Design moisture condition guidelines for pavement design and material assessment

October 2010

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NZ Transport Agency research report 424

ISBN 978-0-478-37122-2 (print)

ISBN 978-0-478-37121-5 (electronic)

ISSN 1173-3756 (print)

ISSN 1173-3764 (electronic)

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Arampamoorthy H, and J Patrick (2010) Design moisture conditions for pavement design and material assessment. *NZ Transport Agency research report 424.* 38pp.

Keywords: chipseal, moisture, New Zealand, pavement failure, potholes, rutting, waterproofing.

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Acknowledgements

The authors would like to acknowledge the help of the following people:

- John Siekmeier, Minnesota Department of Transportation, Office of Materials and Road Research, USA, provided some information related to soil water characteristic curve.
- Karen Wrigglesworth Cook provided editing assistance.
- Dr David Hutchison and David Alabaster were the peer reviewers for this report.

Contents

Executive summary

One of the largest impediments to using a greater range of materials in pavement construction is concern over the effects of water ingress, which may lead to premature pavement failure. All pavement design textbooks stress that the main factor affecting performance is water. New Zealand has traditionally taken a risk-averse approach, with pavements designed using the assumption that construction materials will encounter the worst possible moisture conditions – complete soakage. Development of the NZTA M/4 granular basecourse specification has been focused on obtaining a material that is moisture 'tolerant', which continues the risk-averse approach.

This low-risk approach has led to debate among pavement design practitioners about the many pavements that have performed extremely well despite being composed of materials regarded as substandard.

The aim of this project, undertaken in 2008–2009, is to develop guidelines to estimate existing pavement moisture conditions better. By assuming that in situ moisture conditions are less than saturated, the guidelines will allow pavement designers to develop less conservative pavement designs, and to use base materials regarded as 'moisture sensitive' in areas where the risk of moisture ingress is low.

A model developed in the USA to estimate the equilibrium degree of saturation in subgrade and basecourse materials covers all the mainland states, and is thus applicable to areas of similar climatic conditions to New Zealand. This model has been applied to New Zealand data with the following conclusions:

- The literature review shows that pavements typically settle to an equilibrium moisture content, which is a function of pavement materials and environmental conditions.
- It has been demonstrated that Perera's methodology for estimation of moisture conditions in basecourse is appropriate for New Zealand conditions.
- For granular basecourse, the equilibrium moisture condition is typically in the range of 50–60%.
- For subgrade soils, the equilibrium moisture content is typically greater than 85%. This is higher than predicted and may be associated with the depth to the ground water being closer than assumed in the analysis.
- These values are typical throughout New Zealand's climatic range.

It is recommended that laboratory characterisation of the long-term performance of pavement materials should be performed at 60% saturation for granular bases and at saturated conditions for subgrades.

Abstract

A pavement design model developed in the USA is used to estimate the equilibrium degree of saturation in pavement subgrade and basecourse materials. The model is applicable to all the mainland US states, including areas with similar climatic conditions to New Zealand. The research on which this report is based, which was carried out in 2008–2009, indicates that the US-based model is appropriate to New Zealand conditions, where typical equilibrium moisture conditions are in the range of 50–60% for granular basecourse and typically greater than 85% for fine-grained subgrade soils.

1 Introduction

1.1 Background

Concern over the effects of water ingress is a significant impediment to using a wider range of materials in pavements. All pavement design textbooks stress that the main factor affecting performance is water. New Zealand has traditionally taken a risk-averse design approach and assumed that pavement construction materials will generally encounter the worst possible moisture conditions (soakage). Development of the M/4 granular basecourse specification (Transit New Zealand 2006) has focused on obtaining a material that is moisture 'tolerant', continuing the risk-averse approach.

This low-risk pavement design approach has led to debate among pavement design practitioners about the many New Zealand pavements that have performed extremely well despite being composed of materials considered substandard. With a growing emphasis on sustainable roading, the advantages of a less conservative pavement design approach include preservation and better use of New Zealand's aggregate resources.

The amount of moisture considered unsatisfactory in a pavement layer is the level that results in a high degree of saturation of the material (*not* the absolute moisture content). Therefore, guidelines need to be developed to help pavement designers accurately determine 'design' saturation conditions. These guidelines would cover factors such as an assessment of pavement construction materials, traffic, topography, drainage and climate. When combined with political and user expectations, the guidelines would help determine the appropriate design moisture conditions for each location. If, for example, the pavement has a high traffic loading on a moisture sensitive subgrade, more conservative design parameters should be selected. In contrast, a pavement with low traffic and a moisture tolerant free-draining subgrade would require less conservative design parameters.

A number of research projects have been published which discuss the issue of moisture in pavement design in New Zealand. The most recent research includes Peploe (2002), and Patrick and McLarin (1998). In addition, Ball et al (1999) showed that water can penetrate through a chipseal surface, especially under pressure from traffic.

The research indicates that water can infiltrate a pavement but the extent of infiltration depends on a wide range of factors. High moisture levels reduce the strength of both granular and subgrade layers, although with different pavement failure results. When the granular layers are affected, a pavement experiences shallow shear, rutting and potholing, whereas when moisture affects the subgrade, rutting is typically the predominant failure mechanism.

In a recent NZ Transport Agency (NZTA) research project (Arnold 2008), the rutting resistance of alternative granular pavement materials was assessed using the repeated load triaxial test to simulate the effect of repeated traffic loading. In the research project, moisture conditions were set at levels consistent with a 'dry' pavement. However, material performance in this test is known to vary significantly, depending on the moisture conditions, and the 'standard' method used is to test a saturated sample. This conservative approach results in many materials failing in the test and thus not being regarded as suitable for use. If the pavement designer could be confident that a pavement's moisture conditions would remain below saturation level, then less conservative design parameters could be used.

Knowledge of moisture conditions is also important to determine the leaching potential of recycled materials (Herrington 2006). Where materials are found to generate potentially harmful leachates, knowledge of the factors influencing water flow and methods to prevent water build-up is essential to allow these materials to be used safely.

Several factors can affect moisture in pavement layers. The main factors are:

- thickness of the sealed surface
- distress of the surface layers (eg intensity of the cracks and their width)
- slope of the shoulder and the camber of the seal surface
- effectiveness of drainage
- land terrain
- intensity and duration of rainfall
- depth to water table.

When roads are maintained correctly, adverse effects from these factors are minimal.

A model has been developed in the USA to estimate the degree of saturation in subgrade and basecourse materials. The model covers all the mainland states, including areas with similar climatic conditions to New Zealand (Perera et al, 2004).

The US-based model uses the Thornwaite Index (Thornwaite 1948) as the major climatic input, which was developed in the 1940s, and has precipitation and temperature inputs. This Index has been used in New Zealand for vegetation mapping, and thus 'Indexed' maps of New Zealand are available (Garnier 1950). The Index has also been proposed as an input to estimate pavement moisture conditions in Australia (Jones 2004).

The research reported here is designed to determine the applicability of the American model for New Zealand conditions.

1.2 Aim

The aim of this project is to develop guidelines for estimating the moisture conditions which exist in pavements. Assuming that in situ moisture conditions are less than saturated, the guidelines will allow pavement designers to be less conservative in design than is traditionally the case and, therefore, to use base materials that may be regarded as moisture sensitive in areas where the risk of moisture ingress is low.

2 Literature review

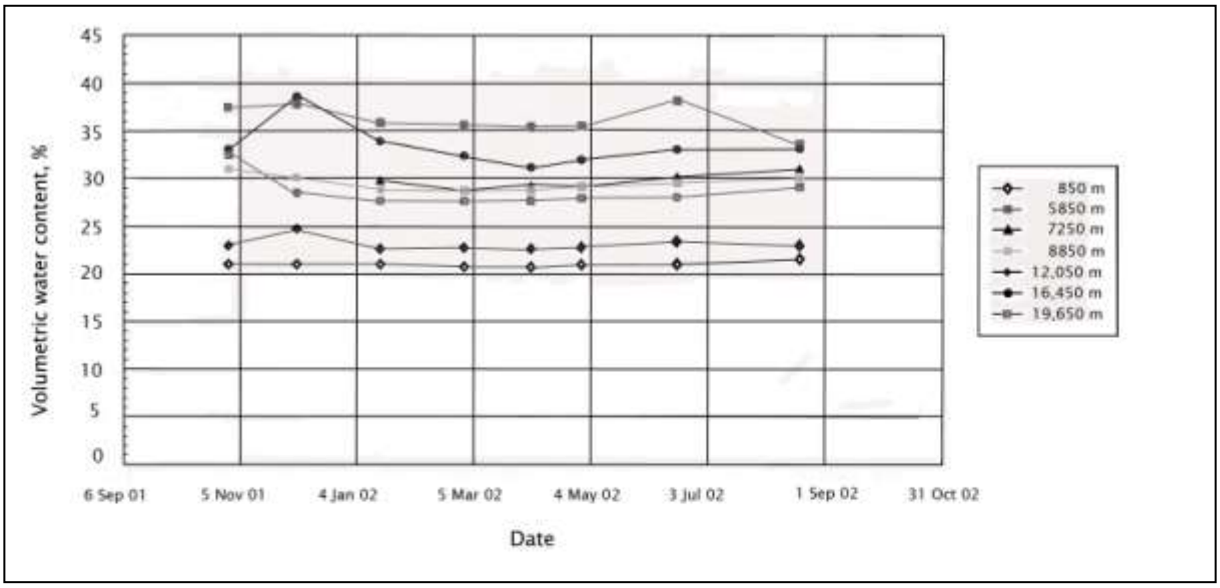
2.1 Research on pavement moisture

AUSTROADS (2004) contains recommendations for determining the typical moisture conditions for laboratory California bearing ratio (CBR) testing for pavement design. The specimen compaction moisture content should be at optimum moisture content (OMC) if the median annual rainfall is less than 800mm; otherwise, it should be 1–1.15 times the OMC. The soaking period is dependent on the drainage conditions for this CBR test. The AUSTROADS manual also notes that 'The design should ensure, either on the basis of knowledge of moisture conditions likely to occur in the locality, or by means of detailed field investigations, that the laboratory test conditions realistically represent in-service moisture conditions.' In New Zealand, the annual rainfall in the coastal area from Canterbury to Dunedin is typically between 500 to 750mm, and most of the rest of the country receives over 750mm per annum (National Institute of Water and Atmospheric Research (NIWA) 2004).

The AUSTROADS guideline suggests that a relationship exists between rainfall and pavement moisture conditions. Several researchers have, however, attempted to find a correlation between rainfall and variations of moisture content by investigating rainfall and moisture data (Peploe 2002; Cumberledge et al 1974; Reid et al 2006; Hossain et al 1997), or by calculating the correlation coefficient directly (Valdez 1991). Almost all of these researchers have ended up with the same conclusion: no relationship exists between rainfall and subgrade moisture variation.

Other researchers have determined that the moisture content beneath a pavement reaches an equilibrium condition some time after the pavement is constructed (Aitchison and Richards 1965; Basma and Al-Suleiman 1991; Richards 1965; Perera et al 2004). Research in New Zealand has confirmed the existence of an equilibrium moisture condition. Figure 2.1, which was taken from Dennison (2002), shows the variation in volumetric moisture content over a one-year period at six sites along a pavement located on flat terrain in the Bay of Plenty. Dennison found no correlation between rainfall and in situ moisture.

Figure 2.1 Equilibrium moisture content over one year in the Bay of Plenty (adapted from Dennison 2002)



Perera et al (2008) note that the equilibrium will not hold where the pavement is subjected to freeze–thaw conditions, or where the water table is within approximately one metre of the surface. They conclude that seasonal effects on moisture content will be insignificant if the point of consideration is 0.9–1.8m from the edge of the pavement. Infiltration through the road shoulders is influenced considerably by moisture closer to each edge of a pavement. Roberson and Siekmeier (2002) measured the saturation in the pavement base, sub-base and subgrade using the Time Domain Reflectometry method, and found that the moisture content in the outer wheelpath is higher than moisture content at the centreline, with a difference of 10–15% saturation. Their graph shows that moisture reaches an equilibrium condition in the long term, with minor short-term fluctuations when precipitation occurs. However, this fluctuation is minimal in comparison to rates of precipitation.

To reduce the moisture variation of the outer wheelpath, consideration has been given to sealing the shoulders. Alternatively, in some situations, a special granular sub-base separator layer can be used to allow rapid drainage. However, the centreline will still remain drier than the outer wheelpath during a single storm event or over a consistently wet season, as water will continually be entering through the pavement shoulders (Roberson and Siekermeier). AUSTROADS (2004) suggests that if an extension of sealing is not possible, then the moisture condition of the outer wheelpath should be the design value.

Moisture conditions are also dependent on the depth of the water table. Drumm and Meier (2003) consider that moisture conditions in pavement layers will be influenced by the water table if its depth from the surface is less than 6m for clay, 3m for sandy clay or silt, and 1m for sand. Lay (1990) noted the same depths for clay and for sand.

The presence of water in soils and aggregates has received attention as in situ measurements of soil suction and pore water pressures have become available. These parameters, including moisture content, influence the strength and stiffness of each pavement layer when these layers are constructed with unbound material. Pore water pressure affects the pressure exerted on adjacent soil particles, and will influence the strength of that material.

Software called THEWET (Wallace 1991) was developed at the Queensland University of Technology to predict moisture movement in pavements. The dry state permeability and suction head values do not need to be specified for this software, as the model assumes they are zero and infinity, respectively. This assumption highlights that the model is not suitable for situations approaching the dry state. Wallace recognises this and advises that the model is most suited to relatively wet conditions corresponding to suction from saturation up to heads of about 10m.

A four-step procedure was given in National Cooperative Highway Research Program (NCHRP) (2000) to estimate equilibrium saturation from the depth of the water table. In this procedure, the matrix suction was estimated from the ground water table depth.

Federal Highway Administration (FHWA) managed several long-term pavement performance (LTPP) sites in the USA and Canada. This site data was used for the investigation of measured and predicted soil saturation for plastic and non-plastic soils (NCHRP 2008). From an estimate of matrix suction, they then made an estimate of the degree of saturation. Figures 2.2 and 2.3 were based on those shown in their report.

Figure 2.2 Predicted and measured degree of saturation for non-plastic soil (adapted from NCHRP 2008)

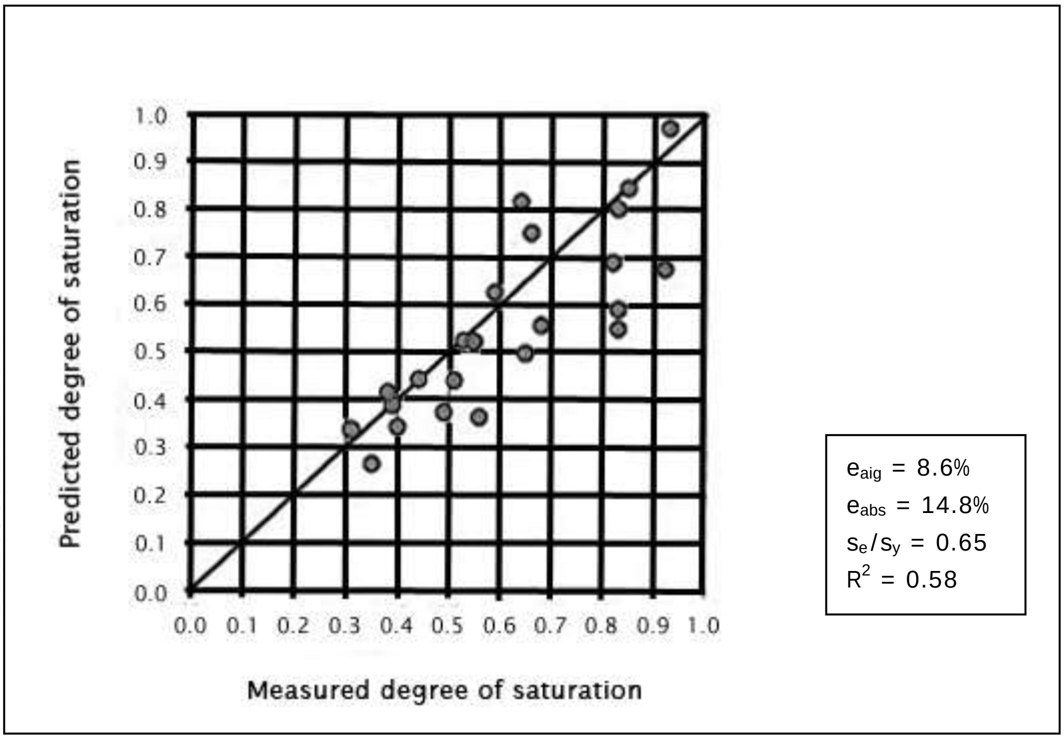


Figure 2.3 Predicted and measured degree of saturation for plastic soil (adapted from NCHRP 2008)

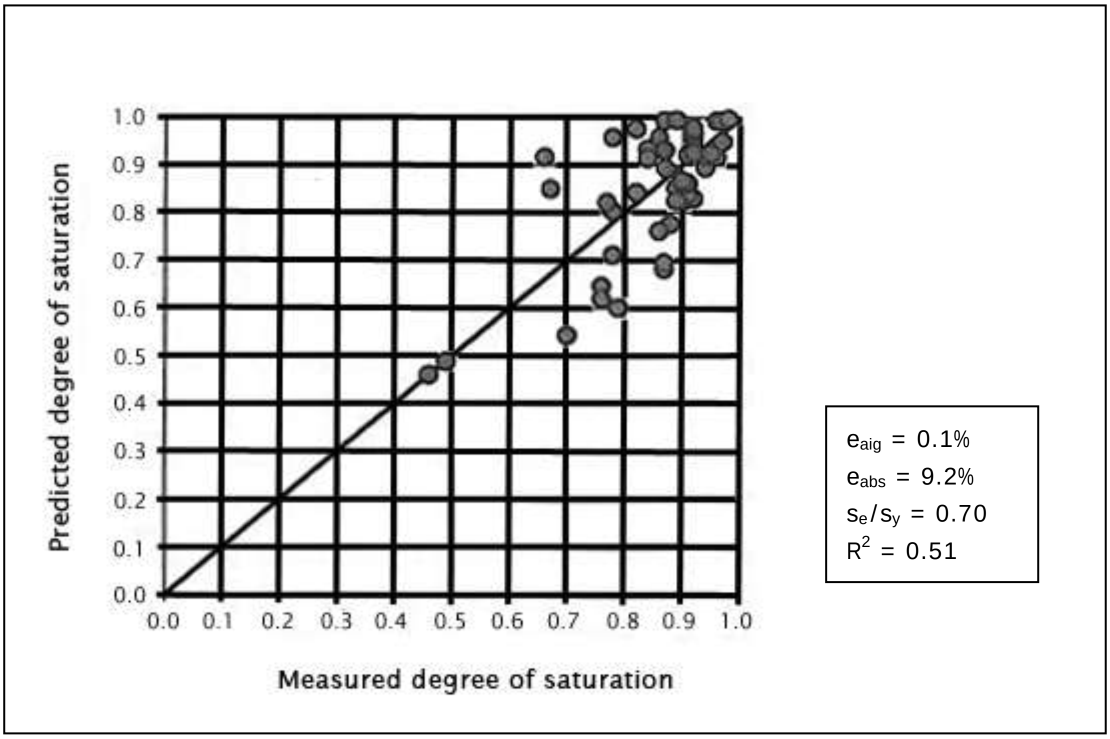


Figure 2.3 shows that for plastic soils, most saturation levels are between 0.7 and 1.0, which is a relatively high degree compared with the non-plastic soils shown in figure 2.2.

Soil suction is an indicator that can measure the capacity of a soil to attract and hold the water (Lee and Wray 1995). Dry soil will cause high suction and wet soil will cause low suction. Water flows from wet to dry soil, with the flow being dependent on the suction gradient, which is similar to a pressure gradient. Total suction is a combination of matrix suction and osmotic suction. Matrix suction is the difference in pressure across the air–water boundary, and can be determined by measuring the capillary action from the surface tension of the water. Osmotic suction is dependent on the concentration of dissolved salts in the soil water. Total suction and matrix suction can be measured using filter paper, as described in Park et al (1999). A transistor psychrometer device, developed in Australia, can be used to measure total suction. Other methods are also available to measure matrix suction (eg thermal conductivity sensors (Nichol et al 2003)).

2.2 Perera et al's prediction model

Perera et al (2004) investigated a number of climatic parameters and found that the equilibrium soil suction beneath highway pavements correlates with the Thornwaite Moisture Index (TMI), the percentage of material passing through a 75µm sieve (P200) and the material plastic index.

Their prediction method is based on a two-step process:

1. Estimate the matrix suction of the material, taking the material's properties and climatic conditions into account.
2. Estimate the degree of saturation by using a soil water characteristic curve (SWCC).

The researchers proposed two material models to estimate the equilibrium soil suction values beneath pavements, when the ground water level is below 0.9m and the point of consideration is greater than 1.8m from the edge of the road.

The matrix suction relationship for granular base material is shown in equation 2.1.

$$h = a + e^{(b + c\,(TMI + 101))} \qquad \text{(Equation 2.1)}$$

Where:

- h is the matrix suction
- a, b and c are the curve-fitting constants
- TMI is the Thornthwaite Moisture Index (Thornwaite 1948).

The values are given in table 2.1, where P75 is the percentage of material passing the 75µm sieve. The relationship is illustrated in figure 2.4.

Table 2.1 Regression constants for the granular base model (taken from Perera et al 2004)

P75	Regression constants		
	a	b	c
4	5.285	3.473	-0.04004
6	6.877	4.402	-0.03726
8	8.621	5.379	-0.03836
10	12.18	6.646	-0.04688
12	15.59	7.581	-0.04904

Figure 2.4 TMI versus matrix suction for basecourse material P75 = percentage of granular material passing through a 75µm sieve (adapted from Perera et al (2004))

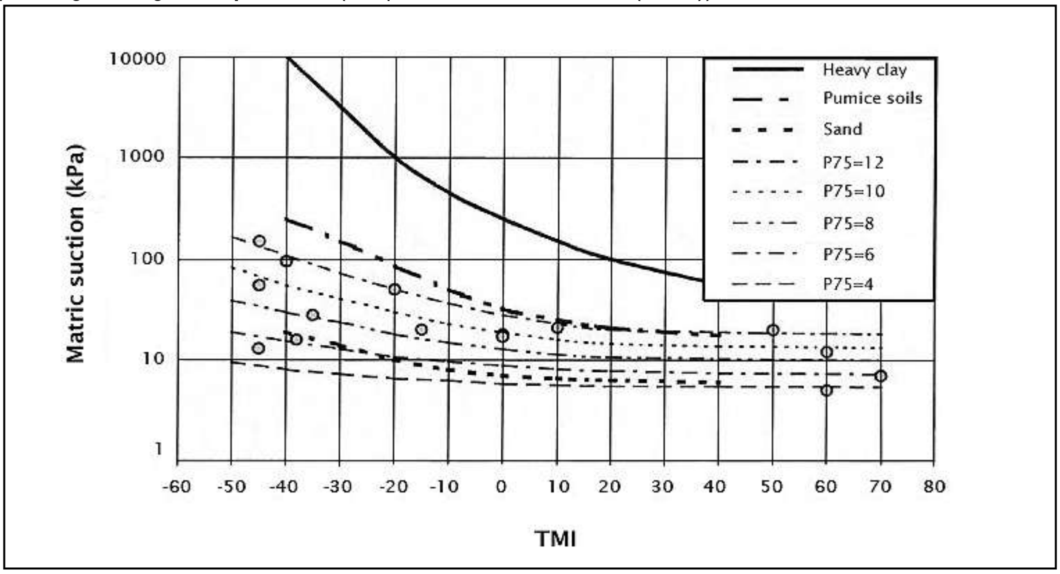


Figure 2.4 shows the relationship between matrix suction and TMI (see section 2.3 in terms of P75. Perera et al (2004) noted that the data analysis showed that suction increased with P75 values and suction decreased when TMI increases. On this basis, Perera et al added the contour lines shown in figure 2.4. They used a similar approach to produce figure 2.5 (details are given in Perera et al (2004)).

The matrix suction for sub-base and subgrade material is calculated using equation 2.2.

$$h = a(e^{(b/(TMI+c)} + d) \qquad \text{(Equation 2.2)}$$

Where:

- h is the matrix suction
- a, b, c and d are the curve fitting constants based on the material's properties
- TMI is the Thornthwaite Moisture Index (Thornwaite 1948).

The values are given in table 2.2 and illustrated in figure 2.5.

Table 2.2 Regression constants for the sub-base and subgrade material (from Perera et al 2004))

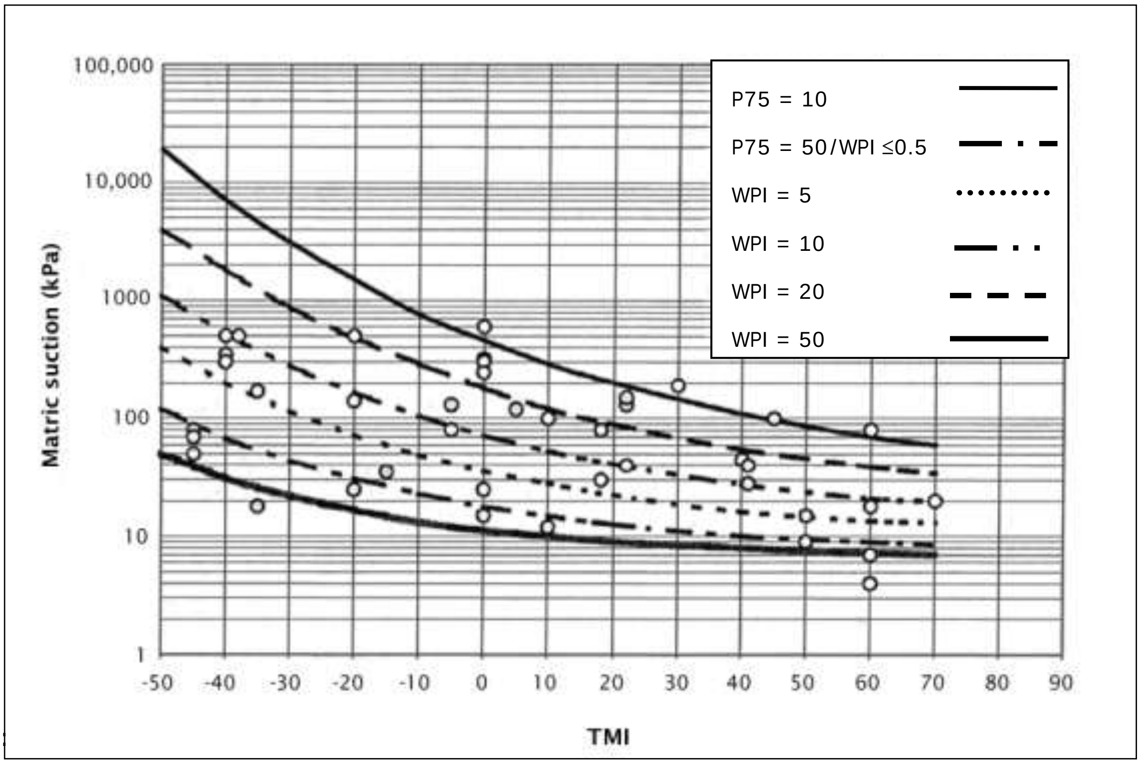
P75* or WPI**	Regression constants			
	a	b	c	d
P75 = 10	0.3	419.07	133.45	15
P75 = 50	0.3	543.48	144.22	14.36
WPI = 0.5	0.3	543.48	144.22	14.36
WPI = 5	0.0113	1461.6	193.97	870.94
WPI = 10	0.01	1759	206	1290
WPI = 20	0.01	2003	210.28	2210
WPI = 50	0.3	1060.8	148.8	72

Notes to table 2.2:

P75 = the percentage passing the 75μm sieve

WPI = the weighted plasticity index, equal to the percentage of material passing through 75μm sieve times the plasticity index.

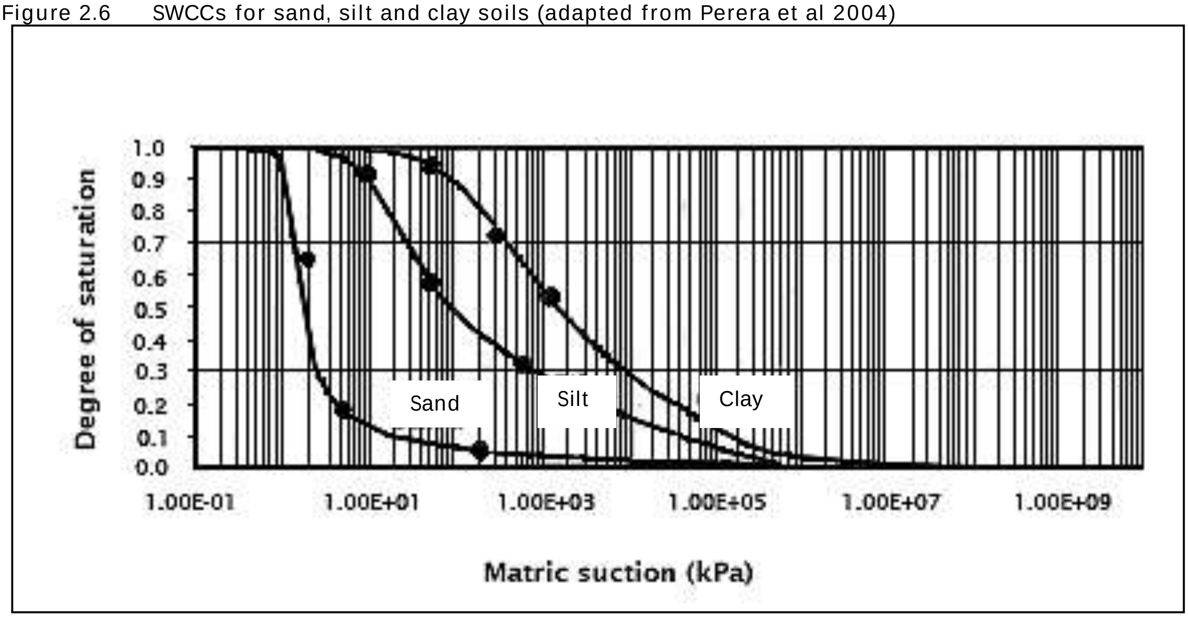
Figure 2.5: TMI versus matrix suction for subgrade material (adapted from Perera et al 2004)



Note: Circles are data points.

From an estimate of the matrix suction, the researchers then estimated the degree of saturation from a SWCC, as illustrated in figure 2.6.

Figure 2.6 SWCCs for sand, silt and clay soils (adapted from Perera et al 2004)



In the research reported here, the methodology used by Perera et al has been followed. The sensitivity of the soil suction estimation and the SWCC have been examined to help determine the expected sensitivity of the estimation.

2.3 The Thornwaite Moisture Index

Soil suction in covered ground is influenced by the water content of the soil, which is, in turn, related to climatic factors (Coleman 1965; Russam and Coleman 1961). These factors can be combined in a climatic index called the Thornthwaite Moisture Index (TMI), which indicates the humidity of a soil and the associated climate condition (Thornthwaite 1948). The TMI depends on the cyclic nature of wetting and drying at a site (ie precipitation and evapotranspiration). The TMI is calculated using equation 2.3.

$$TMI = (100q - 60\,DF)/Pe \qquad \text{(Equation 2.3)}$$

Where:

- q is water runoff (cm)
- DF is the deficit of water for the year in centimetres
- Pe is the potential evapotranspiration of water for the year in centimetres.

A detailed procedure for calculating TMI is given by McKeen and Johnson (1990) in their Appendix 1.

Maps of TMI values for New Zealand locations are given in figures 2.7and 2.8 (adapted from Garnier 1950).

Figure 2.7 TMI for the North Island (modified from Garnier 1950)

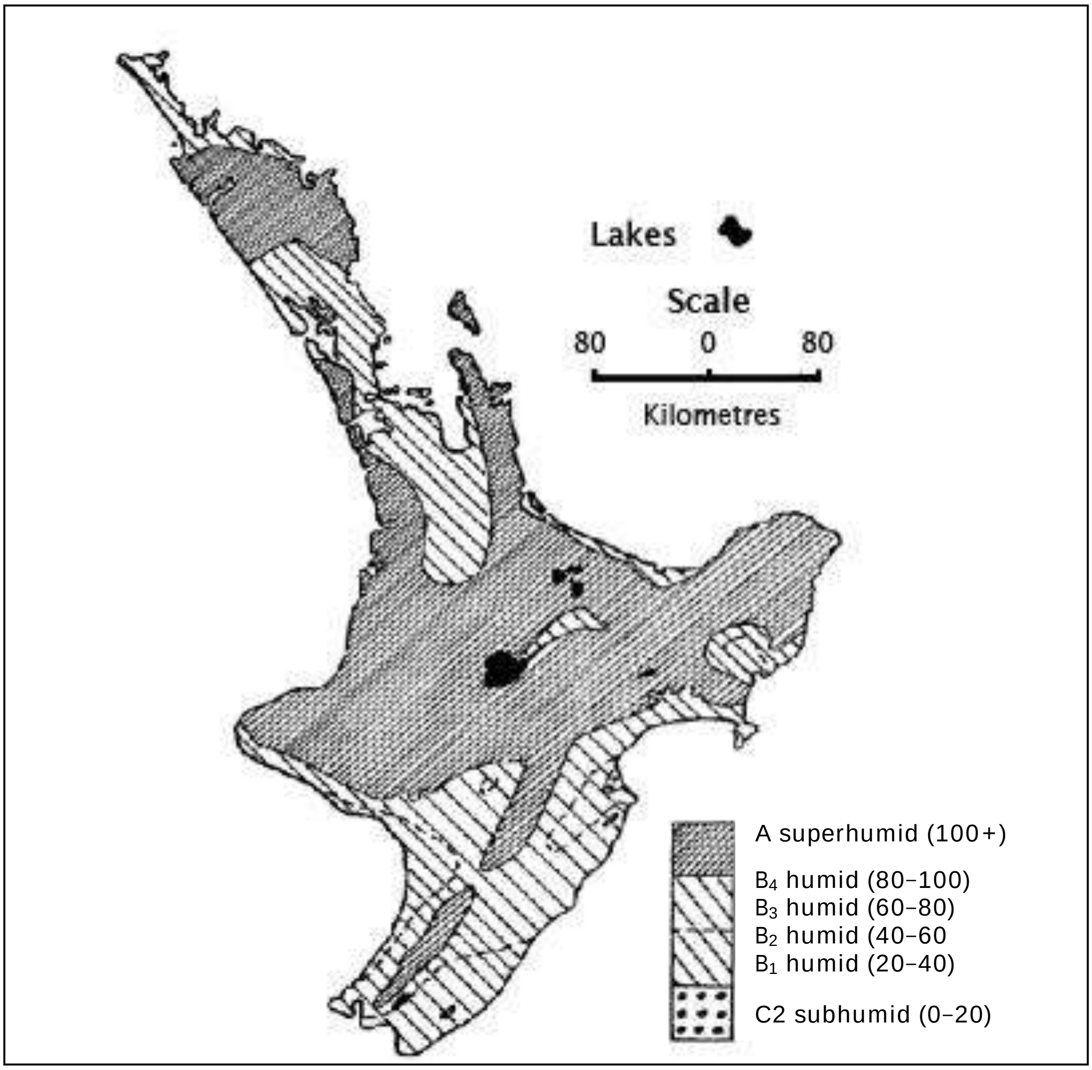
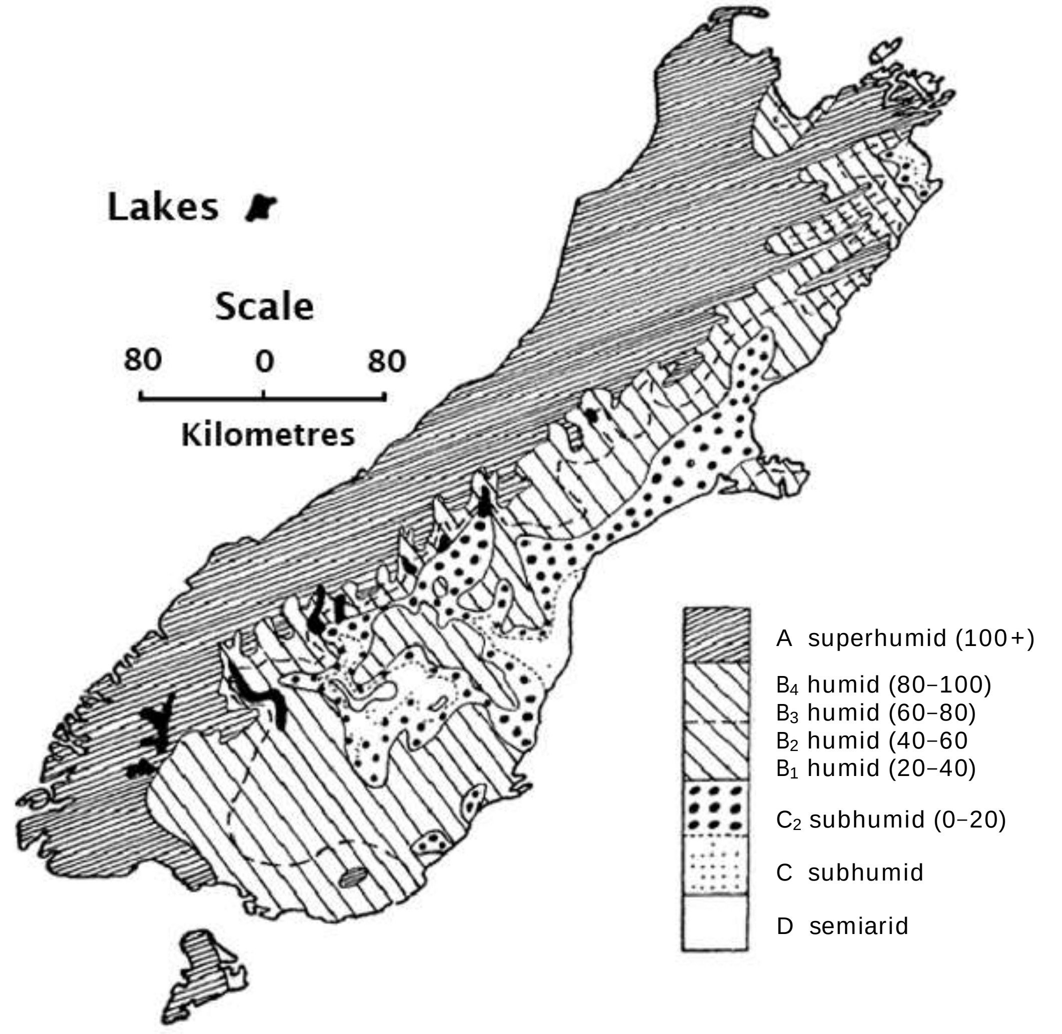


Figure 2.8 TMI for South Island (modified from Garnier 1950)

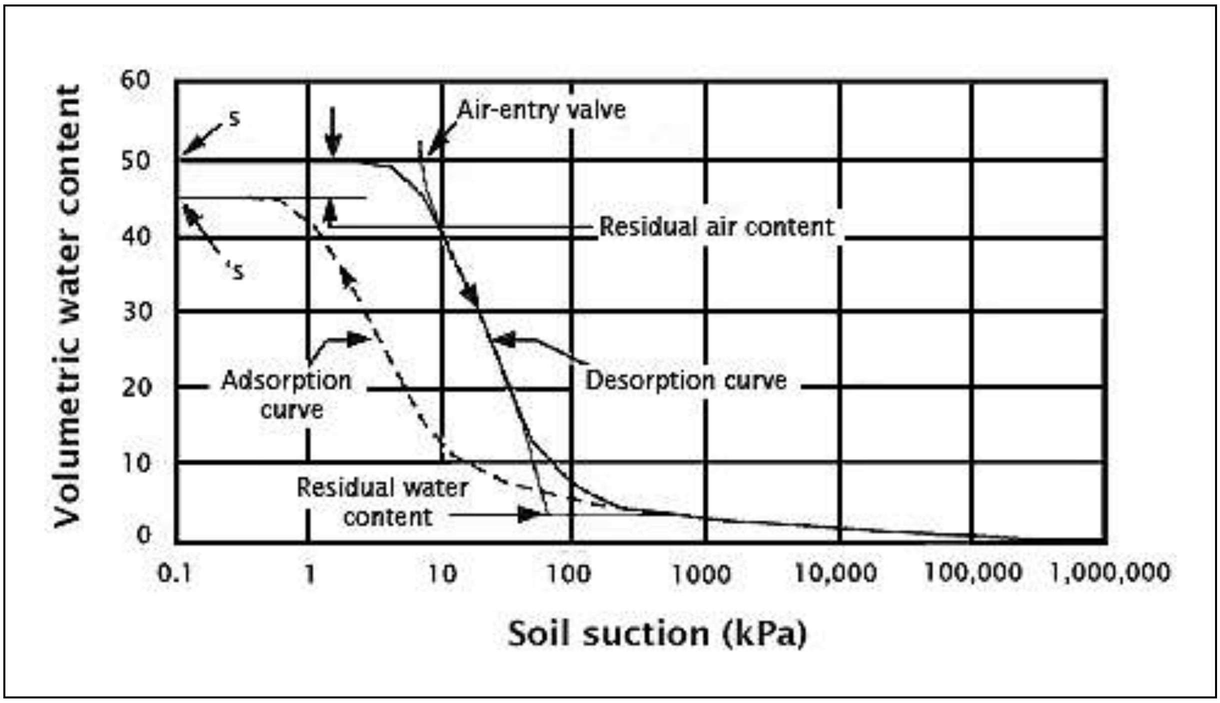


2.4 Soil water characteristic curves

The matrix suction characteristics of a soil are used for predicting soil saturation, with the help of a SWCC. This curve shows the variation of water storage capacity within the macro- and micropores of a soil with respect to suction (Fredlund 1995). A SWCC shows the functional relationship between water content and matrix suction. Water content can be referred to as moisture content or saturation level. Suction is the negative pore pressure related to external air pressure.

In general, soil is a porous media, and the soil's pores are filled with air and water in an unsaturated state. When a soil is fully saturated, all the pores (voids) will be filled with water, leaving no room for any air. The most commonly used terms in this study are water content and saturation level. The water content is the amount of water contained within a soil. The degree of saturation refers to the percentage of voids filled with water. In certain cases, the residual water content is referenced to zero water content (see figure 2.9). Further terms are explained with the help of a typical curve, as shown in figure 2.9.

Figure 2.9 SWCC for a silt soil (taken from Fredlund and Xing 1994)

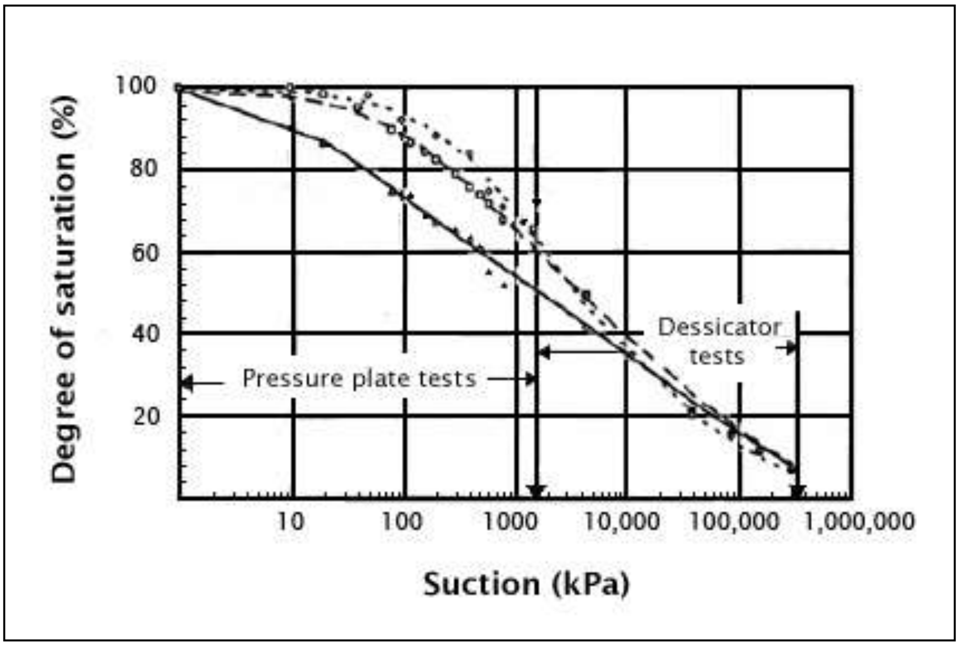


As can be seen from figure 2.9, residual water content is where a large amount of energy would be required to remove the water remaining in a soil. Two curves are shown in figure 2.9: desorption and adsorption curves. The desorption curve shows the relationship between soil water content and suction during the *drying* process. The adsorption curve shows the relationship between soil water content and suction during the *wetting* process. The hysteretic nature of the SWCC is well known, but to simplify matters, most applications will assume a non-hysteretic pattern. Beyond the point of residual water content is an area termed the 'high suction range' or 'residual zone' of unsaturation. In this region, the drying and wetting curves are almost identical, although they differ from one another in the lower suction area range. The air entry value is the suction initially needed for air to enter a fully saturated soil.

Three other terms are defined in the international literature (Vanapalli et al 1999). During the desaturation process, soil passes through three stages: the boundary effect zone, the transition zone and the residual zone. In the boundary effect zone, which ends at the air entry value, soil is fully saturated. The transition zone is where the level of saturation drops rapidly. The air entry value decreases with increasing pore size, and the level of saturation increases rapidly with increasing suction (ie during the drying process). When pore size decreases, the phenomenon is reversed. Pore size is dependent on the proportion of fine particles and the proportion of large particles (ie those greater than 2 mm) within the soil. These are the major differences between clay and basecourse material.

Many experimental tests have been performed to obtain the SWCC for different soil types and conditions. Several factors which influence the SWCC, and the various effects that result, have been reported in a number of published papers. Vanapalli et al (1999) studied the effect of initial water content on the SWCC (see figure 2.10), using a Canadian soil which contained 28% sand, 42% silt and 30% clay. A number of samples were prepared and compacted. Some of the samples were initially wet and others were dry. The method produced samples of different void ratios (eg 0.545, 0.52 and 0.6). These samples were then tested to find the degree of saturation at different suctions. The difference in the degree of saturation between samples compacted when dry compared with samples compacted when wet was up to 20% for suction in the 50–500kPa range. These experiments show that initial moisture conditions or void ratios can have a significant influence on the level of soil saturation at low suction.

Figure 2.10 Soil–water characteristic profile for different initial moulding water contents of a soil (Vanapalli et al 1999).



Vanapalli et al (1999) also investigated matrix suction performance and the degree of saturation for different equivalent pressures. Vanapalli et al's results show that when the matrix suction increases, two levels of structure should be considered – microstructure and macrostructure. Macrostructure controls the SWCC of a dry specimen, especially for the lower suction range. The air entry value for suction and the residual state of saturation both increase with equivalent pressure for a specimen compacted when its water content was below the optimum (dry). In contrast, microstructure controls the SWCC of a specimen compacted when the water content was above the optimum (wet).

In summary, a review of the literature shows that the shape of the SWCC depends on soil type, initial stress and the condition of the specimen during compaction (optimal, wet or optimal dry water content conditions).

A number of mathematical equations have also been proposed in several research studies (eg Fredlund and Xing 1994). In their research, two sets of graphs were shown: one set for plastic soil (clay) and the other for non-plastic soil (sand). The findings of this previous research indicate that other soil types such as fine-grained non-plastic soil are expected to be within the envelope enclosed by the two graphs for clay and sand (see figure 2.6).

For plastic soil, as mentioned previously, the weighted plasticity index (WPI) was the main soil indicator used to correlate with in situ moisture conditions. For non-plastic soils, a grain diameter of D60 (in mm, corresponding to 60% of the grains passing by weight or mass) was the main soil property. A predicted set of SWCCs based on WPI and D60 are given in NCHRP (2000). Fredlund et al (1997) noted that the prediction of SWCCs resulting from the Fredlund and Xing equation (1994) 'tended to be sensitive to the packing porosity and more research is required in this regard.'

The SWCC profile is dependent on a soil's water retention capacity and drainage capability. The speed with which a soil drains depends on the distribution of larger-sized voids, which, in turn, are controlled by larger particles (eg those with a diameter of 19mm). In contrast, the length of time water is retained by a soil depends on the smaller voids (controlled by fine particle distribution (eg 75μm)). The basecourse model for SWCC should therefore consider total particle grading. Almost no large particles can be found in certain types of soils such as silts and clay, making it unnecessary to consider larger particles for the relationship between saturation and suction for these soil types.

The three profiles shown in figure 2.6 are general ones for clay, silt and sand. No specific curve has been drawn for basecourse material containing significant larger stones, meaning that porosity will be high compared to sand, resulting in low matrix suction at high saturation.

In figure 2.11 (from Roberson 2001), three types of granular material are shown: Class 5, Class 6 and selected granular materials. The particle distribution of M/4 basecourse material in New Zealand (Transit New Zealand 2006) is better approximated to Class 6 than to Class 5 (see table 2.3). This curve was therefore selected for estimating the saturation of basecourse material in this project.

Figure 2.11 SWCC curve for Class 5 and 6 and selected granular material (extracted from Roberson 2001)

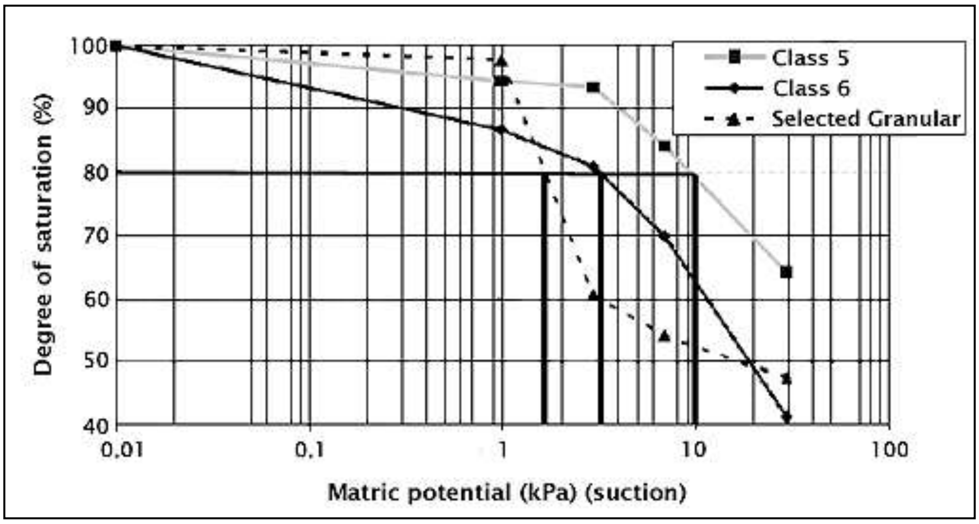


Table 2.3 Particle size comparison between Class 5, Class 6 and New Zealand M/4 basecourse material (Transit New Zealand 2006)

Sieve size (mm)	Percentage of grains passing through the sieve		
	Class		New Zealand M/4 basecourse
	5	6	
25	100+	100	100
19	90–100	90–100	66–81
9.5	50–90	50–85	43–57
4.75	35–80	35–70	28–43
2	20–65	20–55	19–33
0.00043	10–35	10–30	3–14
0.0002	3–10	3–7	0–7

3 Sensitivity

3.1 Granular materials

To examine the sensitivity of the Perera methodology, typical New Zealand field data has been used. Two sets of data were available for sites in Wellington and Timaru (Patrick et al 1998). The first set of measurements was taken before the road was open to traffic, and the second set of measurements was taken after the road had been open to traffic for between two months and one year.

At each location, between 30 and 45 measurements of density and moisture content measurements were taken.

In situ saturation levels were calculated from the test data, which included density and moisture contents obtained with a nuclear densometer using equation 3.1.

$$S = \frac{w}{\left(\frac{D_w}{D_d} - \frac{1}{G_s}\right)} \qquad \text{(Equation 3.1)}$$

Where:

- w is moisture content
- D_w is the unit weight of water
- D_d is the dry unit weight
- G_s is the specific gravity of the soil.

To estimate the saturation level, the TMIs were taken from figures 2.7 and 2.8. The corresponding matrix suction values were then obtained from figure 2.5. Figure 2.5 does not provide values for the relationship between matrix suction and TMI for matrix suction values of between 70 and 100; however, it has been assumed that the curve can reliably be extrapolated over this range. Using figure 2.5, the TMI values for Wellington and Timaru fall between 20 and 100; the matrix suctions are almost constant over this range (see figure 2.4) for each P75 sample (ie percentage of grains passing through a sieve with a mesh size of 75μm).

The M/4 basecourse specification (Transit New Zealand 2006) requires between 4 and 8% of the granular material to pass a 75μm sieve. Figure 2.4 shows that the corresponding matrix suction values are between 6 and 15kPa for the TMI range of 10–70.

Figure 2.11 was used to determine the degree of saturation. For Class 6, the degree of saturation is 55% and 72% for matrix suctions of 15kPa and 6kPa, respectively. Therefore this is the expected range of saturation to occur for an M/4 basecourse in Timaru or Wellington.

Calculated and predicted values are shown in table 3.1. From the field data, the maximum and minimum measured degree of saturation values are 35 and 75. These results indicate that values calculated from field data are similar to estimated values. However, the range in values calculated from the field data indicates that a wide range in degree of saturation is required from the test data.

Table 3.1 Comparison of predicted and measured saturation results for Wellington and Timaru

Site no.	Method	Saturation level (%)		
		Minimum	Average	Maximum
Wellington	Calculated	39	54	75
	Predicted		55–72	
Timaru	Calculated	35	49	62
	Predicted		55–72	

The effect of small changes in measured properties (ie density and moisture) on the degree of saturation are shown in table 3.2. A variation in saturation of 20% can occur through relatively small changes in measured values. Therefore, care is required when interpreting the test results.

Table 3.2 Effect of changes in density and moisture on saturation level

Density	Moisture (%)		
	4	4.5	5
2.29	60.3	67.9	75.4
2.27	57.0	64.1	71.3
2.25	54.0	60.8	67.5

The range of the TMI in New Zealand is between 10 and 100; for basecourse material, this range does not significantly affect the resulting matrix suction. An M/4 basecourse must have a P75 of between 0 and 7%. Typically, at least 3% will pass the 75μm sieve. The matrix suction from figure 2.4 for an M/4 basecourse is therefore 7–10kPa. This is neglecting any change in the fines content that may occur during construction and trafficking.

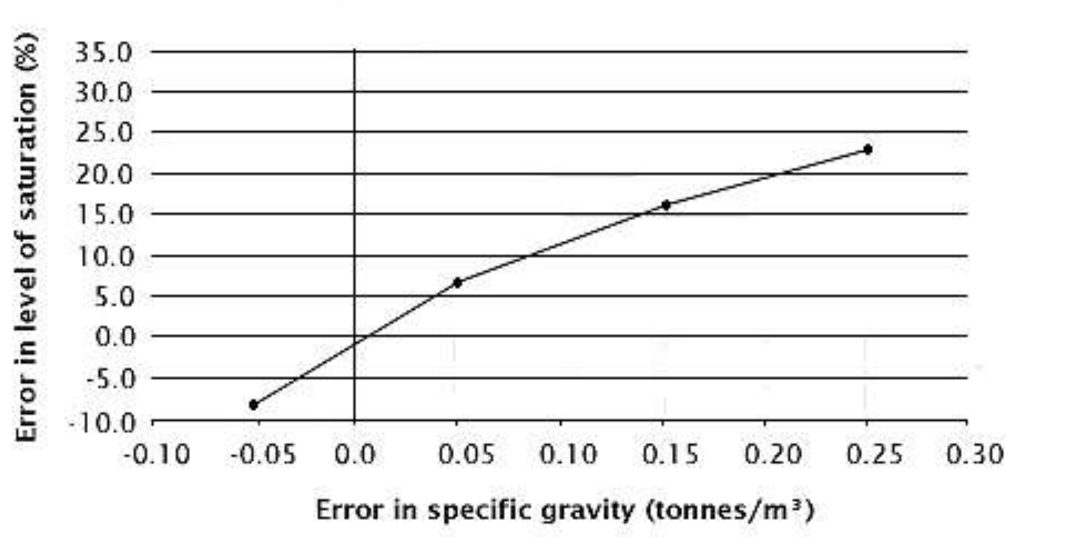
The effects of a small change in suction on the saturation level are significant. For example, the range in suction from 7 to 10kPa is equivalent to a change in saturation from 70 to 63%. It demonstrates that SWCCs should be specially produced for New Zealand basecourse material in order to predict more accurate results.

3.2 Specific gravity

In examining field data, specific gravity will, in most cases, need to be assumed. An analysis was performed to determine the sensitivity for an assumed value of dry density of 2.23tonnes/m^3, a moisture content of 5.2 and the specific gravity of 2.65.

Figure 3.1 shows that the error for calculated saturation can vary by more than 30%, depending on the specific gravity value used. With knowledge of the material type, eg greywacke, the specific gravity can be estimated to within 0.1, which would result in an error of 10% in the degree of saturation.

Figure 3.1 Effect of a change in the specific gravity on the calculated saturation level

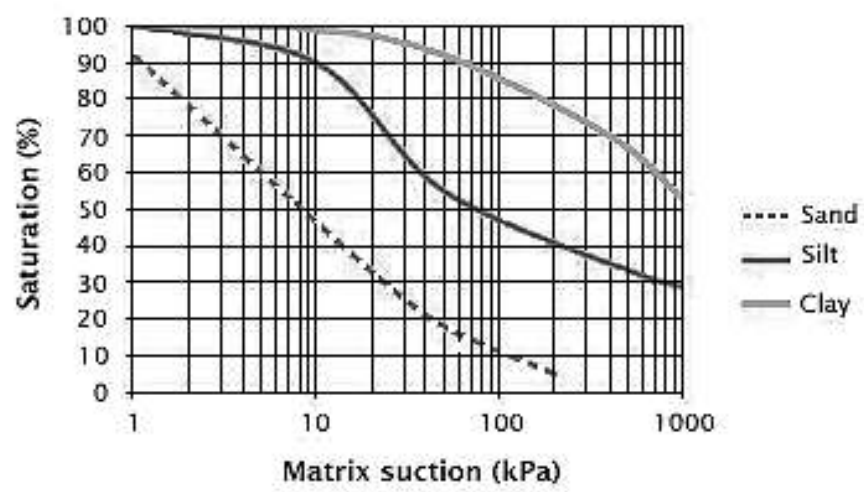


3.3 Subgrade

Figure 2.5 shows that the matrix suction on subgrade soils (with a WPI of less than 50 or a P75 less than 10) can vary from 8 to 300kPa over a TMI range of 10–100 (the typical range for New Zealand). Figure 2.6 shows that at this level of suction, the saturation level for clay and silts is in the 80–95% range. This suggests that, for New Zealand conditions, silt and clay subgrades will be at an equilibrium moisture condition of relatively high saturation levels. The 8–300kPa range of suction for New Zealand conditions is relatively narrow. Figure 3.2, which is a magnification of figure 2.6, shows the wide range in saturation levels that can occur depending on whether the subgrade is clay, silt or sand. Often the subgrade will not fit one of these definitions, and whether the material is classed as a silty clay or clayey silt could make a significant difference in estimating the degree of saturation. For example, at a matrix suction of 100kPa, the difference in degree of saturation could be read as 65% or 80%.

Consequently, when estimating the degree of saturation, a soil's physical description becomes the most sensitive input to the calculations.

Figure 3.2 SWCCs for sand, silt and clay over the range of typical matrix suction in New Zealand conditions



4 Field data

It was initially planned to source data for in situ moisture conditions from test pit data held by Opus' laboratories. To estimate the degree of saturation, both the in situ dry density of the layer and its moisture content are required. It was found that test pit investigations very rarely included density measurements. Furthermore, because the investigations formed part of a rehabilitation treatment design, it could not be guaranteed that the surfacing was sound, or whether water was entering the soil through surfacing defects. Other sources of data were therefore sought.

New Zealand began a long-term pavement performance (LTPP) site monitoring programme in 2000, adding sites to the programme as time went by. For this programme, the NZTA annually recorded pavement performance data, and arranged for test pits to be dug and pavement properties to be determined. Although the data is sufficient to determine the degree of saturation at some sites, a complete dataset has not been collected.

The basecourse materials were assessed using 18 LTPP sites containing sufficient appropriate data. Six of the datasets contained unreliable measurements and were therefore deleted from the analysis. For example, one data reading noted that the sample was moist although the measured moisture content was only 0.3. Because of this contradiction, this particular site was not considered appropriate for analysis. At another site, sub-base data was used instead of measurements from the top because we suspected that the top layer consisted of stabilised material. This possibility was noted in the data log sheet. At yet another site, the data suggested that the sample was sandy gravel and was probably stabilised. However, an SWCC is not readily available for this type of material, so this site was discarded from the sample. Finally we were able to select 12 reliable LTPP sites for analysing the predicted and measured degree of saturation of basecourse material.

The in situ saturation levels were calculated from equation 3.1 using an assumed specific gravity value for the soil. Figure 3.3 compares the predicted and measured degree of saturation of basecourse from the 12 investigated sites. The base data is given in the appendix. The graph shows that, on average, the range of the predicted degree of saturation is close to that measured even though the individual points are not highly correlated. The predicted degree of saturation is between 49 and 73, and the measured degree of saturation is between 43 and 70. The algebraic mean error is 1%, the absolute error is 14% and the standard error is 8.3.

Figure 3.3 Predicted and calculated degree of saturation of basecourse from 14 LTPP locations

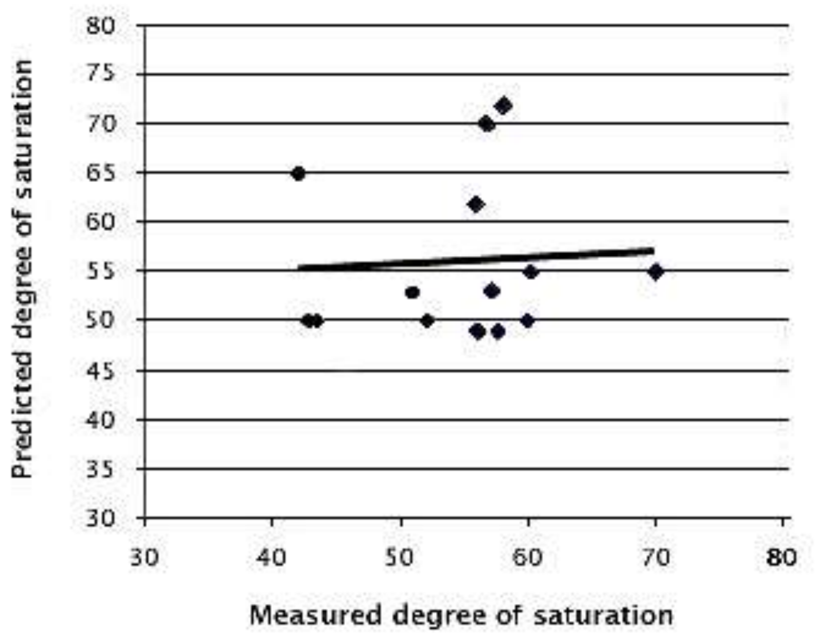


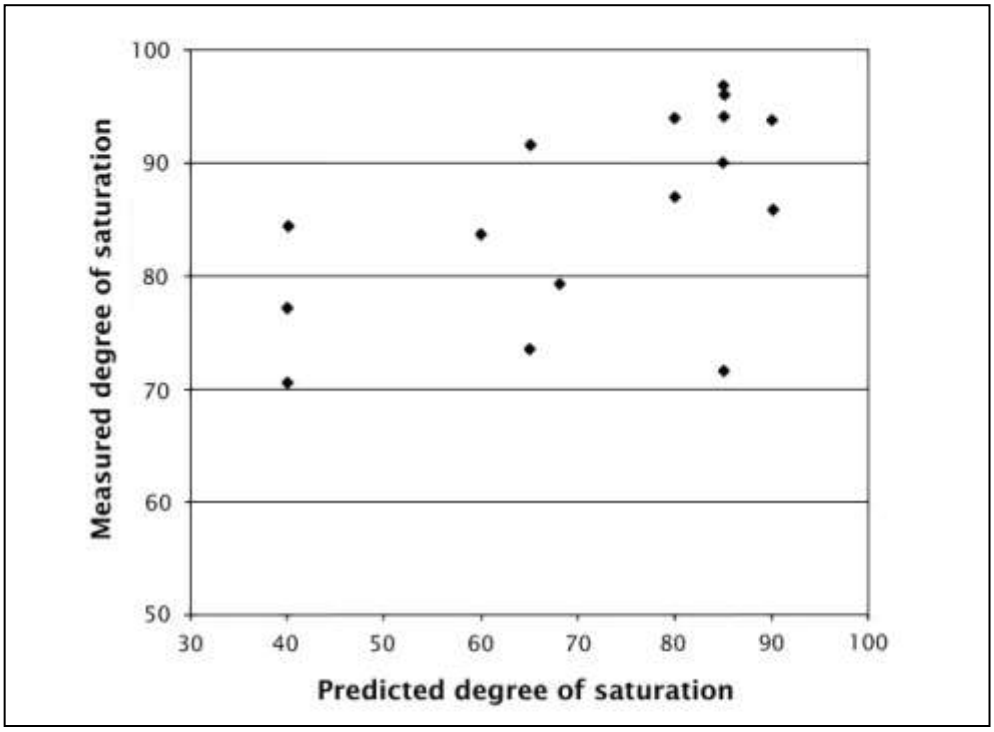
Table 3.3 Statistics of the calculated and predicted degree of saturation for basecourse.

Statistic	Measured degree of saturation	Predicted degree of saturation
97.5 percentile value	62.0	71.5
Average	57.0	56.0
2.5 percentile value	45.5	49.0

Table 3.3 shows the predicted value is slightly higher than the measured value. It should be noted from this table that the 97.5 percentile value of the measured degree of saturation is 62%. The points are scattered within a certain range but the predicted results are not far off from measure values.

Figure 3.4 shows the predicted versus the measured degree of saturation for subgrade soil at the 17 LTPP sites that had sufficient data for an estimation to be made. The full raw data is given in appendix A.

Figure 3.9 Calculated degree of saturation against predicted degree of saturation for subgrade materials



The data appears to be very scattered, but figure 3.4 shows that the measured values fall between 70% and 98%. In contrast, the calculated values show a greater degree of scatter. This scatter is suspected to be associated with the need to estimate the most appropriate material curve to determine the SWCC saturation estimate and with the possibility that the subgrades were influenced by the ground water level. The prediction method is based on the assumption that the ground water level is 6m below ground level for clay, 3m below ground level for sandy clay or silt, and 1m below ground level for sand. The test pit data has no information on the depth to the ground water, and with New Zealand topography, it is possible that in most sites, the ground water will affect the subgrade moisture conditions. The predicted values are systematically offset from measured the values and the relationship could be improved by using the SWCC for a more specific soil type. This would show some reduction in predicted saturation but more specific types of SWCC are not available. We have assumed all the subgrade soils in this research are reasonably close to clay, so we have used the clay SWCC for subgrade soil.

5 Discussion

The field data has tended to confirm previous findings in the literature in that an equilibrium moisture condition appears to exist in pavements. This conclusion is made based on the high degree of agreement between Perera et al's model and the field data.

In this investigation, we were unable to consider the effects of the initial stress or moulding condition on pavement materials, although we were able to consider soil type. In the analysis, it was assumed that initial stress and initial water content had little effect on the degree of saturation for all locations. This appears to have been a valid assumption.

The predicted degree of saturation for basecourse material has an algebraic mean error of -5%, an absolute error of 17% and a standard error of 8.3. The predicted degree of saturation for subgrade material has an algebraic mean error of -7%, an absolute error of 10% and a standard error of 3.3. These values are considered reasonable estimates that can be used as a basis in pavement design.

AUSTROADS (2004) has given typical moisture conditions for laboratory CBR testing. The moisture content of a specimen during compaction should be at the optimum moisture content (OMC) when the median annual rainfall is less than 800mm; otherwise it should be 1–1.15 times the OMC value. The manual also notes that 'the design should ensure, either on the basis of knowledge of moisture conditions likely to occur in the locality, or by means of detailed field investigations, that the laboratory test conditions realistically represent in-service moisture conditions.' The results of this research indicate that basecourse materials testing at optimum conditions will be conservative, as this is typically equivalent to approximately 80% saturation. For subgrades, this research indicates that higher than OMC should be used and that saturation conditions should be the recommended test conditions.

The overall results show that the range of saturation levels for basecourse materials differs from the range for subgrade materials. For basecourse material saturation, ranges fall between 42% and 61%; for subgrade material, they fall between 74% and 99%. This implies that designers should consider the soaked CBR of subgrade for their subgrade design. For repeat load triaxial testing on basecourse material, the specimen should be compacted at OMC, but the test should be done when saturation is at 60%.

These recommendations are only appropriate if the following conditions hold true:

- The water table is below 6m for clay, 3m for sandy clay or silt and 1m for sand. Otherwise, the recommendations given above will not apply.
- If a road shoulder is narrow and unsealed, the moisture content in the outer wheelpath will be slightly higher than that of the inner wheelpath because of the water that has infiltrated through the shoulder.
- If the point of consideration is greater than 1.8m from the seal edge, then the seasonal effect on equilibrium moisture is insignificant.

6 Conclusions and recommendations

The following conclusions can be drawn from this research:

- The literature review shows that pavements typically settle to an equilibrium moisture content that is a function of both pavement materials and environmental conditions.
- It has been demonstrated that Perera **et al**'s methodology (2004) for estimating the moisture conditions of basecourse materials is appropriate for New Zealand conditions.
- For granular basecourse, the equilibrium moisture condition is typically in the range of 50–60% saturation.
- For subgrade soils, the equilibrium moisture condition is typically greater than 85% saturation. This is higher than that predicted and may be associated with the the depth of the ground water being closer than assumed in the analysis.
- These values are typical throughout New Zealand's climatic range.

It is recommended that laboratory characterisation of the long-term performance of pavement materials should be performed at 60% saturation for granular bases and at saturated conditions for subgrades.

7 References

Arnold, G, S Werkemeister and D Alabaster (2008) Performance tests for road aggregates and alternative materials. *Land Transport New Zealand research report 335.* Wellington: Land Transport New Zealand. 102 pp.

Ball, GRA, TC Logan and JE Patrick (1999) Flushing processes in chip-seals: effects of water. *Transfund New Zealand research report 156.* Wellington: Transfund New Zealand.

Coleman, JD (1965) Geology, climate and vegetation as factors affecting soil moisture. Pp93–99 in *Moisture equilibrium and moisture changes in soils beneath covered areas, a symposium in print.* Sydney: Butterworth.

Cumberledge, G, LG Hoffman, CA Bhajandas and JR Cominsky (1974) Moisture variation in highway subgrades and the associated change in surface deflections. *Transportation Research Record 497*: 40–49.

Dennison, D (2002) Te Matai deflection and moisture monitoring. *Opus International Consultants geotechnical report no. 2221.* Hamilton: Opus International Consultants.

Drumm, CE and R Meier (2003) *LTPP data analysis: daily and seasonal variations in insitu material properties.* Washington DC: Transport Research Board.

Fredlund, DG (1995) Prediction of unsaturated soil functions using the soil–water characteristic curve. *Proceedings of the Bength B. Broms Symposium on Geotechnical Engineering, Singapore 13–15 December 1995.*

Fredlund, MD, DG Fredlund and GW Wilson (1997) Prediction of the soil–water characteristic curve from grain-size distribution and volume-mass properties. *3rd Brazilian Symposium on Unsaturated Soils, April 1997, Rio de Janeiro, Brazil.*

Fredlund, DG and A Xing (1994) Equations for the soil–water characteristic curve. *Canadian Geotechnical Journal,* Vol. 31, No. 4: 521–532.

Garnier, BJ (1950) *Thornthwaite's new system of climate classification in its application to New Zealand.* Dunedin: Department of Geography, University of Otago, New Zealand.

Herrington, PR, I Kvatch and K O'Halloran (2006) Assessing the environmental effects of new and recycled materials in road construction: proposed guidelines. *Land Transport New Zealand research report 306.* Wellington: Land Transport New Zealand. 70pp.

Hossain, M, SJ Kotdwala, B Long and AJ Gisi (1997) Subgrade moisture monitoring using time domain reflectometry. Paper No. 970370. *76th annual Transportation Research Board meeting, January 1997, Washington DC.*

Jones, A (2004) Unbound granular pavements. *Road Systems and Engineering Technology Forum, Brisbane, August 2004.*

Lay, GM (1990) *Handbook of road technology, volume 1: planning and pavement.* New York: Gordon and Breach Science Publishers.

Lee, HC and WK Wray (1995) Techniques to evaluate soil suction – a vital unsaturated soil water variable. *Proceedings 1st International Conference on Unsaturated Soils, Balkema, Rotterdam, The Netherlands*: 615–622.

McKeen, RG and LD Johnson (1990) Climate-controlled soil design parameters for mat foundations. *Journal of Geotechnical Engineering, ASCE, Vol. 116, No. 7*: 1073–1094.

NIWA (2004) Mean annual rainfall and temperature, 1971–2000. *NIWA Poster Nos. 4 & 5.* Auckland: NIWA.

National Cooperative Highway Research Program (NCHRP) (2008) Calibration and validation of the enhanced integrated climatic model for pavement design. *Transport Research Board report 602.* Washington, DC: NCHRP.

NCHRP (2000) *Guide for mechanistic-empirical design of new and rehabilitated pavement structures.* Washington DC: NCHRP.

Nichol, C, L Smith and R Beckie (2003) Long-term measurement of matrix suction using thermal conductivity sensors. *Canadian Geotechnical Journal, NRC Canada*: Vol 40: 587–597.

Park, SW RL Lytton and JW Button (1999) Forensic investigation of pavement distortions using soil suction. *Journal of Transportation Engineering. ASCE*, Vol 125, No. 1: 60–66.

Patrick, JE, DJ Alabaster and DMSC Dongol (1998) Pavement density. *Transfund New Zealand research report 100.* Wellington: Transfund New Zealand.

Patrick, JE and MW McLarin (1998) Moisture in pavements: directions for New Zealand research. *Transfund New Zealand research report 111.* Wellington: Transfund New Zealand. 26pp.

Peploe, R (2002) Subgrade moisture conditions for pavement design of New Zealand roads. *Transfund New Zealand research report 238.* Wellington: Transfund New Zealand.

Perera, YY, CE Zapata, WN Houston and SL Houston (2004) Moisture equilibrium beneath highway pavements. *Transportation Research Board 83rd Annual Meeting, January 2004, Washington DC.*

Reid, JM, GI Crabb, J Temporal and M Clark (2006) *A study of water movement in road pavements.* Crowthorne, UK: Transport Research Foundation, Transport Research Laboratory.

Roberson, R (2001) *Material moisture characterization. Draft report.* Saint Paul MN: Minnesota Department of Transportation.

Roberson, R and J Siekmeier J (2002) Determining material moisture characteristics for pavement drainage and mechanistic empirical design. Research bulletin. Accessed 6 September 2010. *http://www.mrr.dot.state.mn.us/research/MnROAD_Project/ResearchBulletins/Determining_Material_Moisture_Characteristics.pdf*.

Russam, K and JD Coleman (1961) The effect of climatic factors on subgrade moisture conditions. *Geotechnique, London Vol. 11*: No.1: 22–28.

Thornthwaite, CW (1948) An approach toward a rational classification of climate. *Geographical Review, Vol. 38* No. 1: 55–94.

Transit New Zealand (2006) M/4 specification for basecourse aggregate. Accessed 2 September 2010. *http://www.nzta.govt.nz/resources/basecourse-aggregate/docs/basecourse-aggregate.pdf.*

Valdez, FS (1991) Subgrade resilient modulus evaluation. *FHWA-GA-91-8801.* Washington, DC: Federal Highway Administration.

Vanapalli, SK, DE Pufahl and DG Fredlund (1999) The influence of soil structure and stress history on the soil-water characteristic of a compacted till. *Geotechnique, 49(2)*:143–159.

Wallace, K (1991) *THEWET 1990 (pavements version) – a program of micro-computer simulation of the wetting-up and drainage of pavements. Software users' manual*. Brisbane: Queensland University of Technology.

Appendix A Basecourse and subgrade data

A1 Basecourse data

Table A1 Data used for analysing basecourse saturation*

Benchmark site ID	P200	Moisture % (w)	Dry unit weight (t/m^3)	Measured degree of saturation	TMI	Matrix suction (kPa)	Estimated degree of saturation
31	13	4.2	2.22	52	70	20	50
32	8	3.5	2.32	58	30	10	49
34	12	4.7	2.2	56	70	20	62
35	14	2.6	2.32	43	70	20	50
36	12	5.3	2.18	60	70	20	50
39	10	3	2.38	60	70	15	55
41	7	3.9	2.28	57	10	9	53
B42-P2	7	4.5	2.18	51	70	9	53
43	11	2.8	2.3	43	10	15	50
B44	4	2.7	2.4	58	10	6	65
B46-P2	3	2.7	2.3	42	90	6	65
48	8	3.4	2.32	56	10	10	49
51	5	5.5	2.14	57	30	7	70
B52	10	8	2.06	70	10	15	55

* The specific gravity of the material is assumed to be 2.7.

A2 Subgrade

Table A2 Subgrade site data and calculations*

Site	Soil type	Estimated P75	Plasticity index	WPI	Moisture % (w)	Dry unit weight (t/m^3)	Measured degree of saturation	TMI	Matrix suction (kPa)	Predicted degree of saturation
1	Silty clay	100	38	38	41	1.24	94	100	40	80
3	Silty clay	100	23	23	35.4	1.34	94	100	30	85
14	Silty clay	100	17	17	31	1.4	90	100	28	85
16	Silty sand	50	28	14	48	1.06	84	80	20	60
18	Silty clay	100	26	26	84.6	0.8	96	80	32	85
20	Silty clay	100	19	19	43.5	1.22	97	100	28	85
21	Silty sand	75	23	17	284.8	1.56	92	100	28	65
22	Sandy silt	50	8	4	24.3	1.46	77	100	14	40
23	Sandy silt	50	5	3	14.9	1.72	71	100	14	40
24	Silt	100	17	17	17.3	1.7	79	80	31	68
26	Silty sand	75	9	7	14.1	1.78	74	100	19	65
29	Clayey silt	100	55	55	127	0.58	94	100	50	90
32	Silty clay	100	13	13	12	1.86	72	80	25	85
35	Sandy gravel	10	28	3	33.5	1.38	95	80	42	10
43	Silt	100	12	12	18.4	1.7	84	20	25	40
48	Silty clay	100	17	17	24.3	1.54	87	20	30	80
49	Clayey silt	100	5	5	9.1	2.1	86	40	15	90
51	Sandy silty	50	7	4	14.7	1.9	94	60	15	20

*The specific gravity is assumed to be 2.7 for all subgrade material.

Appendix B Abbreviations and glossary

AADT:	Annual average daily traffic
Air entry value:	The suction needed for air to initially enter a fully saturated soil
Boundary effect zone:	The zone where soil is fully saturated
CBR:	California bearing ratio
FHWA:	Federal Highway Administration
Hysteretic:	Lag in suction response in wetting soil compare to drying process
LTPP:	Long-term pavement performance
Matrix suction:	The difference in pressure across the air–water boundary
NCHRP:	National Cooperative Highway Research Program
NIWA:	National Institute of Water and Atmospheric Research
OMC:	Optimum moisture content
Osmotic suction:	Suction induced by the concentration of dissolved salts in the soil water
P75:	The grade of soil particles passing through a 75μm sieve
Residual zone:	The zone of unsaturation, where drying and wetting curves are almost identical.
Saturation level:	The amount of water in the soil when all the space between soil particles is full of water. At saturation level, no air space is present between the soil particles.
SH:	State Highway
SWCC:	Soil water characteristic curve
TMI:	Thornwaite Moisture Index
Total suction:	A combination of matrix suction and osmotic suction
Transition zone:	The zone where the level of saturation drops rapidly
Water content:	The amount of water contained within a volume of soil
WPI:	Weighted plasticity index