# Methods of Compaction of Basecourse Aggregate for Repeated Load Triaxial Testing

Pritesh Karan1, Dr Douglas J Wilson2, Dr Tam J Larkin3

1Presenter - PhD Candidate, Faculty of Engineering, University of Auckland, New Zealand

Email: [pkar020@aucklanduni.ac.nz](mailto:pkar020@aucklanduni.ac.nz), Member of – CETANZ, IPENZ TG

2Senior Lecturer (Transportation), Faculty of Engineering, University of Auckland, New Zealand

Email: [dj.wilson@auckland.ac.nz](mailto:dj.wilson@auckland.ac.nz),

3Senior Lecturer (Geomechanics), Faculty of Engineering, University of Auckland, New Zealand

Email: [t.larkin@auckland.ac.nz](mailto:t.larkin@auckland.ac.nz),

# Abstract

This paper presents the results of research undertaken at the University of Auckland to evaluate laboratory methods of compacting basecourse material for “large scale” (250mm diameter by 625mm height) Repeated Load Triaxial (RLT) tests. The methods of compaction evaluated are kneading and vibratory compaction. The majority of laboratories globally use some form of vibratory compaction for the purpose of compacting RLT specimens. This is primarily due to the high energy output of vibratory hammers, making vibratory compaction more efficient at compacting aggregate specimens to higher densities. For this reason most contractors use vibratory rollers for in-field aggregate layer compaction. However, high energy compaction both in the field and especially in laboratory specimens, where specimens are bounded by rigid steel moulds has been shown to cause disintegration of aggregate particles. This paper evaluates if similar Dry Densities (DD) can be achieved for M/4 and permeable basecourse from kneading compaction without crushing aggregate particles. Changes in particle size distributions (PSD’s) can greatly alter the structural and drainage performance of any granular layer. This paper presents the results of evaluating which mode of compaction has the greatest effects on the initial PSD.

# Introduction

Performance characteristics of road pavements are obtained through laboratory based materials testing in conjunction with field testing. The Repeated Load Triaxial (RLT) test is used to evaluate pavement fatigue performance in the laboratory. Although the RLT test itself has been shown to be very effective in predicting pavement performance, the methods of compaction used in laboratories globally to prepare specimens lack appropriate test standard repeatability and reliability and therefore correlation with field compaction. This can lead to serious consequences regarding specifications for field basecourse compaction and performance and can mislead engineers who rely principally on the results of laboratory tests for making decisions concerning the field compaction process.

A poorly compacted layer is characterised by Chilukwa (2013) as having lower density, higher porosity and lower cyclic stiffness than a properly compacted layer. Poor compaction can result in rutting and eventually lead to water ingress in the pavement layer which results in early failure of the pavement. However, the porosity and shear strength of the material is more difficult to obtain. The porosity of a layer is subject to the degree of compaction, the size and shape of particles and DD of aggregates which make up the layer. The PSD of the layer determines the distribution of sizes of aggregates within the layer. Therefore the key performance indicators for this research will be the PSD and DD of specimens.

## Research Objectives

The objectives of this research are to determine the PSD and DD of M/4 and permeable basecourse after kneading and vibratory compaction and in doing so determine which mode of compaction is more suitable for RLT specimen compaction.

# Repeat Load Triaxial (RLT) Testing

The basis of the RLT test is to simulate traffic movement effects on pavement basecourse and this allows pavement fatigue behaviour under cyclic loads to be monitored. It is believed that RLT when used in conjunction with source and production testing can give greater confidence in predicting basecourse performance and ultimately allows an estimate of pavement life under various loading conditions ([Lowe, 2007](#_ENREF_9)).

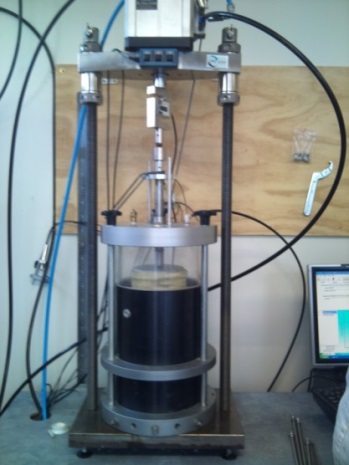
 

Figure 1(a): Conventional RLT apparatus used in New Zealand. Figure 1(b): “Large scale” RLT.

The RLT test uses Linear Variable Displacement Transducers (LVDT’s) to measure vertical, horizontal and occasionally radial deformation. Some small scale RLT tests are performed using a cell of approximately 150mm diameter. However, this restricts the maximum aggregate size to approximately 20mm. The triaxial cell used for the research described in this paper is 250mm in diameter and 625mm high; this allows the inclusion of 37.5 mm particles which is the maximum allowable particle size for M/4 basecourse aggregate in New Zealand. The inclusion of 37.5 mm down aggregate in laboratory tests allows for closer simulation of field basecourse behaviour. The small scale RLT apparatus (150mm Ф x 300mm high) displayed in Figure 1(a) is preferred globally over the large scale RLT in Figure 1(b) due to its ease of use, reduced testing duration and lower operation and consumable costs. However, the small scale RLT cell requires scalping of aggregates with an average least dimension (ALD) greater than 20mm ([Molenaar, 2010](#_ENREF_10), [Shackel, 2006](#_ENREF_17)). Aggregates with an ALD greater than 20mm are seldom tested in the small scale RLT. The lack of size restriction on ALD leads to unreliable and inconsistent results as a consequence of edge effects ([Li, 2013](#_ENREF_8)). The RLT test can effectively measure vertical and lateral deformation and associated stresses, volume change during drained tests and pore pressure during saturated undrained tests. The RLT test allows the deduction of the resilient modulus, Poisson’s ratio and cumulative permanent strain arising from creep deformation, all of which are significant in assessing pavement performance.

# Methods of Laboratory Compaction

Compaction is a key process in the construction of road pavement layers. It is significant in ensuring the structural integrity of the pavement layer as well as having an influence on the engineering properties and performance. Therefore, it is vitally important that field compaction is done correctly. Specifications for basecourse compaction in the field are often a result of aggregate compaction and testing of materials in the laboratory ([NZTA, 2005](#_ENREF_12)). Higher densities produced in laboratories than is possible in the field with less lateral and base restraints, will result in over compaction of aggregates in the field. As a consequence aggregate degradation can occur in the field which alters basecourse performance from that assessed in the laboratory. Variables such as subgrade type, undulating terrain and a lesser degree of lateral confinement in the field make it difficult to simulate field compaction in the laboratory using current methodologies and practices. Some laboratory compaction methods have been developed to simulate the field compaction process in the laboratory.

There are four primary modes of compaction:

* Impact Compaction,
* Static Compaction,
* Kneading Compaction, and
* Vibratory Compaction

For granular soils Impact and Static compaction have been deemed unsuitable due to the nature of cohesionless soil. When a standard load drops on to a sample, the impact compaction has a tendency to dislodge the particles resulting in poor dry densities ([Shahin, 2011](#_ENREF_18), [Chilukwa, 2013](#_ENREF_5), [Kelfkens, 2008](#_ENREF_7), [Karan, 2012](#_ENREF_6)). Static compaction does not provide sufficient particle rearrangement to achieve the required densities. As a result, static and impact compaction will not be further evaluated in this study.

## Kneading Compaction

Kneading compactionrearranges particles into a more dense mass by squeezing particles together. It has previously been used to compact soils heavy in clay content. Its action and particle re-orientation in the laboratory tends to simulate the Sheepsfoot (pad-foot) roller in field. The Sheepsfoot roller can be used for granular material with the presence of some fines. There has been much debate over which laboratory method is ideal for compacting granular material. Toan (1975) stated that the action of flat rollers in the field is a kneading action; therefore it is ideal to use kneading compaction in laboratory testing, since it closely resembles field compaction. The kneading compactor also produces good specimen repeatability and reproducibility which is important when compacting RLT specimens ([Toan, 1975](#_ENREF_20)). On the contrary, Kelfkens (2008) and Chilukwa (2013) believe that static compaction such as kneading compaction is more suitable for cohesive clays than granular material due to the increased particle sizes of roading aggregates.

## Vibratory Hammer Compaction

Vibratory hammer compaction remains one of the most popular methods of compaction for granular soils due to its ease of use, speed and effectiveness. Since field compaction equipment uses vibration to compact aggregates effectively, some researchers believe that vibratory compaction yields a better correlation between field and laboratory results ([Patrick, 2010](#_ENREF_14), [Arnold, 2004](#_ENREF_1), [Chamblin, 1962](#_ENREF_4)). Laboratory compaction by vibratory means can be achieved by using a vibrating hammer or a vibrating table. Chilukwa (2013) and Chamblin (1962) identified that the vibratory hammer is capable of producing densities of specimens comparable to those of the vibratory table. For the purposes of this study, vibratory hammer compaction is considered.

Repeatability and reproducibility become important variables when carrying out RLT tests as it can greatly influence test results ([Toan, 1975](#_ENREF_20)). Eliminating as much variability as possible is highly recommended when comparing results between specimens.

Repeatability tests done by Chilukwa (2013) showed that, the vibratory hammer compaction method was effective in compacting graded crushed stone material and also that vibratory hammer compaction does not result in any significant material disintegration. However, Shahin (2011) clearly states that the New Zealand vibrating hammer compaction test procedure has been proven to provide inconsistent results. Shahin (2011) found up to 20% variation in vibratory compaction maximum dry densities (MDD’s). The variations may be caused by operator error, natural properties, hammer energy, water content, mould size, oversized particles, aggregate degradation and aggregate segregation.

Kneading compaction eliminates some of the variability that arises from operator/technicians, aggregate segregation and the compactor itself. Vibratory hammers with different frequencies produce different results whereas kneading compaction has greater repeatability for a constant foot pressure.

Shahin (2011) and Toan (1975) state that the size of the mould should be 6-8 times greater than the maximum aggregate size. However the New Zealand vibratory hammer standards (NZS 4402: Test 4.1.3.) specify a 150mm diameter mould which is only four times the maximum aggregate size of 37.5 mm ([NZS, 1986](#_ENREF_11)). This inconsistency produces additional variation in compaction results ([Shahin, 2011](#_ENREF_18)). The source of variation is believed to be interlocking of oversized particles in the small 150 mm mould. To avoid such variations, the USA and UK vibratory hammer specifications require scalping of aggregates retained on the 19mm sieve if a 150 mm diameter mould is to be used for compaction ([BS, 1990](#_ENREF_3), [ASTM, 2008](#_ENREF_2)). Similar compaction principles should be applied to RLT compaction specifications in New Zealand where maximum aggregate size of 37.5 mm is used in a 150 mm diameter specimen.

## Energy

Hammer input power rating has a significant influence on the variation of the vibrating hammer compaction test results. This is due to the fact that hammers with high input power ratings apply a greater compactive effort on the specimen during compaction than a hammer with a relatively lower input power rating ([Shahin, 2011](#_ENREF_18)). However, higher compactive efforts also result in greater changes in PSD.

According to NZS 4402 Test 4.1.3 the maximum energy output that can be achieved in laboratory vibratory compaction is 92.7 kJ based on a compaction duration of 180 seconds per layer and energy of 1200W ([Kelfkens, 2008](#_ENREF_7)). The maximum compaction energy for New Zealand is more than twice that of UK or US (around 42kJ). This difference in compaction energy is largely the result of the New Zealand standard allowing an extended compaction duration of 180 seconds rather than 60 seconds in the UK or US standards for hammers with similar output power ratings.

The energy output of the newly developed vibratory hammer and frame at the University of Auckland can be calculated using methods described by Kelfkens (2008) to be 256 kJ using a compaction time of 180 seconds. In order to meet NZS 4402 Test 4.1.3 maximum energy criterion the compaction time per layer is required to be reduced to 85 seconds per layer for 6 layers of compaction (or 65 seconds per layer for 8 layers of compaction). This would equate to the same output energy of 92.5 kJ. However, in this study, majority of compaction was achieved after 60 seconds when 6 layers of compaction were utilised.

## Particle Size Distribution

The stability of an in situ unbound granular layer is derived mainly from particle interlock and surface friction particularly for permeable basecourse layers which have considerably smaller amounts of fines than a typical basecourse layer. The PSD is therefore an important characteristic for strength and stiffness determination. The maximum particle size of an unbound layer is constrained by the layer thickness because roller compaction is only effective up to a depth of approximately 250 mm and layer workability gets difficult if stones of about 30% of layer thickness are present in the layer ([Thom, 2008](#_ENREF_19)). Therefore, particle size and gradation are significant factors to be considered when constructing granular pavement layers. Salt (2011) recommends the PSD of basecourse material tested in RLT tests and compacted in the field needs to be closely controlled in order to maintain consistency and avoid unpredictable performance, even though this is not common practice in New Zealand. A change in PSD has an influence in the degree of saturation and permeability of the basecourse which has a significant influence on its performance ([Salt, 2011](#_ENREF_15)). Salt (2011) goes as far as to say that contractors must do pre and post-compaction PSD of basecourse layers in field in order to control changes in PSD that can hinder pavement performance.

The density and hence stability of an aggregate material is affected by the amount of fines contained in it. Greater amounts of fines can lead to layer instability when traffic loading is applied. In the case of vibratory compaction, high energy compaction can lead to aggregate crushing and the disintegration of larger aggregates, therefore producing greater proportions of fines than expected. This in turn produces unpredictable results in laboratory based tests and accelerated pavement deterioration in the field, even though unrealistically high MDD’s can be achieved in the laboratory due to the increased lateral constraint of the mould. Excessive breakdown to smaller size particles can also lead to an increase in the void content which in turn lowers the MDD that can be achieved and increases the moisture requirement for optimal compaction and sensitivity to water depending upon aggregate mineralogy.

# Compaction Methodology

The aggregate used for this study was Greywacke from a hard rock quarry in the South Auckland region with a solid density of 2.72 t/m3. After the aggregates were confirmed to be of M/4 standard using tests specified in TNZ (2006) they were mixed thoroughly with water to raise the moisture content of the aggregate to the Optimum Water Content (OWC). The OWC of the aggregates used for this study was identified to be between 4-5% ([Karan, 2012](#_ENREF_6)). The OWC obtained for the material used in this research agrees with OWC of similar material in the literature ([Zlender, 2007](#_ENREF_21), [Lowe, 2007](#_ENREF_9), [Shahin, 2011](#_ENREF_18)). The OWC of the basecourse aggregate could lie anywhere between 4-5% without much variation in MDD. The drier end of the OWC has been used in this study. The OWC of the permeable aggregate was identified to be 1%. The low OWC of the permeable aggregates can be attributed to high voids content of the aggregate layer which results in any additional water flowing to the bottom of the specimen.

Once the aggregate was acquired from its source in sealed boxes it was split using a riffle box. After quartering the specimens, the water contents (WC) of both the M/4 and permeable aggregates were raised to optimum and left to cure in sealed containers. They were then compacted using kneading or vibratory hammer compaction.

For vibratory compaction the aggregates can be compacted using two different methods. “Method 1” (suitable for kneading and vibratory compaction) is the more conventional method used globally. It has been previously used by Arnold (2004), Chilikwa (2013) and Kelfkens (2008).

Method 1 involves compacting the aggregates in layers using either kneading or vibratory compaction. The compacted height of each layer is approximately 120mm (3 times maximum aggregate size of 37.5mm). The top 20mm of each layer was scarified using a steel spatula to reduce any layering effects, leaving an effective compacted layer height of approximately 100mm. This effectively provided 6 layers of compaction. This method of compaction is based around achieving a target density for each layer, where the density of each layer contributes to the overall density of the specimen. This method is commonly used in practice and seldom results in exceedance of maximum energy requirements of NZS (1986) which is the standard for vibratory hammer compaction in laboratories in New Zealand.

“Method 2” (only suitable for vibratory compaction) utilises the maximum allowable energy per layer specified by NZS 4402 Test 4.1.3 NZS (1986) which has been previously determined. It involves compacting the specimen in 6 layers but instead of aiming for a target density as in Method 1 using this method involves compacting each layer for 60 seconds with 6 layers being utilised.

In this study, due to time restrictions only Method 2 is used for vibratory compaction of materials and Method 1 is used for kneading compaction without targeting any particular density for both the M/4 and permeable basecourse. For kneading compaction each layer is compacted at a foot pressure of 1000 kPa for 25 tamps per layer with a dwell time of 2 seconds per tamp.

Once the specimens were compacted they were removed from the mould in “layers” and dried separately in ovens overnight. After 24 hours of drying at 103°C, post compaction PSD tests were undertaken using sieves ranging from 37.5mm to 0.075mm. The M/4 PSD envelope adopted from New Zealand Transport Agency and the permeable envelope which was adopted and reconstructed from work done by Professor Brian Shackel were used as benchmarks for this study ([NZTA, 2006](#_ENREF_13), [Shackel, 2001](#_ENREF_16)).

# Results and Discussion

PSD and DD tests were undertaken on M/4 and permeable aggregates compacted at OWC using kneading and vibratory compaction. Due to the larger specimen size and therefore longer specimen preparation time, limited tests were possible within the timeframe of this study. There was one specimen prepared for kneading compaction and one specimen prepared for vibratory compaction.

## M/4 Aggregates

Figure 2 shows the results of PSD testing on M/4 aggregates compacted at 4% water content (WC) using kneading compaction. Despite deviations from the M/4 envelopes across all aggregate sizes the PSD of all layers of compaction are within 10% of the ‘pre compaction’ PSD and within the envelopes. These set of PSD test results agree with work undertaken by Toan (1975) where he found minimal changes in post compaction PSD’s for basecourse compacted at a foot pressure of 1000 kPa using the kneading compactor.

Figure 2: Compaction of M/4 aggregates at 4% WC using Kneading Compaction.

A similar trend in post compaction PSD of M/4 material was found between both vibratory and kneading compaction. Figure 3 shows that there is little change in PSD as a result of vibratory compaction. Most of the layers tested are within the M/4 basecourse envelopes from NZTA. This is contrary to the research done by Shahin (2011) and comparable to work done by Chilukwa (2013). A reason for the inconsistencies in results may be due to reproducibility issues identified by Shahin (2011) and compacting large aggregates in a small mould using different vibratory hammers. The larger diameter mould was predicted to reduce the effects of aggregate degradation and this is somewhat evident from Figure 3. In comparison, if a similar material was compacted in the field using similar energy levels (which is often not the case), the effects of aggregate degradation can be predicted to be further reduced as there is even lesser rigid confinement of the aggregates than that present when using the large mould. The rigid walls of the compaction mould as well as testing larger aggregates than specified in the small mould can contribute to the degradation of aggregates.

Figure 3: Compaction of M/4 aggregates at 4% WC using vibratory compaction.

There is very little deviation from their pre compaction states for both kneading and vibratory compaction when the amount of vibratory energy is carefully controlled. This leads to the conclusion that there is no significant aggregate degradation occurring from vibratory or kneading compaction of M/4 aggregate when it is compacted using a 250mm diameter by 625mm high mould. This may not be the case in a standard CBR mould (150mm diameter by 125mm specimen height) which is frequently used to test the MDD of this material. The results may also vary for the small scale RLT where a 150mm diameter by 300mm high mould is used. The effects of these moulds on aggregate degradation should be further evaluated.

## Permeable Aggregates

The results of post kneading compaction of the permeable aggregates that were compacted at 1% WC are illustrated in Figure 4. The trend in Figure 4 is different from the PSD trends displayed in Figure 2. There is a reduction in fines (materials passing the 2.36mm sieve) for layers 2 to 5 and there is a significant increase in fines content for layer 1. This can be a result of aggregate segregation. This is possible for permeable aggregates and not the M/4 aggregates due to the higher voids content of permeable aggregates. There are a lot more void spaces in permeable mixes giving the finer aggregates room to travel to the bottom of the specimen. The effects of transportation of fines to the bottom can be analysed by undertaking permeability and RLT tests to check if this affects the specimens’ permeability and structural performance (this will be considered in future research). The effects of aggregate segregation in the field also need to be better understood in order to correlate with basecourse performance in the laboratory.

Figure 4: Compaction of permeable aggregates at 1% WC using kneading compaction.

Only four layers were compacted for the permeable aggregate using vibratory compaction due to the failure of the vibratory compactor after compaction of the fourth layer. Repair of the vibratory compactor was not possible within the timeframe of this research. Despite this, Figure 5 shows a similar trend to Figure 4, where the permeable specimen was compacted using the kneading compactor. In Figure 5 there is an increase in fines content for layer 1 whilst a reduction in fines content for layers 2 to 4, similar to Figure 4. Therefore the effects of not compacting layers 5 and 6 can be considered to be minimal. This may be due to a reduction in segregation for layers 5 and 6 as a result of the increased height (625 mm) of the specimen. The PSD results displayed in Figure 5 coincide with Shahin’s (2011) conclusion that vibratory hammer compaction may lead to segregation of aggregates. This is also the case for kneading compaction.

The increase in fines content of layer 1 shown in Figures 4 and 5 may be due to aggregate segregation rather then aggregate crushing at the bottom of the specimen because if there was aggregate crushing taking place then there would also be a gradual increase in fines content from layer 6 (or layer 4 for Figure 5) to layer 2.

Figure 5: Compaction of Permeable aggregates at 1% WC using Vibratory Compaction.

Results show that there is no permeable aggregate degradation as a result of either vibratory or kneading compaction but rather fines transportation. The PSD results of Figures 2, 3, 4 and 5 suggest that either mode of compaction is suitable for compaction of M/4 or permeable aggregates. However, the dry densities achieved through both modes of compaction displayed in Table 1, suggest otherwise.

Table 1: Dry densities achieved from Kneading and Vibratory compaction.

|  |  |  |
| --- | --- | --- |
| Dry Density (kg/m³) | | |
| Compaction Type | M/4 Basecourse | Permeable Basecourse |
| Kneading | 2043 | 1853 |
| Vibratory | 2070 | 1961 |

Table 1 shows that for M/4 aggregates, both the vibratory and kneading modes of compaction achieved reasonably similar densities. However vibratory hammer compaction achieved a significantly greater density than kneading compaction for the permeable basecourse. Based purely on laboratory compaction densities, this leads to the conclusion that vibratory compaction is more suitable for the compaction of both M/4 and Permeable aggregates in the laboratory if a larger 250mm diameter by 625mm high mould is used. Plateau testing identifies the MDD achieved in the field; procedures of how to undertake them are outlined in TNZ (2005). Plateau testing should be undertaken to determine the densities that can be achieved for both these aggregate grading’s before a laboratory method of compaction is chosen.

# Conclusions

On the basis of test results at hand, the following conclusions can be drawn:

* The small RLT mould can lead to the degradation of aggregates if appropriate maximum aggregate sizes to specimen size ratios are not adhered to.
* The larger RLT mould reduces aggregate degradation when compared to PSD test results of vibratory compaction in the smaller mould.
* Maximum aggregate size to specimen diameter ratio of at least 1:6 which has been determined through a review of the literature must be adhered to when compacting basecourse aggregate in the laboratory.
* Failure to do so will result in non-representative densities and aggregate degradation in the laboratory that are unrealistic in terms of setting a specification target for field density.
* Field compaction to laboratory compaction calibration should be considered to take account of the differences between laboratory test and field conditions.

# Future Research

In this study, due to time limitations limited tests were possible. In future, at least three tests for each aggregate type should be undertaken to increase the statistical validity of the results obtained for a particular mode of compaction and demonstrate repeatability.

Vibratory testing should be done using both Methods 1 and 2 described in this research to evaluate the effects of aggregate degradation that arise from the method of compaction.

Post compaction PSD tests should be done using the CBR and small scale RLT mould to identify the effects of testing the full New Zealand basecourse spectrum in these moulds and in doing so identify aggregate degradation effects as a result of mould size.

Field density testing should be done on both the M/4 and permeable aggregates to validate the densities of the materials achieved in the laboratory.

# Acknowledgements

The authors would like to thank Wentao Li and the University of Auckland, Faculty of Engineering laboratory technicians and staff for their assistance during testing. The authors would also like to thank Jayden Ellis and Stevensons aggregates for technical advice and assistance with resources during the course of this study.

# References

ARNOLD, G. 2004. *Rutting of Granular Pavements.* Doctor of Philosophy, University of Nottingham.

ASTM 2008. D7382-07. *Standard Test Methods for Determination of Maximum Dry Unit Weight and Water Content Range for Effective Compaction of Granular Soils Using Vibrating Hammer.* ASTM International.

BS 1990. 1377: Part 4. *British Standard methods of test for Soils of Civil Engineering Purposes. Part 4. Compaction - related tests: Method for Determination of Dry Density/Moisture Content using Vibrating Hammer.* British Standards Institution.

CHAMBLIN, B. B. 1962. Compaction and Correlation Between Compaction and Classification Data. *In:* BURGGRAF, F., ORLAND, H.P (ed.) *Compaction characteristics of some base and subbase materials.* Washington: National Acadamy of Sciences - National Research Council.

CHILUKWA, N. N. 2013. *Vibratory Hammer Compaction of Granular Materials.* Master of Engineering, Stellenbosch University.

KARAN, P. 2012. California Bearing Ratio and Repeated Load Triaxial testing. *Summer Research Project.* Auckland: University of Auckland.

KELFKENS, R. W. C. 2008. *Vibratory Hammer Compaction of Bitumen Stabilized Materials.* Master of Science, Stellenbosch Univeristy.

LI, W., WILSON, DJ., LARKIN, TJ. 2013. The Application of Large Scale RLT Testing for the Improvement of Unbound Granular Pavements. *NZIHT.* Auckland.

LOWE, J. Evaluation of the Repeated Load Triaxial Test and its potential for Classifying Basecourse Aggregates. The IOQ and AQA NZ Annual Combined Conference, 2007.

MOLENAAR, A., ARAYA, A., HOUBEN, L 2010. Characterization of Unbound Granular Materials Using Repeated Load CBR and Triaxial Testing. *Geotechnical Special Publication*.

NZS 1986. New Zealand Vibrating Hammer Compaction Test. *NZS 4402 Test 4.1.3.* New Zealand: NZTA.

NZTA 2005. Specification for Construction of Unbond Granular Pavement Layers. *TNZ B/02.* New Zealand: NZTA.

NZTA 2006. TNZ M/4: 2006. *Specification for Basecourse Aggregate.* New Zealand: NZTA.

PATRICK, J., WERKMEISTER, S 2010. Compaction of thick granular layers. NZTA: NZTA.

SALT, G., STEVENS, D. 2011. Extending pavement life: investigation of premature distress in unbound granular pavements. *NZTA research report 459.* Auckland: NZTA.

SHACKEL, B. 2001. Materials and Construction Specifications for Reconstruction of Smith Street, Manly, between Pine and Alexander Streets using Permeable Paving. School of Civil and Environmental Engineering: University of New South Wales.

SHACKEL, B. Design of Permeable Paving subject to Traffic. 8th International Conference on Concrete Block Paving, 2006 San Francisco, California, USA.

SHAHIN, A. W. 2011. *Investigation of the Variability in the Results of the NZ Vibrating Hammer Compaction Test.* Master of Engineering, University of Auckland.

THOM, N. 2008. *Principles of Pavement Engineering,* University of Nottingham, Thomas Telford Ltd.

TOAN, D. V. 1975. *Effects of basecourse saturation on flexible pavement performance.* Doctor of Philosophy, University of Auckland.

ZLENDER, B. 2007. Prediction of Permanent Deformation of Pavement's Unbounded Layers Based on Cyclic Triaxial Tests. *American Journal of Applied Sciences,* 5**,** 22-28.