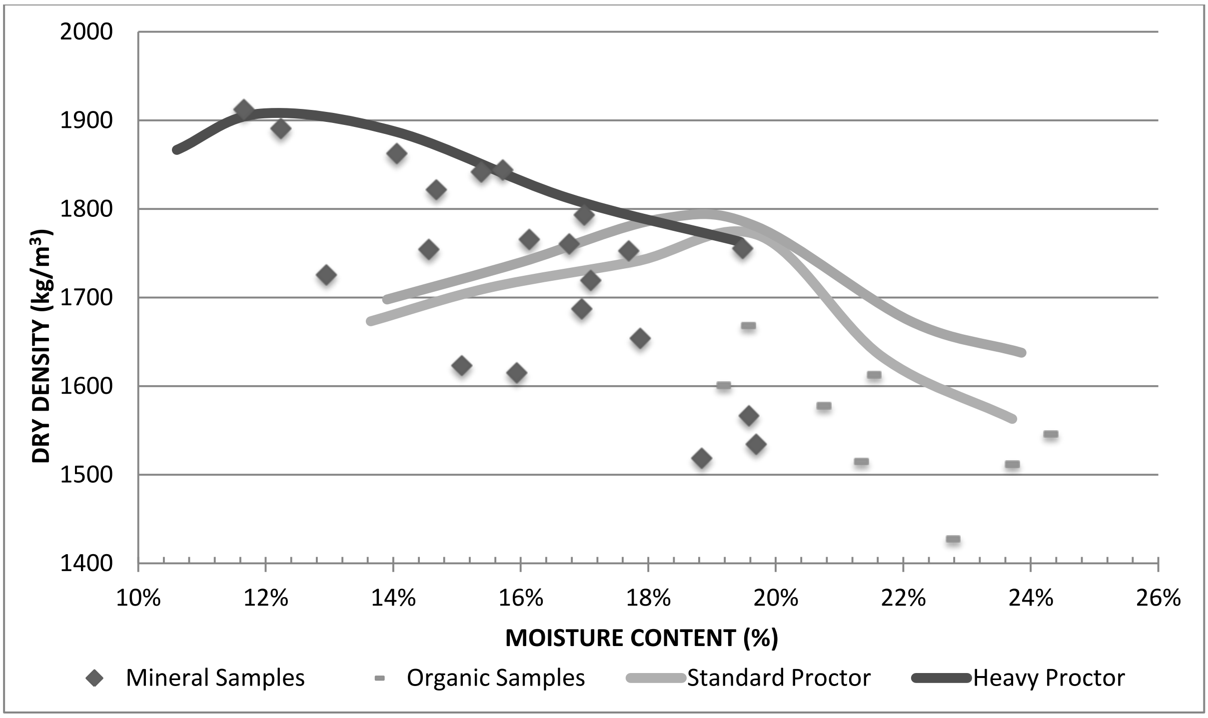

Figure 4. Dry density of 29 soil cores compared with density achieved by laboratory compaction.

In Figure 4 the dry densities and moisture contents of the twenty-nine soil samples are plotted alongside the ideal compaction curves obtained from laboratory testing. Organic samples were generally less compacted and had higher moisture contents, highlighting the importance of removing organic soils during road construction.

Figure 4 also demonstrates that moisture content appears to be strongly correlated with dry density. A linear relationship between MC and a dataset combining both soil types has an R^2 of 0.72, when comparing solely mineral samples produces a lesser R^2 of 0.49. Moisture content during compaction is an important determinant of dry density but for a causal relationship to exist a compactive effort must have previously occurred at a time when the moisture contents are similar to those observed in testing. This is highly unlikely and therefore the relationship is assumed to be casual, further testing could be undertaken to explore this phenomenon.

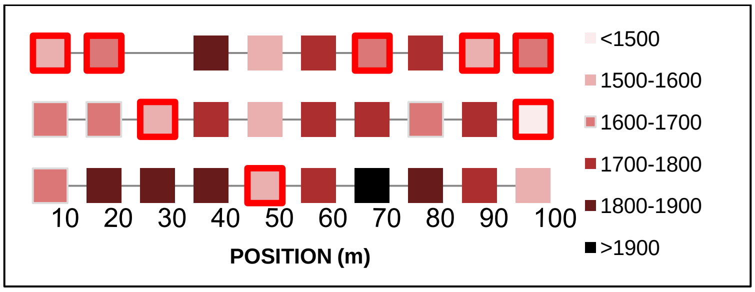

Figure 5. A pictogram representing the distribution of dry soil density throughout the road. Organic samples in red borders.

Figure 5 shows that the variability in soil density along the road was relatively random. The average densities for the inside, middle and outside of the subgrade were 1760kg/m^3, 1640kg/m^3 and 1650kg/m^3 respectively. An independent t-test was used to compare the means of the dry densities:

Table 6. Independent t-tests comparing the dry densities across the subgrade.

Comparison	Levene's Test	t-test for Equality of Means			95% CI of the Difference of Means	
	Sig.	t	df	Sig.	Lower	Upper
In - Mid	0.458	2.102	18	0.050	0.052	238.8
In - Out	0.562	1.785	17	0.092	-19.2	229.5
Mid - Out	0.848	-0.264	17	0.795	-122.2	95.3

Levene's test affirms the assumption of equal variance in each test. These results show that there is no evidence to suggest significant differences in dry density between the inside - outside or middle - outside. The independent t–test comparing inside and middle produces a Sig. of 0.050 with the 95% CI only just excluding unity. This suggests they are significantly different but only just meet the criteria. The significance of a t – test comparing small sample sizes (10 in this case) is not highly robust and so this result is treated with caution.

6. CONCLUSIONS

This research shows that for the subgrade tested there was considerable variation in bearing strength (COV = 75%) as well as dry density (COV = 7.8%). These variations are large enough to pose practical difficulties in implementing design choices.

The average CBR was 12.1% with values ranging from 2% to 41%, in practical terms this ranges from extremely weak to extremely strong. Selecting a pavement thickness reflecting the average CBR would almost certainly result in premature road failure. The variability in bearing strength was high enough to indicate that CBR testing using a CIST could be very vulnerable to the bias for small sample sizes.

Subgrade dry density variation was less than for bearing strength; despite this it was still considerable in terms of practical consequences. The majority of samples did not meet typical Civil Engineering target densities however a number greatly exceeded them. This was not adequately explained by the soil parameters measured by the study.

This study also showed that a portion of the existing subgrade contained organic soil. These organic soils had a lower than average bearing capacity and density, highlighting the importance of stripping organic soil during road construction.

7. REFERENCES

ARRB (1998). *A guide to the design of pavements for light traffic*. APRG Report 21. Australian Road Research Board, Victoria, Australia.

Austroads (2009). *Guide to pavement technology, part 8: pavement construction*. Austroads. Sydney, Australia.

Austroads (2007). *Guide to pavement technology, part 4: pavement materials*. Austroads. Sydney, Australia.

Austroads (2004) *Pavement design. A guide to the structural design of road pavements.* Austroads. Sydney, Australia

Fairbrother, S. (2011). *Estimating forest road aggregate strength by measuring fundamental aggregate properties*. Proceedings for the Council on Forest Engineering Annual Meeting, Quebec City, Canada, 2011.

___________. (2011). *Improved pavement design for aggregate surfaced roads*. Low volume roads workshop 2011, Queenstown, New Zealand. Retrieved from: http://www.roads.co.nz/Queenstown Pdf files/Fri 13.20 Simon Fairbrother.pdf

Fairbrother, S., McGregor, R. and Aleksandrov, I. (2010) *Development of a correlation equation between Clegg impact values and California bearing ratio for in-field strength assessment of forest road subgrades.* 33rd Annual Council on Forest Engineering Meeting, Jun 2010. Auburn, AL, USA. Retrieved from: http://frec.vt.edu/cofe/documents/2010/Fairbrother_McGregor_Aleksandrov_CIV_CBR.pdf

Giummarra, G. (Ed.). (2009). *Unsealed Roads Manual: Guidelines to Good Practice.* ARRB Group. Victoria, Australia.

Lea, J. D. (2010). *The effect of spatial variability on the reliability of pavements* (PhD Dissertation, University of California, Davis). Retrieved from: http://search.proquest.com.ezproxy.canterbury.ac.nz/docview/522113875?accountid=14499

New Zealand Forest Owners Association. (2012). *New Zealand Forest Road Engineering Manual*. Wellington, New Zealand.

Saha, N. (2008). *Evaluation of subgrade strength and flexible pavement designs for reliability.* (Master's thesis, University of Mexico). Retrieved from: http://repository.unm.edu/bitstream/handle/1928/7640/Nayan_Thesis.pdf

Standards NZ (1986). *NZS 4402:1986 Methods of Testing Soils for Civil Engineering Purposes.* Standards New Zealand. Wellington.

Wasniak D. L. (1999). *Subgrade and base variability on the Ohio SHRP test road.* (Master's thesis, Ohio University). Retrieved from: http://etd.ohiolink.edu/send-pdf.cgi/Wasniak%20Daniel.pdf?ohiou1175276775

White, D., Harrington, D., Ceylan, H., & Rupnow, T. Centre for Portland Cement Pavement Technology, (2005). *Fly ash soil stabilization for non-uniform subgrade soils, volume ii: Influence of subgrade non-uniformity on PCC pavement performance* (IHRB Project TR-461; FHWA Project 4). Retrieved from website: http://www.ctre.iastate.edu/reports/tr461_vol2.pdf