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Engineering Characteristics of Construction Waste for Western Australian Road and Highway Materials

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Doctor of Philosophy
of
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DECLARATION

This thesis contains no material, which has been accepted for the award of any other degree or diploma in any university.

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

The following publications have resulted from the work carried out for this degree.

Refereed journal and conference papers:

1. Narantuya, B., Komsun, S., Jitsangiam, P., Nikraz, H., (2010). "Sustainable use of Construction and Demolition (C&D) waste as a road base material", *ICSBE UII 2010 International Conference on Sustainable Built Environment, Kandy, Sri Lanka. 12-14 December 2010.*

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Date…….

ABSTRACT

This study examines the use of concrete waste by-products as a new source of road construction material in Western Australia (WA). The amount of construction waste in Western Australia increases annually, whilst natural rock aggregate is in shortage.

This research focuses on whether recycled concrete, derived from various sources such as by-products from the processes of manufacturing ready-mixed concrete and waste from construction and demolition (C&D), is a viable option for use as a base and sub-base course material in road building in WA.

A series of laboratory tests were conducted to determine the physical, engineering and performance properties of selected research materials to evaluate their respective potential utilisation. The results demonstrate that the concrete waste materials selected from the companies: Holcim Ltd, All Earth, Capital Demolition and C&D Recycling are suitable for use as base and sub-base layers of flexible pavement in Western Australia.

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LIST OF NOTATIONS

M_R	=	Resilient modulus
σ_d	=	Deviator stress
σ_3	=	Confining stress
σ_m	=	Mean normal stress
ε_r	=	Recoverable axial strain
θ	=	Bulk stress
k_1, k_2	=	Regression parameters
p_a	=	Air pressure
τ	=	Octahedral stress
N	=	Number of loading
ε_t	=	Tensile strain at bottom of asphalt layer
ε_c	=	Compressive strain at top of sub-grade level
c	=	Cohesion
φ	=	Friction angle
E	=	Elastic modulus
ν	=	Poisson's ratio
f	=	Shear modulus
t	=	Thickness of layers in pavement structure
E11	=	Horizontal tensile strain
E22	=	Vertical compressive strain
U2	=	Vertical displacement
Cu	=	Coefficient of uniformity
Cc	=	Coefficient of curvature
D_{10}	=	Particle size at 10 % passing
D_{30}	=	Particle size at 30 % passing
D_{60}	=	Particle size at 60 % passing
S	=	Silica
CaO	=	Calcium Oxide
SiO_2	=	Silica Oxide
Al_2O_3	=	Aluminium Oxide
Fe_2O_3	=	Iron Oxide

G_s	=	Specific gravity
SC	=	refer to unified soil classification chart of Unified Soil Classification
GP	=	refer to unified soil classification chart of Unified Soil Classification
GW	=	refer to unified soil classification chart of Unified Soil Classification
LL	=	Liquid Limit
PL	=	Plastic Limit
PI	=	Plastic Index
SEM	=	Scanning Electron Microscope
PSD	=	Particle Size Distribution
MDCS	=	Maximum Dry Compressive Strength
UCS	=	Unconfined Compressive Strength
RLT	=	Repeated Load Triaxial
SADT	=	Standard axle with Dual Tyres
ESA	=	Equivalent Single Axle
OMC	=	Optimum Moisture Content
MDD	=	Maximum Dry Density
CBR	=	California Bearing Ratio
CRB	=	Crushed Rock Base
LA	=	Los Angeles Abrasion value
PCC	=	Portland cement concrete
MRWA	=	Main Roads department of Western Australia
ME	=	Mechanical-Empirical
WCCW	=	Washout Crushed Concrete Waste
RAP	=	Reclaimed Asphalt Pavement
RCC	=	Recycled Crushed Concrete
RAC	=	Recycled Asphalt Concrete
D	=	Predicted level of distress
DR	=	Drainage conditions
UDI	=	Urban Distress Index
PSC	=	Pavement Structural Condition
m	=	Soil slope coefficient

AGE = Pavement age

CHAPTER 1

INTRODUCTION

1.1 Objective and scope

The objective of this research is to outline opportunities to use Washout Crushed Concrete waste (WCCW) and construction and demolition (C&D) waste in the road construction industry. This research aims to:

I. Study the characteristics of WCCW and C&D waste in terms of their physical, performance and engineering properties as detailed below:

- Physical properties with respect to: shape and size of grains, surface texture, specific gravity, Atterberg limits, and mineral contents.

- Engineering properties with respect to: gradation, maximum dry density, strength[1] and compaction.

II. Determine a suitable stabilisation method for raw WCCW dependent upon its particle content. The particle re-grading process was investigated with the aim of improving its material properties.

III. Study the engineering properties of modified WCCW. This covered the following test processes: determination of the maximum dry density (MDD), the optimum moisture content (OMC), the California Bearing Ratio (CBR), the shear parameters, resilient modulus characteristics, and permanent characteristics for pavement design.

IV. Make comparisons of the properties of original and re-graded WCCW and C&D materials with the minimum property requirements of road bases.

[1] The strength characteristics of WCCW and C&D were simulated under various load conditions. Strength test methods such as triaxial tests and unconfined compressive strength tests were utilised.

V. Evaluate the potential use of original and re-graded WCCW and C&D for the construction of road bases based on experimental results.

1.2 Background

The Department of the Senate (2010), reported that the amount of solid waste generated in Australia is increasing annually. The 2006 Productivity Commission's *Waste Management* report noted that 32.4 million tonnes of solid waste was generated in 2002-03. Of this, approximately 27% was municipal waste, 29% was commercial and industrial waste and 42% was construction and demolition (C&D) waste. Due to the expansion of the construction industry, the amount of construction and demolition waste continues to rise dramatically.

Bowman & Associates (2009) state that the largest single source of landfill waste in Western Australia is the material and soil from construction and demolition activities. In 2002-03, C&D waste constituted 50% of landfill waste. In 2004-05, recycling activity grew steadily so that by 2006-07, approximately 21% of C&D waste was recycled.

The construction and demolition industry produces large volumes of heavy waste material including concrete, wood, steel, bricks, and asphalt. This material has the capacity to be used for road bases and sub-bases thereby reducing the drain on limited conventional natural rock aggregate resources. There is a lack of research on and knowledge of C&D waste material, guidelines for its use and its various specifications. Therefore its functionality may be limited. To recover the material for potential use, it is essential to continue research into its properties to determine how it can be used and what limitations and specifications or guidelines may be associated with its implementation.

Kio et al. (2002) investigated using recycled concrete made from limestone aggregates (RCLA), sourced from the demolition of old concrete buildings, roads and runways, as road base material in the United States of America. The materials

were sampled from Florida and tests determined aggregate gradation, Los Angeles Abrasion (LA), and load testing. According to the Florida Department Of Transportation, the Los Angeles Abrasion of natural aggregate used for base courses is less than 45%, while the LA of the RCLA lies between 41.62% and 47.60%. In terms of load testing under medium traffic conditions, RCLA did not rut but displayed 16 transverse cracks and one longitudinal crack. The authors concluded that RCLA pavement is harder than a pavement constructed with limestone rock.

Berthelot et al (2008) used recycled asphalt concrete (RAC) and Portland Cement Concrete (PCC) as base course pavement material in the city of Saskatoon, Canada. Materials were sampled from the crushing process of stockpiled asphalt and Portland Cement Concrete. As a result, the CBR and dynamic modulus were 51.4% and 1018 MPa and in the case of PCC, these parameters were 109.2% and 960MPa.

The economic and environmental benefits of using recycled concrete have become evident in recent years so much so that by the early 1990's, a number of Australian municipalities had undertaken significant use of recycled crushed concrete aggregate for local road construction and other engineering uses.

Western Australia has a number of recycling companies that recover C&D waste from different sources. In this research, recycled materials were chosen from the following companies: Holcim, C&D Recycling, Capital Demolition and Earthworks, and the All Earth Group.

The volume of C&D material produced by C&D Recycling, Capital Demolition and Earthworks and the All Earth Group is approximately 225,000 cubic metres annually. Original waste from various construction sites is taken to the company's recycling areas where timber, paper, steel and green waste are removed. The remaining synthetic hard materials[2] are crushed and screened by special equipment in quarries. Finally, aggregates of homogeneous composition and uniform particle size are produced for use in concrete and road bases.

[2] Concrete, cement and bricks.

Approximately 30,000 tonnes of WCCW is produced annually in the concrete batching plants of Holcim Ltd. The recycling process for WCCW differs markedly from that for C&D materials. WCCW is collected from the concrete mixer's drum and then washed at concrete batching plants. It is common practice in the ready-mixed concrete industry to thoroughly clean the inside of a drum at the end of each day. The trucks are cleaned with water and the resultant concrete residue/water mix, placed in a wash pit. When the concrete residue settles to the bottom of the wash pit completely, the water is removed from the pit. Finally, the settled waste is removed from the wash pit and transferred to a limestone quarry at Postans in Western Australia. There the washed concrete waste is put into a two-step mobile crusher to create the final WCCW.

1.3 Significance

The significance of this research is in identifying a means of effectively utilising both WCCW from concrete-batching plants and C&D material in the road construction industry. This would provide a new and plentiful source of construction materials at a time when traditional sources are declining. This could reduce construction costs in the road industry and contribute towards saving our natural energy resources.

The research approach

To achieve the objectives of this research, the study was carried out employing the following methodology as shown in Figure 1.1.

Literature review

For the first stage of the research, a detailed literature review was conducted in order to assess current knowledge on the subject. The review was restricted to information on flexible pavement performance and the mechanical behaviour of pavement base course materials. The use of recycled materials as a road base course material was also included in the review.

The characterisation of WCCW and C&D

The purpose of the second stage of the research was to determine how the properties of WCCW and C&D waste would influence their behaviour in road construction activities. The factors investigated were: physical and engineering properties and performance responses.

The stabilisation of WCCW

The third stage of the research examined a stabilisation method for WCCW in which a mechanical re-grading method is demonstrated.

Performance laboratory tests and investigation

Stage four examined the performance properties of WCCW and C&D waste, their shear strength parameters, resilient moduli and permanent deformation for the purpose of numerical modelling design for pavements.

Evaluation

Stage five evaluated the synthetic aggregate produced from WCCW and C&D waste in accordance with Main Roads Department of Western Australia (MRWA) Specification 501. The materials' physical and engineering properties, including triaxial tests for various condition strengths were compared with the minimum requirements of the general specifications for road materials. Previous specifications set by MRWA for crushed recycled concrete, finite element modelling and numerical modelling were also used. These comparisons were undertaken to confirm that all compliance requirements were met.

Recommendations

Several recommendations were made for further research.

1.4 Thesis outline

This thesis consists of six chapters.

Chapter 1 consists of an introduction to the entire research study in general and highlights its objectives, scope, methodology, and organisation.

Chapter 2 presents a review of the literature relevant to the behaviour of pavement systems, especially flexible pavements. The review also includes information on: fundamental knowledge and research work performed in pavement function, flexible pavement analysis and design, the mechanical behaviour of base course materials, and the use of recycled material in road construction.

Chapter 3 describes the experimental program, materials to be tested, testing methods, and procedures.

Chapter 4 discusses and summarises the results of the tests, including Construction and Demolition (C&D) waste and Washout Crushed Concrete Waste (WCCW) material characteristics for road construction materials.

Chapter 5 presents the general pavement design of the WCCW and C&D waste for road bases, using CIRCLY 5.0, and the finite element analysis for the determination of the vertical and horizontal strains occurring in pavement layers.

Chapter 6 provides a summary of conclusions and makes recommendation for further research.

The thesis ends with appendices.

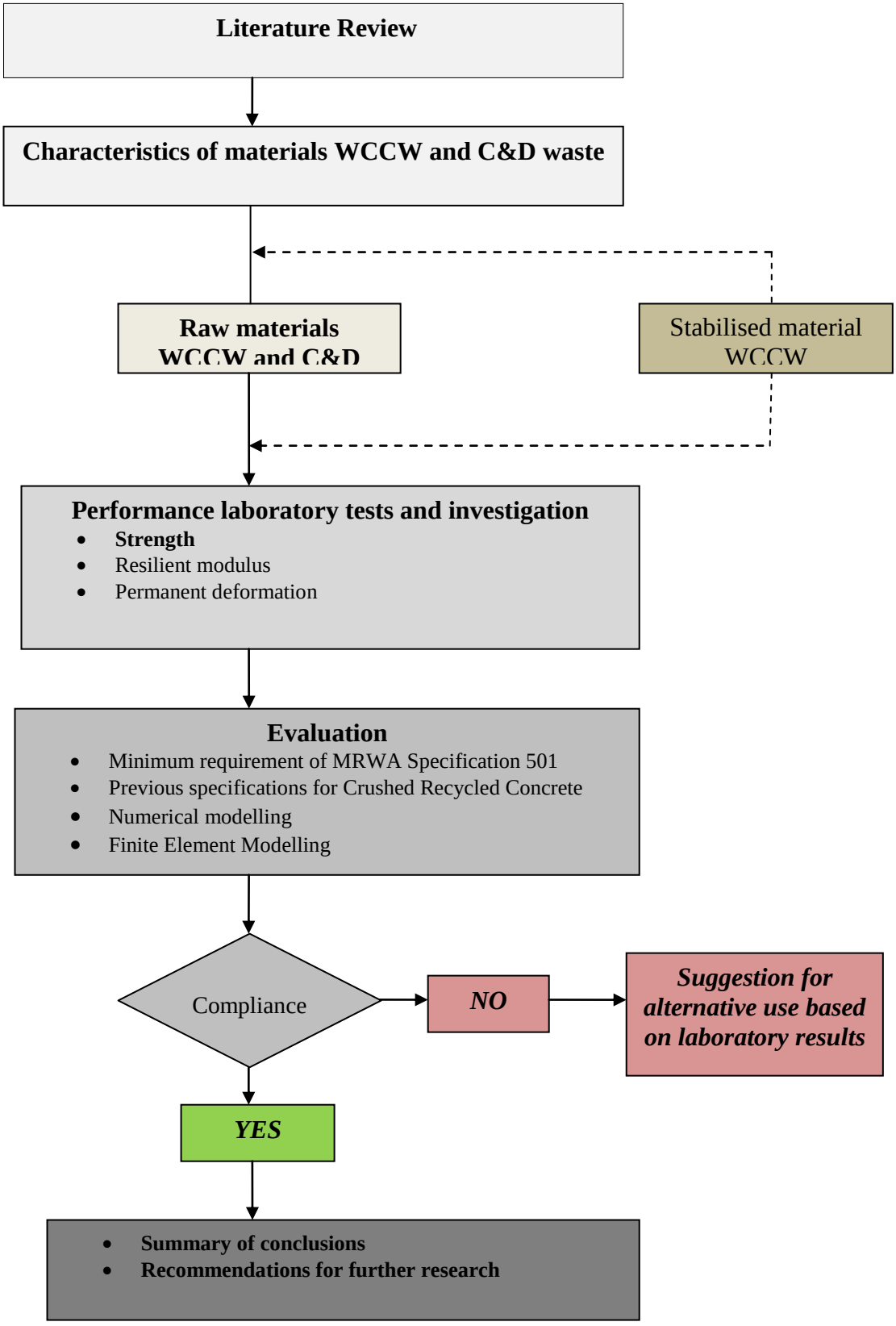


Figure 1.1 Research methodology chart

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

In this chapter, discussion is given over to: the basic concepts regarding flexible pavement, pavement performance, analysis and design procedures, significant pavement material characteristics, environmental effects on pavement behaviour and finally, failure criteria.

2.1 Pavement definition and function

Pavement or road surface is the durable surface material laid down on an area to carry loads from vehicular or food traffic.

The main role of the pavement is for the structure to support an applied traffic load without excessive deformation and cracking during its design life. Furthermore, the pavement has to be smooth to improve ride comfort and to permit drainage for the elimination of moisture from surrounding areas.

The ancient Romans built their roads from stone and concrete. At around the beginning of the 19th century, binding agents began to be used to assist aggregate cohesion and improve the durability of roads. By the end beginning of the 20th century, two principal pavement types, flexible and rigid, were being built throughout world.

Depending on traffic conditions, pavement capacity, and the surrounding environmental area, a pavement is designed by using different materials of various thicknesses.

2.1.1 Flexible pavement

A pavement which is covered by a mixture of sand and gravel or crushed stone, compacted with a bituminous binder (asphalt), is termed *flexible*. It has sufficient plasticity to absorb shock. This will be explained in detail in 2.2.

2.1.2 Rigid pavement

A rigid pavement surface is made of concrete, composed of coarse and fine aggregates and Portland cement, and is often reinforced with steel bars or mesh (Yoder E 1975). In contrast to flexible pavement, rigid pavement or cement concrete pavement has a high modulus of surface elasticity, therefore, under loading, pavement structure deflection is lower than that of flexible pavements.

According to Flaherty (1974), rigid pavement structure is a two or three layer system as can be seen in Figure 2.1. It consists of a Portland Cement Concrete (PCC) surface, a sub-grade, and an underlying base course. Generally, the thickness of the surface is 150mm to 300mm depending on traffic load capacity. The main characteristics are strength, friction, smoothness, noise control, and drainage (Transportation 2003).

In rigid pavement structure, the sub-base layer is optional. If the condition of the sub-grade soil used is poor and prepared with materials of insufficient strength or low load-bearing capacity, a sub-base is interposed between the PCC surface and the sub-grade.

A sub-base in a rigid pavement does not so much influence the structural ability of the pavement as provide permanent support for the PCC surface (concrete slab) to maintain stability under conditions where there is poor drainage, mud-pumping, frost, swell, shrinkage of high-volume change soils and construction traffic
(Flaherty 1974).

The distribution of the applied load from a wheel occurs over a wide area of the structure layers as shown in Figure 2.2.

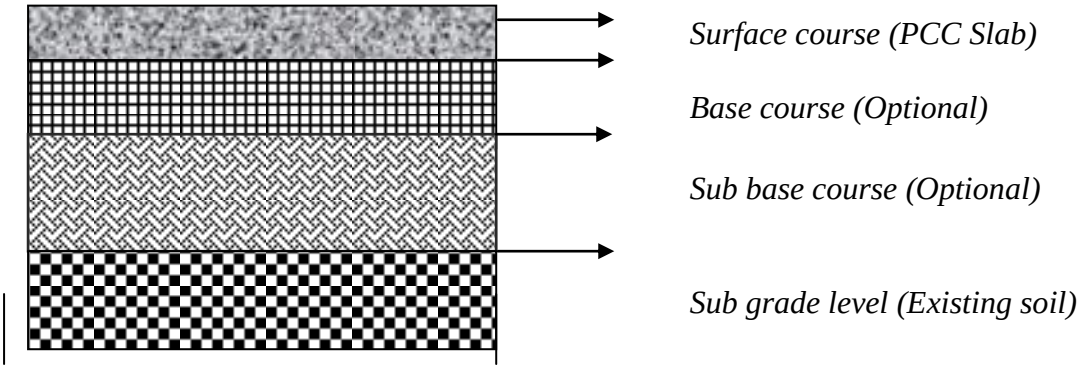


Figure 2.1 Basic Rigid Pavement Structure

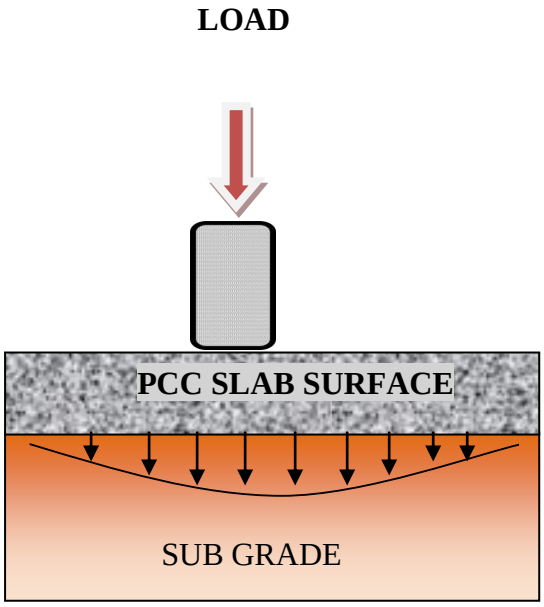


Figure 2.2 Rigid pavement load distribution

2.2 Flexible pavement analysis and design

2.2.1 Pavement structure and materials

Pavement which is covered with a mixture of sand and gravel or crushed stone, compacted with a bituminous binder (asphalt), is termed flexible. It has sufficient plasticity to absorb shock. Under loading, the flexible pavement structure deflects or flexes. It has three layers, the base course, the sub-base, and the sub-grade as shown in Figure 2.3.

The surface course of the flexible pavement in direct contact with traffic loads is produced from asphalt, a mixture of components of coarse and fine aggregates, and a bituminous binder.

The base course is beneath the wearing surface and is usually prepared from materials with a higher load bearing capacity than the sub-base layer and the main load carrying course in the pavement. It generally consists of unstabilised and stabilised durable aggregates.

The sub-base layer is laid between the base layer and sub-grade layer; it is usually prepared from lower quality materials than the base course but is of better quality than sub-grade soils (Transportation 2003). The function of this layer is not only to provide structural support but also to improve drainage and reduce freeze-thawing damage. Crushed rock is well-suited as a material for the sub-base. However, there are two limitations: thickness, and cost. Therefore, other natural resource materials should be investigated for utilisation as a sub-base (ACTA 1988).

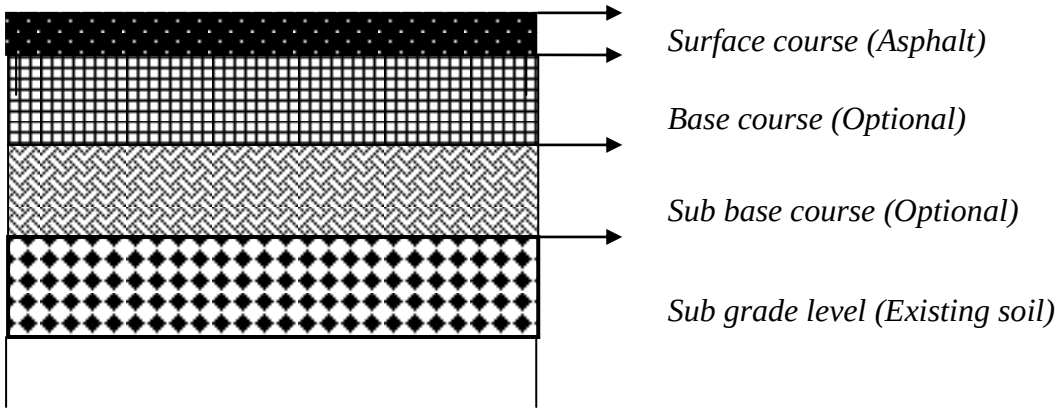


Figure 2.3 Basic Flexible Pavement Structure

(Steve Muench 2003)

The sub-grade is the foundation of natural earth, it can be mechanically stabilised with (well compacted) weak filling natural resource materials (Nikraz 2009).

2.2.2 Pavement distress and response

A flexible pavement must be able to transmit wheel loads to the sub-grade without undergoing excessive deformation (Drakos 2005). Each layer works under a load from the layers above, spreads it out, and then passes the load on to the next layer below. Applied wheel loads are distributed through the flexible pavement to the sub-grade as shown in Figure 2.4. In the lower layers, the stress from the wheel loading is dispersed over a large area and is therefore of much smaller intensity. As a result, the sub-grade and sub-base are subject to significantly smaller stresses as compared with the base course and asphalt (wearing surface).

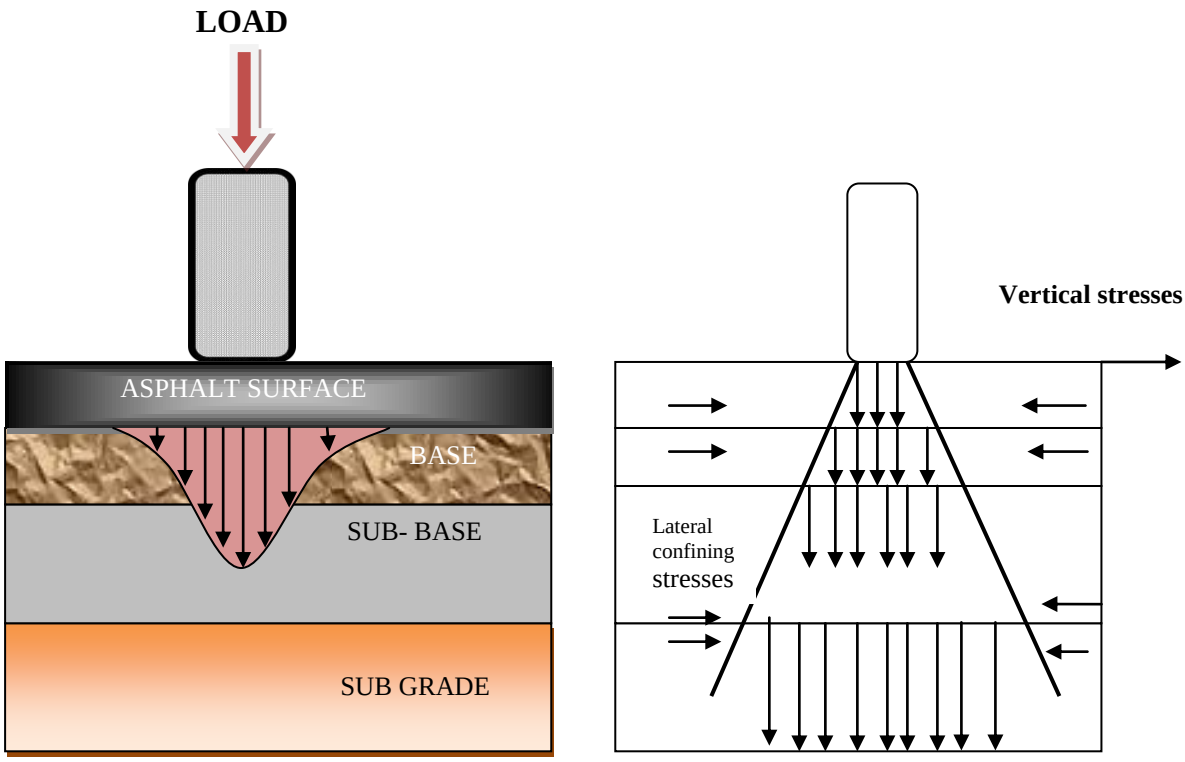
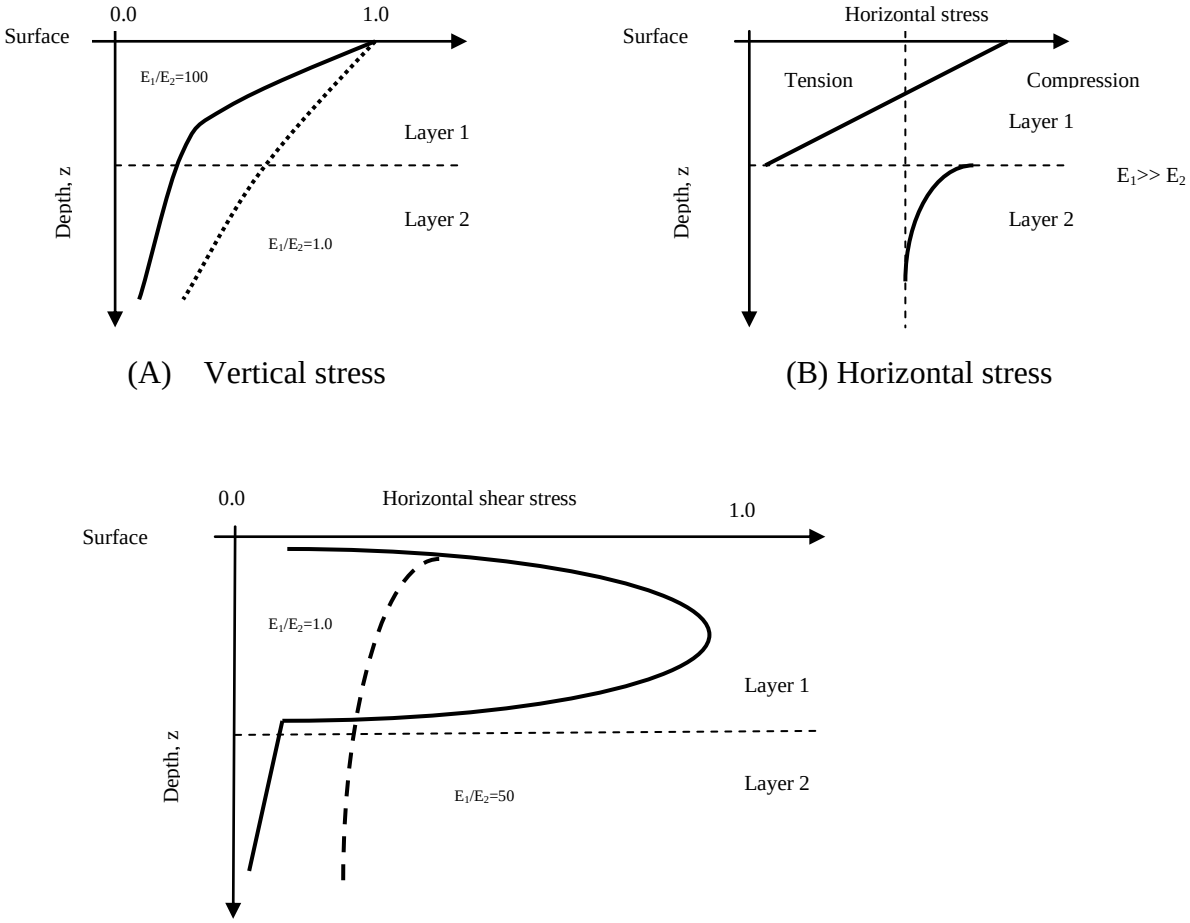


Figure 2.4 Flexible pavement load distribution

(Muench, 2003), (Drakos, 2005)

Under repeated traffic loads, the flexible pavement undergoes three main stresses: vertical, horizontal, and shear. Two-dimensional layered elastic programs were used to calculate these stresses. More recently, three-dimensional finite element programs have provided calculations that are more accurate.

Generally, the stress distribution in flexible pavement is complex. The two-dimensional layered elastic programs illustrate typical stress distribution as shown in Figure 2.5.



(A) Vertical stress

(B) Horizontal stress

(C) Shear stress

Figure 2.5 Typical Two-Layer flexible pavement stresses as calculated by the two-dimensional linear elastic model (Muench, 2003)

According to Figure 2.5, vertical, horizontal, and shear stresses are spread differently in pavement layers depending on the layer's elastic modulus. In diagram (A) and (C), the vertical and shear stresses are distributed evenly in layers and are reduced uniformly when the elastic modules are almost similar. The big difference in the elastic modulus is that the upper layer is stiffer than the lower layer where most of the vertical shear stress is distributed. In terms of horizontal stress, in diagram (B), the upper layer works under compression and the lower layer is in tension except in the layer interfaces.

The visible evidence of deterioration of a pavement is distress, and this depends on traffic loads, environmental effects, and other internal and external factors that cause physical damage to the structure. The most common flexible pavement distresses are presented in Table 2.1 (Administration 2006).

Table 2.1 Flexible pavement distresses

Category	**Distress Type**
Cracking	Longitudinal, fatigue, transverse, reflective, block, edge
Deformation	Rutting, corrugation, shoving, depression, overlay, bumps
Deterioration	Delamination, potholes, patching, raveling, stripping, polished, aggregate, pumping
Mat problem Seal coats	Segregation, checking bleeding
Seal coats	Rock loss, segregation, bleeding/fat spots, delamination

Some typical pavement distresses are illustrated in Table 2.2, (sourced from the North America Asphalt Institute website: http://www.asphaltinstitute.org/).

The distress index (DI) is the parameter used to determine the age of the distressed pavement and the amount of time remaining before renewal is necessary.

Various researchers have created prediction models of distress indexes. The Texas Department of Transportation conceived one remarkable Artificial Neural Network-based model (ANN). This model can predict fatigue and rutting cracking to 86% and 98% of the desired values, within ± 20% error. For tensile, compressive strains, the model predicts 96% of the desired values with ±10% error (Abu-Lebdeh et al. 2003).

The Washington State Department of Transportation (WSDOT) gives the equation of the prediction of the pavement condition as follows:

$$psc = c\text{-}m \times A^{P} \qquad (2\text{-}1)$$

where : psc is the pavement structure condition, A is the age, or the time since construction, c is the model constant for maximum ration (100), m is the slope coefficient, and p is the selected constant which controls the degree of curvature of the performance curve (Transportation 2003).

AI-Mansour (1999) determined the urban distress index (UDI) based on research in Saudi Arabia on the Riyadh street network. This is demonstrated in the following equation:

$$UDI = a + b \times AGE^{n} + c \times ADT + d \times DR \qquad (2\text{-}2)$$

where: AGE is pavement age, n = 1 or 2, ADT is annual daily traffic (0 = low traffic, 1= high traffic), DR is drainage condition (0 = without drainage, 1= with drainage), a,b,c,d are regression coefficients.

Dossy (Abu-Lebdeh et al. 2003) presents the distress index model considering pavement age, environmental temperature, rainfall level, pavement thickness, and traffic conditions.

$$D = \alpha \; x \; e^{-\left(\frac{\aleph\varepsilon\delta\rho}{N}\right)\beta} \qquad (2\text{-}3)$$

where D is the predicted level of distress, N is age of the pavement, α, β, ρ are shape parameters estimated by regression, and $\varepsilon, \aleph, \delta$ are adjustments for environmental conditions, traffic conditions and pavement structure, respectively.

Table 2.2 Pavement distress types

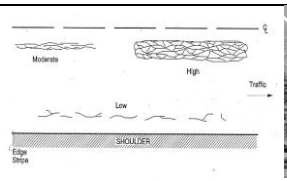
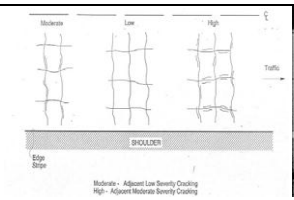
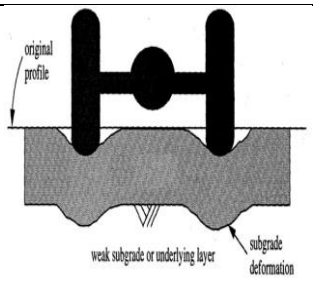
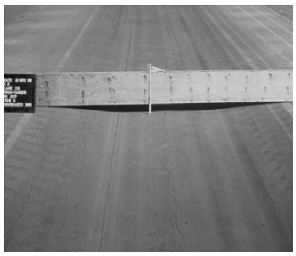
Type of distress and possible cause	Example photos
Fatigue Cracking • Excessive loading • Weak layers • Thin surface or base • Poor drainage	
Block Cracking • Old and dried out mix • Mix was applied too dry • Asphalt mix content is incorrect	
Longitudinal & Transverse Cracking • Shrinkage of the asphalt layer • Poorly constructed paving joint • Daily temperature cycling • Improper operation of the paver	
Settlement/Grade Depression • Settlement or failure in the lower pavement layers • Improper construction techniques	
Patching/Pothole • Poor surface mixtures • Weak spots in the base or sub-grade • Severity of the surrounding distress and traffic action accelerate potholes	
Rutting • Consolidation or lateral movement of any of the pavement layers or the sub-grade under traffic • Insufficient design thickness • Lack of compaction and weak asphalt mixtures • Weaknesses in the pavement layers due to moisture infiltration	 

Table 2.3 Test measures for aggregate properties and performance

(ARRB Consulting)

Performance parameter	Related aggregate property	Test measures
Fatigue cracking	Stiffness	Resilient modulus, Poisson's ratio, gradation, fines content, particle angularity and surface texture, frost susceptibility, degradation of particles, density
Rutting, corrugations	Shear strength	Failure stress, angle of internal friction, cohesion, gradation, fines content, particle, geometrics (texture, shape, angularity), density, moisture effects
Fatigue cracking, rutting, corrugations	Toughness	Particle strength, particle degradation, particle size, gradation, high fines
	Durability	Particle deterioration, strength loss
	Frost susceptibility	Permeability, gradation, percent minus 0.02 mm size, density, nature of fines
	Permeability	Gradation, fines content, density

2.2.3 Current pavement analysis and design procedure

Flexible pavement design procedure is the determination of the applicable pavement thickness and material composition based on the main design factors: stresses, strains, and deflections due to traffic load and environmental conditions.

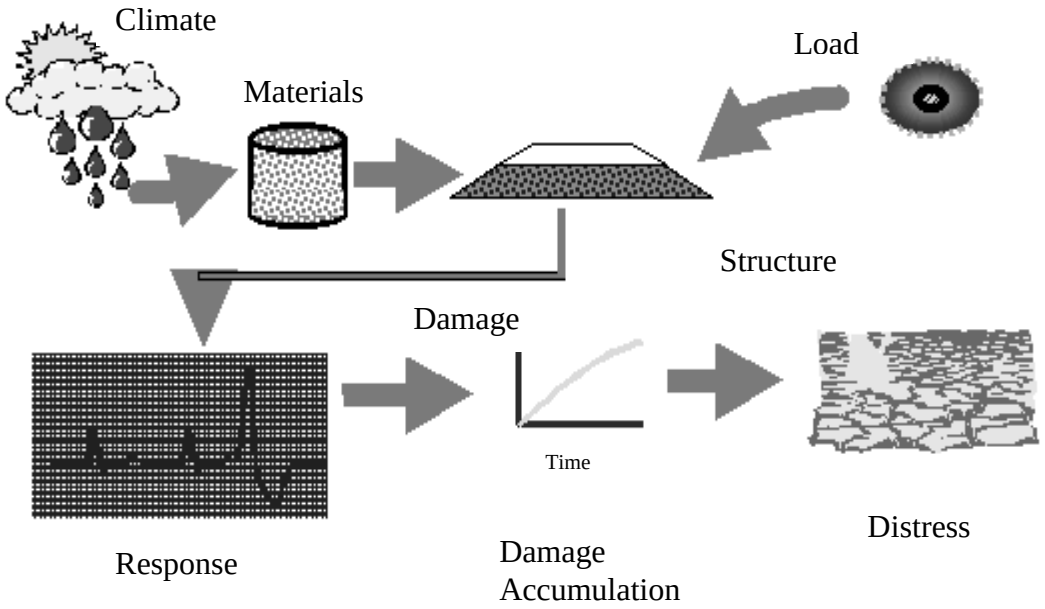


Figure 2.6 General lifetime of a pavement

(C-SHRP 2006)

Figure 2.6 shows the general lifetime of a pavement, which is subject to damage from the influences of traffic loading, material properties, and climate change. With increasing age, this damage accumulates, leading to distress or failure of the pavement. A correct design process is crucial in preventing pavement distress caused by base layer deformation and flexural cracking of the asphalt surface under the above conditions. Correct design will extend life of the pavement (Nikraz 2009).

According to the 1997 TAC Guide (C-SHRP 2006), the pavement design process is based mainly on the parameters of traffic loading, environmental conditions, pavement material properties and thicknesses. There are three basic methods of pavement structure design in Canada: the experience-based method, which is a pre-calculation of the pavement thickness based upon previous data, the empirical method, based on experimental results, and the surface deflection method, based on the measurement of the elastic rebound on the surface with a single axle-truck load of 80kN, using a Benkelman beam device.

Basically, two main design methods are currently being employed: the empirical design (ED), and the mechanical-empirical design (ME) (Transportation 2003).

An empirical analysis of flexible design is based on experimental results of the physical properties and strength parameters of the materials proposed for use in the pavement layers. This method is widely used and has two requirements: an empirical equation and an empirical computer program using the 1993 AASHTO Guide (Transportation 2003).

According to the 1993 AASHTO Guide, the empirical equation, (2-4), below, is widely used and encompasses the basic parameters: loss in serviceability, amount and type of traffic, and pavement thickness. Other parameters included in the equation are: predicted loading, reliability, pavement structure, sub-grade support by the resilient modulus, layer coefficients, and drainage coefficients:

$$\log_{10}(W_{18})=Z_R x S_0+9.36x\log_{10}(SN+1)-0.20+\frac{\log_{10}\left(\frac{\Delta PSI}{4.2-1.5}\right)}{0.40+\frac{1094}{(SN+1)^{5.19}}}+2.32x\log_{10}(M_R)-8.07 \qquad (2\text{-}4)$$

where: W_{18} = predicted number of 80kn ESALs

Z_R = standard normal deviate

S_0 = combined standard error of traffic and performance prediction

SN = structural number (an index that is indicative of the total pavement thickness required)= $a_1 D_1+a_2 D_2 m_2+a_3 D_3 m_3+\ldots$

ΔPSI = difference between the initial design serviceability index, p_0 and the design terminal serviceability index,p_t

M_R = sub-grade resilient modulus (in psi)

The mechanical-empirical design on the other hand is based on the mechanics of the materials determined by wheel load and pavement responses: stresses, strains, and deflections (Krishna 2007). There are a number of different types of mechanical models: layered elastic, dynamic, and visco elastic. Figure 2.7 illustrates the general mechanical process of pavement design.

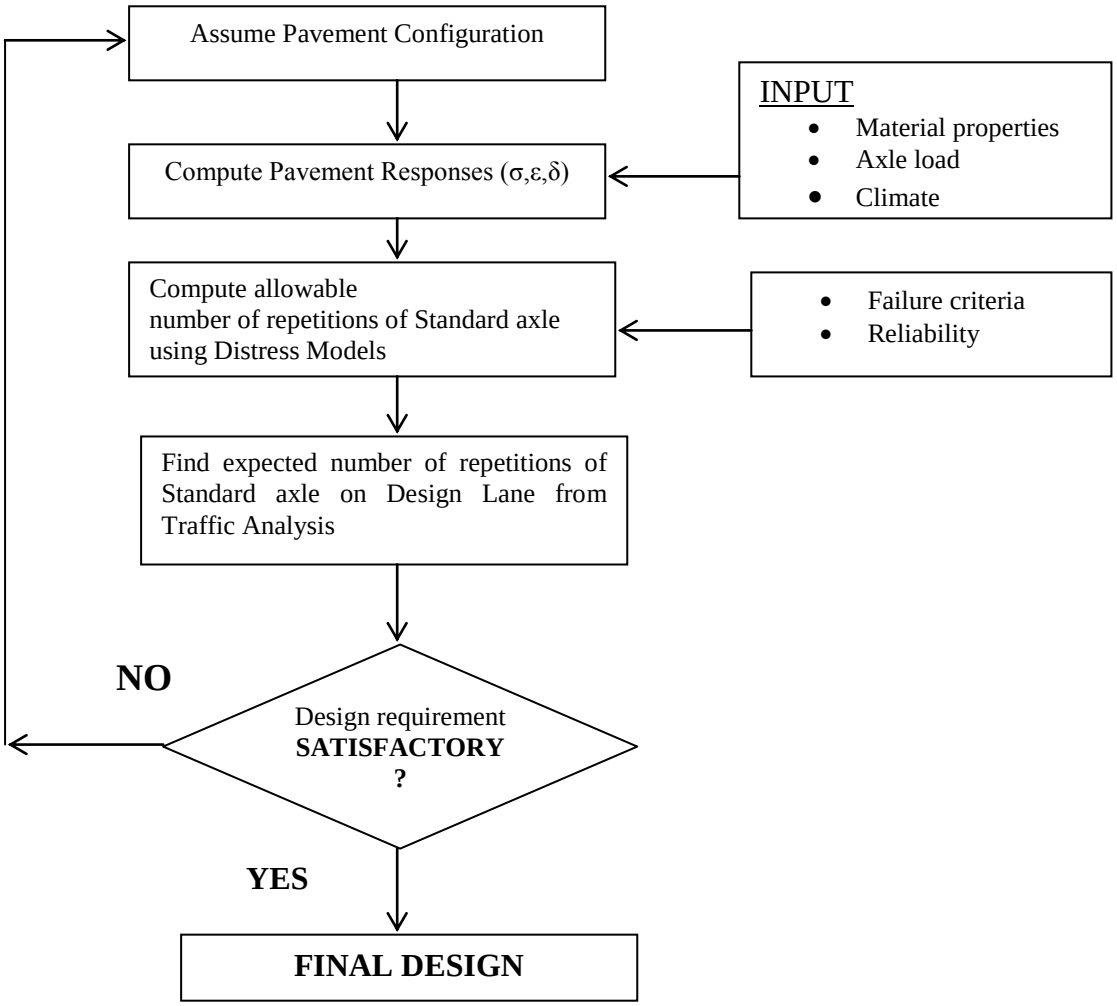


Figure 2.7 General Mechanistic Method of Pavement Design

In Australia, up until 1970, empirical methods were generally used in pavement design procedures, with material properties such as particle size distribution, plasticity and compaction being the main characteristics under consideration. In 1979, the National Association of Australian State Road Authorities (NAASRA), published the Interim Guide to Pavement Thickness Design. In the Guide, it was suggested that pavement design be based on the criteria of: design traffic, sub-grade evaluation, material properties, construction and maintenance influences, and environmental factors.

In 1987, the mechanical design process, using linear elastic analysis was developed and initially published in Australia through the NAASPA Guide, as the Structural

Design of Road Pavement. It was updated in 1992, with a change of name, to the Austroads Guide to the Structural Design of Road Pavements.

According to the Austroads Guide 2008, the following four processes are used in new flexible pavement design:

1. F1-Granular pavement with (<25mm) bituminous surfacing: The method is to determine the sub-grade design of the CBR, the thickness cover required for sub-grade conditions and estimated traffic, the estimate of cumulative traffic over the life of the design in terms of ESAs, the estimated minimum base requirements and modifications for desired terminal roughness.
2. F2-Granular pavement with asphalt surfacing up to 100 mm: The method is to determine the thickness of cover using F1, the pavement stiffness factor, deflection under a Standard axle, then reduce deflection by 5% for each 25 mm of AC surfacing, and check the reduced deflection against tolerable deflection and minimum base requirements.
3. F3-Pavement containing a bound layer or asphalt > 100 mm: The method is to determine the thickness cover using F1, select the pavement's total thickness, adjust the pavement layer thickness to satisfy cover requirements for each unbound layer, assign values to elastic parameters (Young's modulus, Poisson's ratio) for each layer, estimate deflection under a Standard axle, check the estimated deflection against tolerable deflection and, if inadequate, reduce the thickness of bound layers and minimum base requirements.
4. F3B- Pavement containing a bound layer or asphalt < 100 mm: This method is used to determine the thickness cover using F1 and F2 (as appropriate) and individual layer thickness (t_i), from suggested layer equivalencies (a_i) and the relationship: T= $\sum a_i t_i$, also checking the minimum base requirements.

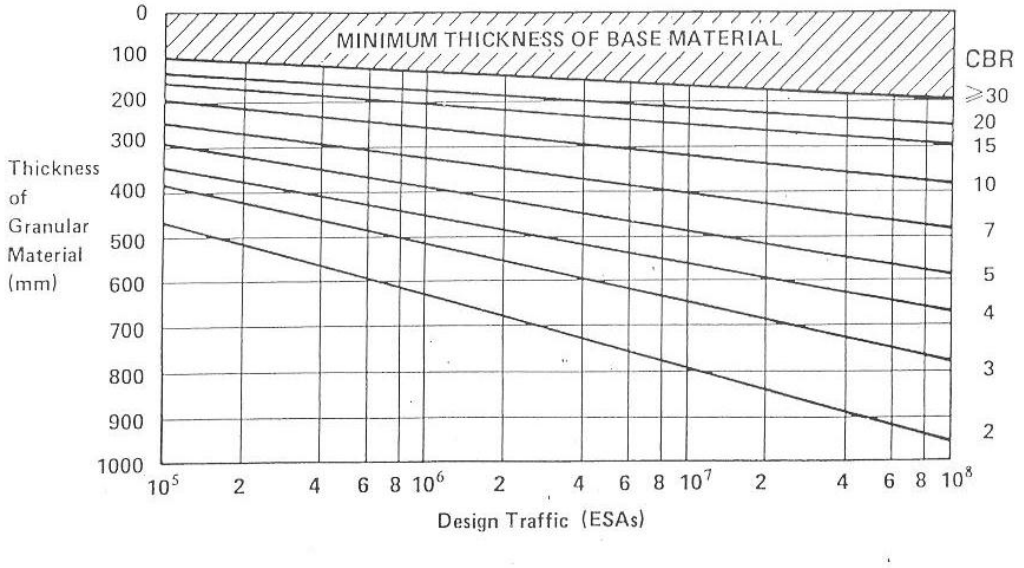


Figure 2.8 Design chart for flexible pavement

(Austroads,1992)

Having determined the design sub-grade CBR and design traffic, the total required thickness of a granular flexible pavement can be chosen directly from Figure 2.8.

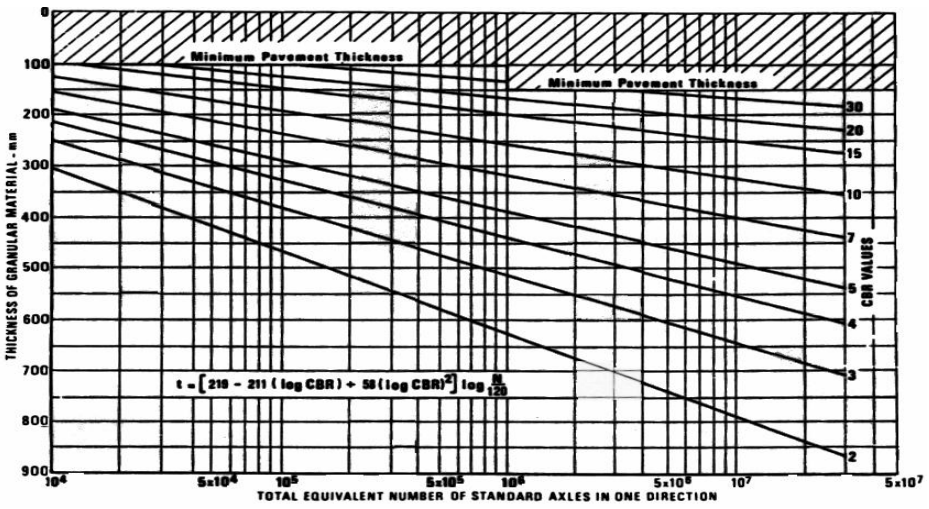


Figure 2.9 NAASPA 1979 design chart

As can been seen, the Austroads 1992 design chart Figure 2.8 is similar to the NAASPA 1979 chart shown in Figure 2.9, with the exception of minimum pavement thickness and design traffic values.

Austroads developed its general mechanistic design procedure in 2004, based on the structural analysis of multi-layered pavement under different conditions, as shown in Figure 2.10. The procedure includes the following steps:

1. Evaluate the main parameters, including construction and maintenance, environmental factors, materials and performance, and traffic conditions
2. Conduct a trial test of the pavement
3. Analyse the trial pavement to determine acceptable traffic
4. Evaluate the acceptable traffic with the design traffic. If unsuccessful, a new trial pavement is chosen and tested until a satisfactory pavement is found.

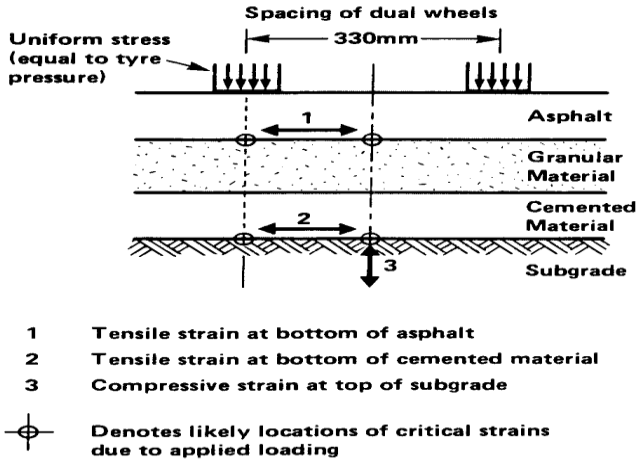


Figure 2.10 Standard axle loading used in the Austroads pavement design model for mechanistic design of flexible pavements (Austroads, 2004)

This model considers the following specific characteristics:

- Materials, except for the sub-grade and granular layers, are homogenous, elastic, and isotropic
- The computer software CIRCLY is used to calculate the response from the loading
- The critical responses are from the horizontal tensile strain at the bottom of the asphalt or sub-base layers and the vertical compressive strain at the sub-grade layer

- Under Standard axle loading, the critical responses occur under one wheel through vertical axes
- The tyre pressure contact stress is in the range 550-750kPa (Nikraz, 2009).

2.2.4 CIRCLY 5.0 (MINCAD Systems 2004)

A layered elastic computer program, CIRCLY, is the lead software widely used in the mechanical analysis and design of road pavements in Australia and New Zealand. It was initially presented in 1977 and it calculated the polynomial type radial variations in contact stress and multiple loads close to real traffic loading conditions. In 1998, Version 2.4 was used and in late 1996, Version 3.0 appeared. Version 4.0 was released in early 1999 and included an automatic thickness design capability. Version 4.1 (2003), was further updated in 2004 to Version 5.0 (MINCAD 2004).

In the early versions, up to 4.0, the program calculated the stresses, strains, and displacements in the layered elastic system. However, CIRCLY 4 started to include additional calculations in strains, for the design and the plotting of results (Wardle 1998).

The system calculates the cumulative damage induced by a traffic spectrum consisting of user-specified vehicle types and load configurations. As well as using the usual equivalent single-wheel and load approximations, other contributors, such as foundation engineering and settlement analysis, may also be analysed using CIRCLY.

CIRCLY has creative advantages such as the ability to select: cross-anisotropic and isotropic material properties, fully continuous (rough) or fully frictionless layer interfaces, various types of load involving vertical, horizontal, torsion, non-uniform surface contact stress distributions, and automatic sub-layering of unbound granular materials.

CIRCLY is based on integral transform techniques and has remarkable advantages over other linear elastic analysis techniques, for example, finite element methods (FEM) use a considerably larger amount of computer time.

2.3 Recycled road base materials

2.3.1 Various types of recycled road base materials

The effective utilisation of recycled materials from the industrial sector is part of ongoing research programs all over the world as well in Australia. Many researchers have investigated this area using recycled materials as second-class materials in sub-base and base courses for low volume roads. These materials include: recycled concrete with limestone, reclaimed asphalt pavement (RAP), recycled crushed concrete (RCC), recycled asphalt concrete, Portland cement concrete and recycled crushed brick and concrete.

Recycled materials are used materials, and as such, they have reduced mechanical properties compared to the original material. It is impossible to use standards or specifications written for road base course materials directly. Furthermore, following social development, the number of recycled materials in use today is rapidly increasing. As result, the description of research related to recycled materials as base course material in pavements and the demonstration of precise standards and specifications must constantly be revised.

Dimitri et al. (1998) investigated using mixtures of reclaimed asphalt pavement (RAP) and recycled crushed concrete (RCC) as base course pavement materials. In this research, the main influencing factor was the amount of RAP in the mixture. Three mixes of different proportions were chosen for laboratory test procedures. An increase of the RAP amount followed low moisture content, decreased the resilient modulus, and improved the permanent strain of the mixture. The maximum dry compressive strengths were between 2.9MPa and 4.3MPa. The mixtures had the ability of self-cementing. Optimum moisture contents (OMC) were between 10.7-

11.4% and unconfined compressive strengths 0.2MPa - 1.0MPa. The resilient modulus from triaxial testing was 230MPa - 280MPa.

Resende et al. (1999) studied the possibility of using cement quarry material in Pedreira Contagem, Brasilia (Brazil). Firstly, the compaction and California Bearing Ratio (CBR) and the resilient modulus of the material were determined in the laboratory. An experimental road segment for a low traffic road was constructed for the field tests: CBR, dynamic cone penetration, plate loading, pencel pressuremeter, Benkelman beam, and falling weight deflectometer. The results showed cement quarry material can be used as a flexible pavement course material for low traffic roads in Brasilia. However, displacements increased due to the attendant weather conditions of the rainy season.

Kio et al. (2002) investigated recycled concrete as road base material in the United States of America. The recycled concrete was made with limestone aggregate (RCLA), sourced from the demolition of old concrete buildings, roads, and runways. The materials sampled from Florida were used in tests to determine aggregate gradation, Los Angeles Abrasion (LA) and load testing. According to the Florida Department of Transportation, the LA of natural aggregate used for base course is less than 45% while the LA of the RCLA lay between 41.62% and 47.60%. In terms of load testing, under medium traffic conditions, RCLA did not rut but showed 16 transverse cracks and one long crack. The conclusion was that RCLA pavement is harder than pavement constructed by lime rock.

Berthelot et al. (2008) investigated recycled asphalt concrete (RAC) and Portland cement concrete (PCC) from the City of Saskatoon (Canada), for viability as base course pavement materials. Materials from the crushing process of stockpiled asphalt and Portland cement concrete were sampled. The requirement in the City of Saskatoon specification, for the content of particle size to be over 5.0 mm was realised in both RAC and PCC. The CBR and dynamic modulus were also tested in both materials. In terms of RAC, the CBR and dynamic modulus were 51.4% and 1018MPa and for PPC these parameters were 109.2% and 960MPa.

In 2008, the Welshpool Road trials were performed under heavy traffic conditions on an 860 m road section. The trials were performed by replacing the limestone sub-base with recycled materials, pure crushed concrete and mixed-hard concrete demolition materials. From a repeat loading tri-axial test (RLT) at 98% of MDD, 0% of OMC, 240kPa vertical stress and 125kPa confining stress, the modulus value was 430MPa for pure crushed concrete and 500MPa for mixed-hard concrete demolition material. According to the particle size distribution test, after compaction, increasing amounts of fine particles occurred.

It was concluded that these materials could be used as a base and sub-base in low and medium traffic roads and as a sub-base only in high traffic roads (Leek 2008).

The properties of recycled materials significantly influence pavement performance and it is not possible to use base course material standards and specifications directly. Leek (2010), suggested that some significant physical, chemical and mechanical properties of the recycled aggregate particle need to be determined and investigated (see Table 2.4).

Table 2.4 Recycled aggregate particle properties which influence pavement performance

Physical properties	**Chemical properties**	**Mechanical properties**
• Particle gradation and shape (max/min sizes) • Particle surface texture • Pore structure, absorption, porosity • Permeability (hydraulic properties) • Specific gravity • Thermal properties • Volume change (in wetting & drying) • Freezing/ thawing resistance • Deleterious substances	• Solubility • Base exchange • Surface change • Chemical reactivity (resistance to attack by chemicals, chemical compound reactivity, oxidation and hydration reactivity, organic material reactivity) • Chloride content • ph-level	• Particle strength • Particle stiffness • Wear resistance • Resistance to degradation • Particle shape of abraded fragments

2.3.2 Construction and Demolition (C&D) materials in Australia

In 1995 pavement engineers from MRWA created the first draft specification using recycled C&D materials from road construction. However, this was not followed up until 2003.

In 2003-2004 MRWA conducted a small project, which was the construction of 400 metres of roadway using 125mm of crushed recycled concrete as a base course. The conclusion was that "the crushed recycled concrete is a superior base course to the crushed rock base".

In August 2006, MRWA released a revision of Specification 501- Pavements, which included specifications for recycled concrete base (RCRB) materials.

The limits for foreign material amounts, particle size distribution, and other acceptable engineering properties of crushed recycled concrete for the sub-base of pavement are presented in Table 2.5, Table 2.6 and Table 2.7 respectively. The limits of foreign material amounts, particle size distribution, and other acceptable engineering properties of crushed recycled concrete for the base course of pavement are outlined in Table 2.8, Table 2.9, and Table 2.10 respectively (MRWA, 2007).

Table 2.5 Limits of foreign material in crushed recycled concrete: Sub-base material

Material	**Maximum % retained by mass on 4.75 mm sieve**
High density material (brick, glass, etc)	15
Low density materials (plastic, plaster, etc)	3
Wood and other vegetable matter	1

Table 2.6 Particle size distribution in crushed recycled concrete: Sub-base material

AS Sieve Size (mm)	% Passing by mass
37.5	100
19.0	71-100
4.75	36-65
0.075	2-14

Table 2.7 Other acceptance limits in crushed recycled concrete: Sub-base material

Test	Limits	Test method
Los Angeles Abrasion Value	45.0% max	WA 220.1
Liquid Limit (Cone penetrometer)	45.0% max	WA 120.2
Linear Shrinkage	4.0 % max	WA 123.1
California Bearing Ratio (CBR) (Soaked 4 days) at 94% of MDD and 100% of OMC)	50 % min	WA 141.1

Table 2.8 Limits of foreign material in crushed recycled concrete: Base material

Material	Maximum % retained by mass on 4.75 mm sieve
High density material (brick, glass, etc)	5
Low density materials (plastic, plaster, etc)	2
Wood and other vegetable matter	0.5
Asbestos	0

Table 2.9 Particle size distribution in crushed recycled concrete: Base material

AS 1152 Sieve Size (mm)	% Passing by mass target grading	% Passing by mass
26.5	100	100
19.0	100	95-100
9.5	70	59-80
4.75	50	41-60
2.36	37	29-45
1.18	26	20-35
0.600	19	13-27
0.425	16	10-23
0.300	13	8-20
0.150	10	5-14
0.075	8	3-11

Table 2.10 Other acceptance limits in crushed recycled concrete: Base material

Test	Limits	Test method
Los Angeles Abrasion Value	40.0% max	WA 220.1
Liquid Limit (Cone penetrometer)	35.0% max	WA 120.2
Linear Shrinkage	3.0 % max	WA 123.1
Maximum dry compressive strength	1.7 MPa min	WA 140.1
California Bearing Ratio (CBR) (Soaked 4 days) at 98% of MDD and 100% of OMC)	100 % min	WA 141.1
Unconfined compressive strength (UCS-7 days cured and 4 hours immersed)	0.6 MPa to 1.0 MPa	WA 143.1

Note: Suitable for 20 Year design traffic < 5 x 10^6 ESA

Modified Specification 501, released on 10 November 2008, was based on the testing of crushed recycled concrete used for base course pavement in the Perth to Bunbury Highway. The updated limits are shown in Table 2.11 and Table 2.12.

Table 2.11 Updated limit of foreign material crushed recycled concrete: Base material

Material	Maximum % retained by mass on 4.75 mm sieve
High density material (brick, glass, etc)	10%

Table 2.12 Updated "other acceptance limits" in crushed recycled concrete : Base material

Test	Limits	Test method
Maximum dry compressive strength	0.8 MPa min	WA 140.1
Unconfined compressive strength (UCS-7 days cured and 4 hours immersed)	0 MPa to 1.0 MPa	WA 143.1

2.4 Mineralogy

Mineralogical contents determine the shape of individual soil particles and influence their properties, structure and soil mechanics. Gravel, sand, silt, clay are the main particles in the soil. Coarse grained soils gravel and sand mostly consist of siliceous minerals such as quartz, feldspar, hornblende, and mica. In terms of clay, the main minerals are kaolinite, montmorillonite, and illite.

The quartz particles in sand have a low chemical activation due to hardness, well-ordered structure, stability and bulky shape. Due to weathering, they are generally angular, sub-angular, rounded and surrounded. For example, land sand minerals are angular whereas river sand minerals are rounded.

Siliceous minerals have the following structure: amorphous (minerals without a regular structure such as glass, pitchstone, rhyolite and basalt), cryptocrystalline (a complex with a crystalline structure such as tuffs and rhyolites), microcrystalline (fine-grained texture which can easily match crystals such as basalt), crystalline

(containing crystals such as holocrystalline (100% glass) and hypohayline. Quartz, tridymite and cristobalite are three crystalline forms of SiO_2 (Ineson 1990).

The content of sand in soil has a great influence on the mechanical properties of the material such as gradation, compaction, and particle shape. This type of soil is sensitive to moisture content due to the pores between particles. It has high water penetration and a lower consolidation (Flaherty 1974).

Clay minerals are very small, flat or flake-shaped. Clay that is somewhere between massive and fissile is called "bedded". Layered structures also result from layer variations in particle size, e.g. regularly inter-layered silt and clay are common in glacial lakebeds and this is called "varved" clay, which is then termed "stratified."

Kaolinite

The clay mineral, Kaolinite is prolific and very stable, with little tendency for volume change when exposed to water. The kaolinite layers are stickded together to form relatively thick plate-shaped particles. Its composition is that of a silica and one alumina sheet, strongly joined together by hydrogen bonds (Figure 2.12). The plasticity, cohesion, shrinkage and swelling properties of kaolinite are very low when compared with other silicate clays. The caution exchange capacity (the number of milliequivalent (m.e) ions that 100 grams of the soil can adsorb), of a kaolinite mineral is between 5 and 15.

Montmorillonite

Montmorillonite has irregular plate shapes and is fibrous because of the weak bond between its layers. It readily absorbs water between the layers. This mineral has a great tendency for large volume change. The composition is that of an alumina sheet sandwiched between two silica sheets to form a layer (Figure 2.11). Iron or magnesium may replace the alumina in the aluminium sheet. The caution exchange capacity of montmorillonite is between 80 and 100.

Illite

Illite has an irregular plate shape and is more plastic than kaolinite. It does not expand when exposed to water unless a potassium deficiency exists. This clay is most prevalent in marine deposits. The composition is that of an alumina sheet sandwiched between two silica sheets to form a layer. Potassium provides the bond between the layers. The strength of this potassium bond is somewhere between that of a hydrogen bond of kaolinite and the water linkage of montmorillonite, and the result is that the illites have properties that are of an intermediate level between two clay minerals. The caution exchange capacity of the illite mineral is between 15 and 40.

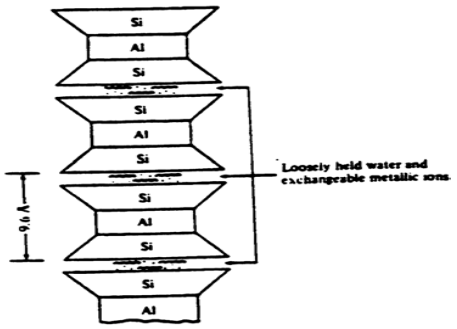


Figure 2.11 Montmorillonite

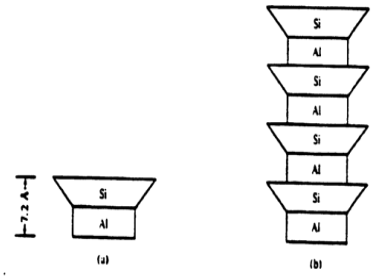


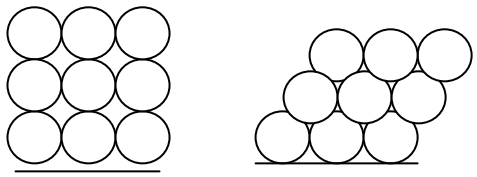
Figure 2.12 Kaolinite

2.5 Soil structure

Soil structure is the form the soil takes, based on its physical and chemical properties; it is the geometric arrangement of soil particles with respect to one another. The process of sedimentation or rock weathering creates the initial soil structure. Among the many factors that affect soil structure are the shape, size, and mineral composition of the soil particles, and the nature and composition of soil water. The basic terminology used to define soil structure is: single-grained, honeycombed, flocculated and/or dispersed with variations, dependent upon the composition of the soil.

Single –grained structure

A single-grained structure is the simplest type of soil, the most general examples being coarse-grained sand and gravel. These materials are non-cohesive and individual mineral particles are not orderly. In single-grained structures, soil particles are in a stable position, with each particle in contact with surrounding particles. For similar sized particles, large variations in the void ratio (defined as the ratio of the volume of void spaces to the volume of solid soil particles), are related to the relative position of the particles. Depending on the void ratio, the single-grained structure has a loose and a dense state as shown in Figure 2.13. The void variation ranges from 0.91 to 0.35. It expresses the density of material and furthermore, shows the physical properties of soil, for example, the smaller the void ratio, the higher the strength and the lower the compressibility and permeability of the soil. The loose state occurs when the soil contains a high void ratio and the dense state occurs when the soil has a low void ratio. Dense soil increases in volume when it is under deformation, while loose soils decrease in volume when deformed by vibration or compaction.



Loose state (a) ***Dense state (b)***

Figure 2.13 A single-grained structure

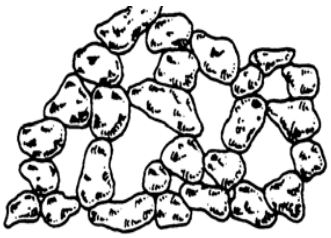


Figure 2.14 A honeycomb structure

Honeycomb structure

Mineral particles in this structure touch each other at a few points as result of intermolecular attraction between grains. The honeycomb structure is found in fine silt and clays. Grains settling slowly in quiet waters or loosely dumped moist soil, can develop a particle to particle contact that bridges relatively large void spaces between aggregates and carries the weight of the overlaying material. Soils that exhibit honeycombed structures (Figure 2.14), have large void ratios and can carry the weight of overlay soils. However, under heavy loads or shock loading, the structure breaks down, resulting in large settlements.

Flocculent structure

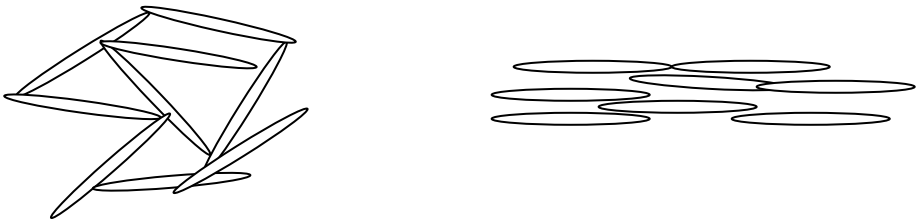
Clay deposits developed from clay particles that have settled out of suspension in a salt or fresh water environment tend toward a "flocculated" structure (Figure 2.9 (a)), whereby the attraction and contact between many of the clay particles is through an edge-to-face arrangement.

Clay deposits with flocculent structures have high void ratios, low density, and high water content. Their structure however, is quite strong and the clay is resistant to external forces because of the attraction between particles. If the environment surrounding the clay is changed, for example, when salts leach out of the deposit (as occurs when ocean deposits are raised above sea level and fresh water penetrates the soil), the attraction and strength between particles can be markedly decreased.

Clays that have been further transported after being deposited (by glacial action, or when used in man-made earth fill) are reworked or remoulded by the transportation process. The remoulded particle structure is more of a parallel arrangement, or orientation of particles, than exists in the flocculent condition. Such a particle arrangement is considered a "dispersed" or oriented structure as can be seen in Figure 2.15 (b).

When used for construction, clays that are in a flocculent condition before use, generally lose strength because of remoulding. Following remoulding, and the passage of time, the strength does increase, though it never returns to the strength of the originally undisturbed clay. The reasons for this partial increase appear to be related to a time-dependent rebuilding from the remoulded dispersed structure, toward a less dispersed, more flocculent structure.

In the dispersed condition, the equilibrium of forces between particles is disturbed. With time, the particles become sufficiently reoriented; only very small movements are necessary to reacquire a structure in which the forces between particles are again in equilibrium. This phenomenon of strength loss and strength gain, with change in volume or water content is called thixotropy.



Flocculated (a) ***Dispersed (b)***

Figure 2.15 Flocculent structure

Soil microstructure constitutes how the individual mineral and rock grains occur in relation to one another, to void spaces, interstitial water and air. Described below are the following soil structure types: single-grained, wedge-block, massive, dispersed massive and layered.

Single-Grained Structure: (e.g. clean sands and gravels). Individual grains are touching at points of contact. No cementation occurs, but through the capillary attraction of water, cementation is transient and disappears on wetting or thoroughly drying. Clean silt and sand-silt mixtures such as loam with very little clay also exhibit a single-grained structure, being easily pulverised by hand or by slaking (i.e. disintegrating under water).

Wedge-Block Structure: This occurs if clay is present in sufficient quantities to bond the silt grains, sand and gravel into a stronger structure, e.g. in clay capping of low-volume municipal roads. Clay grains occur as oriented coatings on larger grains and they concentrate into wedge-shaped rings or bridges at the grain's contact points. Wedging action leads to low tensile strength as the grains are readily plucked apart. However shearing strength is high because of the difficulty in sliding the wedges. Shearing strength is at a maximum with 9% to 14% clay. If the amount of clay is 15%, the wedge-block structure disappears and the sand or silt grains become separated and "float" in a matrix of clay.

Massive Structures: If 25% to 30% clay is present to form a matrix enclosing coarser grains, the structure of the clay dictates the structural behaviour of the soil. Normally clay particles are "flocculated" or held together by electrostatic attractions arising from electrical surface charges. The edge of one particle is attracted to the face of another resulting in a "house of cards" structure. Flocculation is very sensitive to the type and amount of water available and the salts in solution. Water erodes flocculated clay by dispersing it, separating and diluting the grains and keeping them agitated.

Dispersed Massive Structure: When ionic attraction forces between clay particles lessen because of the leaching of soluble salts or disruption by chemical remoulding or erosion by water, the clay may become "dispersed".

- Quick clays - Natural clays that become dispersed by agitation. They are usually marine clays with a flocculent structure that has become unstable, as the soluble salt has gradually leached out.

- Sensitive clays ("thixotropic clays") - This type of clay experience a temporary partial dispersion when it is remoulded or reworked by hand or machine.

Layered Structures:
"Preferred Orientation" of clay mineral grains is formed as result of the direction in layering, usually a plane of weakness (due to long consolidation under pressure). Extreme "Preferred Orientation" in some shales means that they are "fissile" or easily split.

2.6 Rehydrating reaction

Research into the rehydration reaction and the rehydration process (at low temperatures), of aged concrete material in cement paste has been limited. Information on the rehydration process followed by the dehydration process in concrete materials at high temperatures between 200-800^0 C, is also scarce.

Cement in concrete, as the primary binder material, consists of four main compounds: C_3S ($3CaO\ SiO_2$), C_2S ($2CaO\ SiO_2$), C_3A ($3CaO\ Al_2O_3$), C_4AF ($4CaO\ Al_2O_3Fe_2O_3$). When cement is mixed with water, these compounds react with the water and produce the C-H-H gel and $Ca(OH)_2$, a process named hydration reaction. As a result of the hydration reaction, the cement paste becomes firm and hardens.

A rehydration reaction is a recovery of the compounds found in the initial hydration process. Basically, the dehydration of the C-S-H, CaO and non-crystal phases is a fundamental condition of the rehydration process.

Shui et al. (2008) showed that continuously heating the hardened cement paste of fine recycled concrete aggregate to 800^oC, results in the cement paste losing free and bound water (dehydration) in the main crystalline phases, C-S-H gel, larnite C_2S, CH, ettringite, $CaCO_3$ and calcium oxide CaO. When mixed with water again, these phases CaO and CH slowly form a CH solution that provides a reformation of the dehydrated C-S-H gel and ettringite by rehydration. Through rehydration, initial hydration products are rejuvenated and commence building a hardened cement paste, resulting in improved compressive strength of the material. Nonetheless, the reformed microstructure of the rehydrated cement paste is weaker than ordinary cement paste and contains more capillary pores (Alonso 2004).

Alonso reviewed the rehydration process of dehydrated cement phases in temperature values between $20\text{-}750^0$ C, as can be seen in Figure 2.16. Under these conditions, the rehydration of the C-H-S results in nesosilicate, which is new formation phase of C-S-H at 750^0 C. Larnite is unaltered but CaO would be present in the rehydration process of the C-S-H. Ettringite is rehydrated (Alonso 2004).

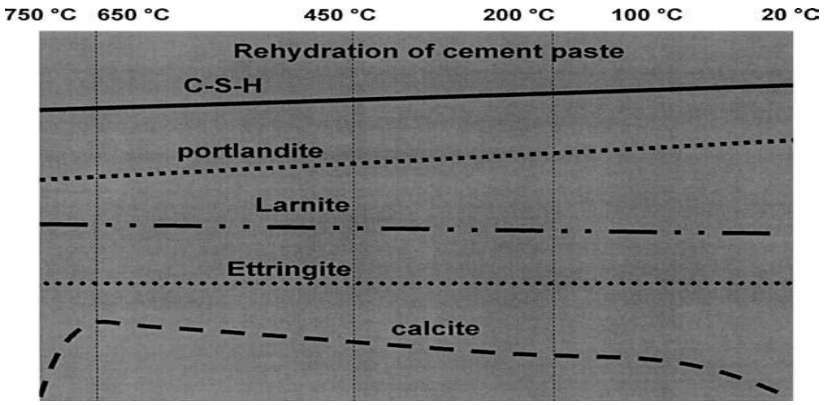


Figure 2.16 The rehydration of dehydrated cement paste phases after exposure to high temperatures (Alonso C. 2004)

2.7 The resilient modulus

The resilient modulus test is conducted to determine the elastic properties of pavement material and is one of the main input parameters for the design of pavements. It is demonstrated as the ration of deviator stress applied to the pavement layers and the resilient axial deformation recovered after release of the deviator stress. In fact, it is an estimation of the material modulus of elasticity (E) under quickly applied loads (Transportation 2003).

Mathematically, the resilient modulus, M_r , has been defined as:

$$M_r \text{ (or } E_r) = \frac{\sigma_d}{\varepsilon_r} \qquad (2\text{-}5)$$

where : M_R = resilient modulus

E_R = elastic modulus

σ_D = stress (applied load/ cross sectional area)

ε_r = recoverable axial strain

As indicated in Equation 2-5, the larger the recoverable deformation, the smaller the resilient modulus (poor sub-grade).

The resilient modulus can be determined by several types of models, Moossazadeh and Witczak (1981), Hunlap (1963), Seed et al. (1967), May and Witchaz (1981) and

Uzan (1985). Among these models, the most popular one is generally called the K-Θ model. It assumes that the resilient modulus can be related to the sum of principal stresses Θ according to the :

$$M_R = k_1 \Theta^{k_2} \qquad (2\text{-}6)$$

where k_1 and k_2 are regression parameters

$\Theta = \sigma_d + 2\sigma_3$

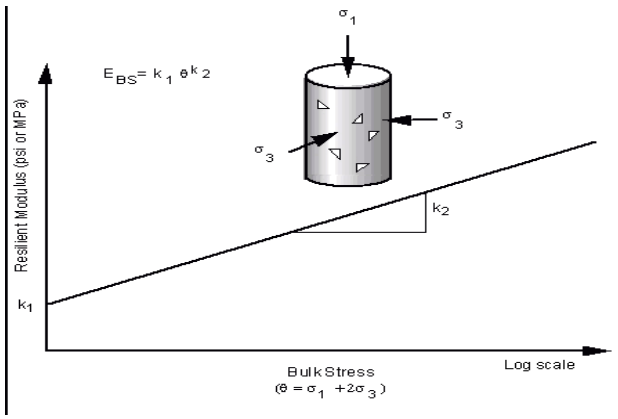
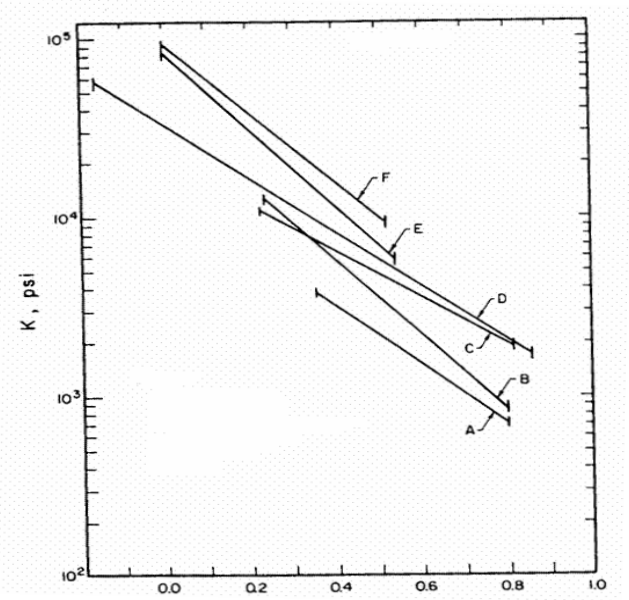


Figure 2.17 Resilient modulus vs bulk stress for unstabilised coarse grained materials

(Kim and Labuz, 2007), (Alam, Abdelrahman and a.Schram 2009)

Figure 2.18 shows an increase in M_R with bulk stress for coarse material.



F: Sl A: Silty Sands

B: Sand Gravels

C: Sand Aggregate Blends

D: Crushed Stone

E: Limerock

Figure 2.18 An increase in M_R with bulk stress for coarse material

From an analysis of site data, May and Witczak (1981) concluded that the resilient modulus not only related to the sum of the principal stresses but also to shear strain levels. Uzan (1985), suggested the following relationship and shear strain influence:

$$M_r = k_1\Theta^{k}{}_2\sigma_d{}^{k}{}_4 \qquad (2\text{-}7)$$

where k_1k_2 and k_4 are regression parameters and σ_d is the deviator stress.

Moossazaden and Witczah (1981) proposed the following relationship for the demonstration of the resilient modulus :

$$M_r = k_1 \left(\frac{\sigma_d}{p_a}\right)^{k}{}_2 \qquad (2\text{-}8)$$

Where k_1 (y-intercept) and k_2 (slope of the line) are coefficients from a linear regression analysis and p_a is a reference pressure.

Dunlap (1963) suggests the following correlation:

$$M_r = k_1 \left(\frac{\sigma_3}{p_a}\right)^{k}{}_2 \qquad (2\text{-}9)$$

Where k_1 and k_2 are regression coefficients and σ_3 is the confining stress. Deviator stress influence is not covered in this correlation.

Seed et al (1967) present the resilient modulus depend on the principal stresses

$$M_r = k_1 \left(\frac{\sigma_{sum}}{p_a}\right)^{k}{}_2 \qquad (2\text{-}10)$$

where $\sigma_{sum} = \sigma_1 + \sigma_2 + \sigma_3$ or $\sigma_1 + 2\sigma_3$

Equation 2-7 and 2-8 do not consider the effect of shear stress on the resilient modulus of material.

May and Witzchan (1981) and Uzan (1985) present a model that considers the effects of shear stress and confining stress and deviator stress.

$$M_r = k_1 \left(\frac{\sigma_{sum}}{p_a}\right)^{k_2} \left(\frac{\sigma_d}{p_a}\right)^{k_3} \qquad (2\text{-}11)$$

Vuong's model (David 2007) was developed in 2005. This model can help to predict the resilient modulus of granular material at a given depth (H) and stress level.

$$M_r = k_1 \text{ x } \left(\frac{\sigma_m}{Pa} + 1\right)^{k_2} \text{ x } \left(\frac{\tau}{Pa} + 1\right)^{k_3} \qquad (2\text{-}12)$$

where: M_r = resilient modulus (MPa)

σ_m = mean normal stress at depth H (MPa) = $(\sigma_1 + 2\sigma_3)/3$

τ = octahedral shear stress at depth H = $(\sqrt{2})(\sigma_1 - \sigma_3)/3$

Pa = reference stress (atmospheric pressure 100 kPa)

- k_1 = initial resilient modulus (at zero stress)

k_2 = exponent of mean stress factor

k_3 = exponent for shear stress factor

According to the Washington State Department of Transportation (2003), the resilient modulus ranges for base materials are 137.2-240.6MPa and for sub-grade materials 47.6-260.6MPa.

The main influencing factors for M_R are: deviator stress, confining pressure, water content and dry density, method of compaction, thixotropy, and freeze-thaw cycles.

According to Yoder and Witczak (Yoder 1975), for fine-graded soil, the M_R decreases as the deviator stress increases, until it reaches constant values, when it then starts to increase slightly with the increased deviator stress. Additionally, in

cases of granular material, both the confining pressure and the deviator stress have significant effects on M_R.

Lee et al. (Kim Daehyeon 2007) found that the different confining pressure influences for the resilient modulus are significant for cohesive sub-grades. Furthermore, the water content in a sub-grade has a strong influence on the decreasing of M_R. However, for granular sub-grades, the water content remotely influences M_R.

In 1993 the AASHTO Guide (Transportation 2003), used an empirical equation to demonstrate the relationship between the material characteristics of CBR and the M_R.

$$M_R = 2555 \text{ x } CBR^{0.64} \qquad (2\text{-}13)$$

2.8 The permanent deformation

Permanent (plastic) deformation occurs in pavements under repetitive traffic loading; the number of load cycles is therefore an important factor in considering any analysis of the plastic deformation of pavement materials. This deformation is irreversible. The concentration of the deformation at excessive rutting during cycle-loading leads to the failure of the pavement. In other words, the permanent deformation parameter predicts the development of rutting in the granular base course (Perez 2006).

Several researchers have presented permanent deformation modules depending on the number of loading cycles and stress levels as shown in Table 2.3 (Perez 2006).

Table 2.13 Permanent deformation models

Model Equation	Model Name	Parameters
Models linking permanent deformation to the number of the loading cycles		
$\varepsilon_p^1(\%) = A \times N^B$	Sweere model	*A, B* *N= number of the loading*
$\varepsilon_p^1(\%) = (m \times N + A)(1-e^{-B \times N})$	Wolff and Visser model	*A, B, m*
$\varepsilon_p^1(\%)=A \times N^B+C$	Paute et al. model	*A, B, C*
$\varepsilon_p^1(\%) = A \times [1-(\frac{N}{100})^{-B}]$		*A, B*
Models linking permanent deformation to stress		
$A = \frac{\frac{q}{(p+p*)}}{a-b\frac{q}{p+p*}}$	Paute et al. model	*A, a , b, p^* = s/m, where $q = m\ p + s$ is the failure equation of the material*
$\frac{\varepsilon_{1p(N_{ref})}}{(L/p_0)}=a \times (\frac{q}{p})^b_{max}$	Lekarp model	*a ,b, N_{ref}, $L= (q^2 + p^2)^{0.5}$, $p_o = 100\ kPa$*

Sweere suggested that with the large number of load repetitions (10^6), a log-log approach should be applied. The results are expressed in the equation in Table 2.13. However, for up to 1.2 million load reputations, the Sweere model failed to give reliable estimates of permanent strain. The Wolff and Visser model suggested an improved stress-strain model, as the experiment results showed that in the first stage of the load repetitions, the permanent strain increased rapidly and then moved slowly to the next stage. Finally, the rate increased at a constant value.

Paute et al. showed, in a model linking permanent deformation to the number of the loading cycles, the accumulated strain after an initial period of 100 cycles. Thus, in a model linking permanent deformation to stress, he defined a limit value for the maximum permanent axial strain that varies with the maximum shear stress ration. In this equation, A increases when the maximum shear stress increases (Lekarp 1998).

As the deformation of granular materials is highly stress-dependent, recent model development has been based mainly on the shakedown concept, according to which the shakedown concept, applied to the permanent deformation behaviour of unbound material, can be divided into three stages: below plastic shakedown limit, below plastic creep limit, and below static failure, as seen in Figure 2. 19.

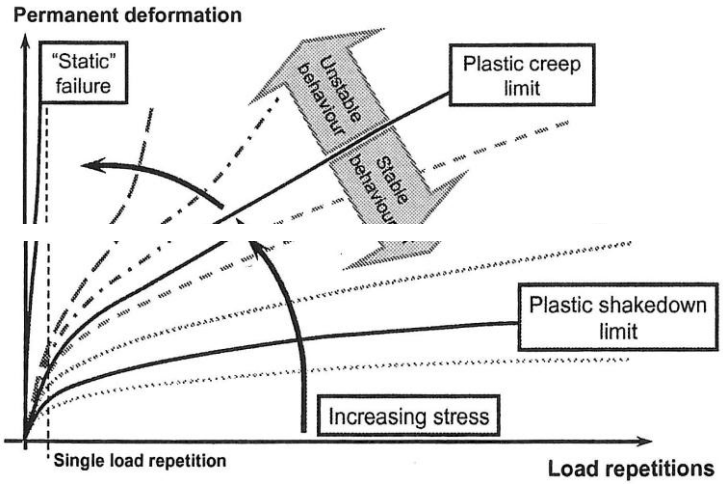


Figure 2.19 The Shakedown Theory applied to the permanent deformation behaviour of unbound granular material

(Theyse et al.2007)

Below the plastic shakedown limit, the incremental plastic strain per load cycle decreases with increasing numbers of load cycles until finally approaching zero. Between the plastic shakedown and the plastic creep limits, the incremental plastic strain approaches a constant value at high load repetitions. Above the plastic creep limit, the incremental plastic strain increases with the number of loading cycles, resulting in incremental failure of the material and the exponential increase of plastic deformations. The shakedown theory was developed from triaxial test results (Theyse 2007).

The characteristics of the material (particle size distribution, particle size and shape, content of fines content, degree of compaction), structural factors (the number of load repetitions, the geometry of the structure), environmental conditions, and loading factors affect permanent deformation.

Hoff, Freidrikson, and Lekarp state that maximum grain size provides an ability to withstand deformation.

Kolisajia, states that the content of fine particle size influences the material's deformation properties (Korkiala-Tanttu 2009). He also determined the relationship between the degree of compaction and permanent deformation. He observed that the growth of the degree of compaction follows the rate of permanent deformation.

Odermatt et al. showed that material types influence permanent deformation and that crushed rock material needs more compaction than natural gravel, which has a low deformation ability.

2.9 Environmental effects on pavement behaviour

One of the main factors that influence pavement deterioration is climate, including temperature and rainfall changes.

In cold climates, the temperature drops in winter and rises in spring. As a consequence large temperature variations affect the failure of pavement systems. During winter, an ice lens, consisting of ice crystals, is initially formed, originating in the base and sub-grade and resulting in increased stiffness of the unbound layers as well as the bituminous layers. In contrast, in spring, these ice lenses melt and the pavement system saturates. Under these conditions, if the pavement has heavy traffic loading, significant settlements can occur. Technically, this action under temperature change is termed 'frost action'.

According to Yoder, soil frost susceptibility, air, soil temperature and sources of water are important factors in frost action. All organic soils that contain more than 3 % by weight of particles finer than 0.02 mm are frost susceptible. A soil with a high capillary potential can produce ice lenses more easily.

Simonsen states that freeze-thaw cycles at temperature change in cold countries, influence the mechanical properties of pavement, such as shear strength, resilient

modulus, permeability, and consistency limit. In fine grained materials, the resilient modulus decreases by 50-60% due to freeze-thaw (Simonsen Erik 1999).

Wang mentions that snow removal from pavement in winter is of concern in cold region countries. Traditionally, de-icing chemical salts have been used for melting snow in countries such as the USA and China. However, this method has a negative impact on pavements, including concrete corrosion and environmental pollution. The hydronic snow-melting system, where heated pipes are installed and spaced small distances apart in horizontal and inclined pavements, prevents the pavement's material properties from the attacks of chemical de-icing (Wang Huajun 2010).

Asaeda has pointed out that in hot weather, a pavement easily absorbs heat during the day and loses it to the atmosphere at night. This process influences the air temperature, increasing it in urban thermal environments (Asaeda Takashi 2000).

The influence of climate change on pavement behaviour is one of the main topics of current research on road infrastructure.

The influence of climate change on road systems is both direct and indirect. Direct influences include rainfall, temperature change, and water content, and there is a loss of surface waterproofing as the pavement deteriorates. Indirect influences include population growth and activity, altering the demand for roads.

In Australia, the climate influence index on pavement deterioration is classified by the 'Thornthwaite moisture index' in the Pavement Lifecycle Costing Model (PLCM) and the Highway Development and Management 4 (HDM4) model.
This index is calculated based on the statistical data of parameters including rainfall, climate temperature, evapotranspiration, and length of daylight hours in the area. According to the Thornthwaite moisture index, higher values indicate fast road deterioration while lower values indicate slower road deterioration. The roads in warmer and wetter areas deteriorate more easily than roads in other areas. Additionally, it affects the growth of the Thornthwaite moisture index. In the case of Australia, this index value is higher in the South-West of Western Australia, North-

East Victoria, and Southern NSW than in south-western Tasmania and the top end of Queensland, where the Thornthwaite moisture index value is lower.

2.10 Models and failure criteria

Failure criteria determine the stresses which the structure has to withstand from maximum load levels. Two failure criteria are considered in Figure 2.20; the tensile strain at the bottom of the asphalt layer and the spare compressive strain at the top of the sub-grade layer that damages pavement durability. If the pavement surface has cracked 20% and has ruts to a depth of 20 mm, the pavement is considered to have failed.

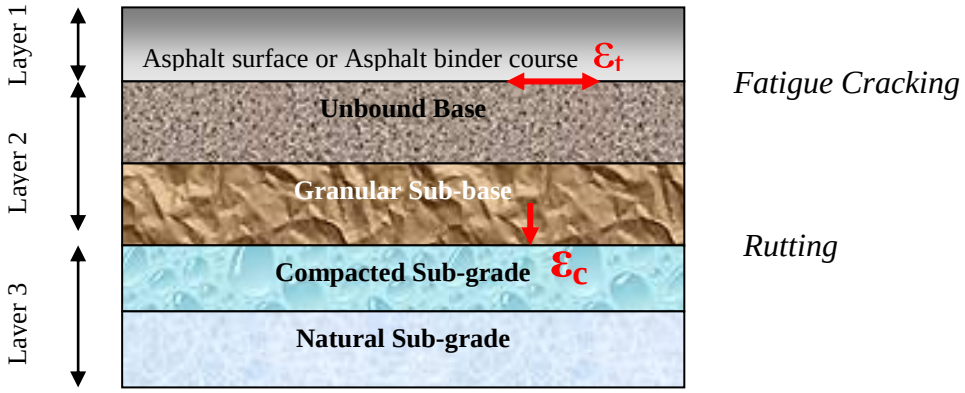


Figure 2.20 Fatigue cracking and Rutting

One accepted failure criterion for fatigue cracking over 10% of the wheel path area, developed by Finn et al. (1977) is:

$$\log N_f = 15.947 - 3.2911 \log\left(\frac{\varepsilon_t}{10^{-6}}\right) - 0.854 \log\left(\frac{E_{AC}}{10^3}\right) \qquad (2\text{-}13)$$

where: N_f = number of cycles to failure

ε_t = horizontal tensile strain at the bottom of the HMA layers

E_{AC} = elastic modulus of the HMA

The fatigue cracking model is

$$N_f = k_3 \left[\frac{1}{\varepsilon_t}\right]^{k_1} \left[\frac{1}{E}\right]^{k_2} \qquad (2\text{-}14)$$

where: N_f = number of cumulative Standard axles to produce a 20% cracked surface area

ε_t = tensile strain at the bottom of the bituminous layers

E = elastic modulus of the bituminous surface (MPa)

k_1 k_2 = laboratory calibrated parameters

k_3 = transfer parameter

Another fatigue cracking model is expected by the elastic modulus of the bituminous surface and the tensile strain at the bottom of the bituminous layer:

$$N_f = 2.21 \times 10^{-4} \left[\frac{1}{\varepsilon_t}\right]^{3.39} \left[\frac{1}{E}\right]^{0.854} \quad (2\text{-}15)$$

N_f = number of cumulative Standard axles to produce a 20% cracked surface area

ε_t = tensile strain at the bottom of bituminous layers

E = the elastic modulus of the bituminous surface (MPa)

Rutting failure criterion is more complicated to predict than cracking criteria. Rutting occurs from depressions in wheel paths creating a weak pavement structure. The vertical compressive strain (ε_v) at the top of the sub-grade layer is the main characteristic of the failure criteria.

$$N_f = 1.077 \times 10^{18} \left(\frac{10^{-6}}{\varepsilon_v}\right)^{4.4843} \quad (2\text{-}16)$$

where: N_f = number of cycles to failure

ε_v = vertical compressive strain at the top of the sub-grade layer

$$N_R = k_5 \left(\frac{1}{\varepsilon_c}\right)^{k}{}_4 \quad (2\text{-}17)$$

N_R = number of repetitions to rutting failure

ε_c = vertical sub-grade strain

k_4 k_5 = calibrated parameters

$$N_R = 4.156 \times 10^{-8} \left(\frac{1}{\varepsilon_c}\right)^{4.5337} \quad (2\text{-}18)$$

N_R = number of cumulative Standard axles to produce 20 mm rutting

ε_c = vertical sub-grade strain

Deflection, the linear change of the dimension criteria, was developed in the AASHO Road Test and Roads in 1962 and by the Transportation Association of Canada (RTAC) based on the deflections which occurred in spring weather conditions (Transportation 2003).

An AASHO deflection criterion is:

$$\log W_{2.5} = 9.40 + 1.32 \log L_1 - 3.25 \log d_{sn} \quad (2\text{-}19)$$

where: $W_{2.5}$= number of applications of the axle load L_1 sustained by the pavement to a terminal serviceability index of 2.5

L_1= single axle load (kips)

d_{sn} = Benkelman Beam springtime measured pavement surface deflection (0.001in) measured at the AASHO Road Test after 'disappearance of frost'

The RTAS criteria is:

$$BB = 10^{[0.40824 - 0.30103(\log ESAL)]} \quad (2\text{-}20)$$

where: BB= maximum rebound deflection at a standard temperature of 21^0C

ESAL = 80kN (1800lb) single axle loads

The following Table 2.14 shows the limiting deflection for both criteria:

Table 2.14 Limiting Deflections

Loads to Failure	Limiting spring deflection (in)	
	AASHO Road Test	RTAS
10,000	0.148	0.100
100,000	0.072	0.080
1,000,000	0.036	0.040
10,000,000	0.018	0.020

Tom and Krishna (2007), determined the fatigue cracking modulus by the number of load repetitions of cracking though the tensile strain at the bottom of the binder layer and the elasticity module (Krishna 2007).

$$N_f = f_1 (\in_t)^{-f_2} \text{ x } (E)^{-f_3} \qquad (2\text{-}21)$$

where, N_f is the number of load repetitions for a certain percentage of cracking, $\in_t$ is the tensile strain at the bottom of the binder course, E is the modulus of elasticity, and f_1, f_2, f_3 are constants.

Wardle and Bruce showed that pavement damage caused from cracking and rutting failure, is calculated by employing mechanical design method failure criteria or 'performance relationships', and expressed in the following equation (Wardle 1998):

$$N = \left[\frac{k}{\varepsilon}\right]^b \qquad (2\text{-}22)$$

where: N = predicted life (repetitions)

k = material constant

b = damage exponent of the material

ε = load-induced strain

CHAPTER 3

RESEARCH METHODOLOGY AND EXPERIMENTAL PROGRAM

3.1 Overview

This chapter reports on the research methodology and experimental programs used in the present study. The main objective was to evaluate the possibility of using Washed and Crushed Concrete Waste (WCCW) and Construction and Demolition (C&D) waste as a material for road bases. The research plan was designed to facilitate laboratory work and can be seen in Figure 3.1.

To achieve this objective, the research methodology and the experimental programs were divided in two parts:

- **Part 1** –Undestanding the Laboratory Characteristics of WCCW and C&D material.
- **Part 2**- Undestanding the suitability of WCCW and C&D material for Road base and sub base..

When the methodology and experimental programs of each part were finalised, test results were gathered and analysed and then used in the design for the construction of road bases.

This chapter describes the test methods, apparatus, and test procedures of each part of the research in detail. Tests were conducted in the Geomechanics Laboratory, at the Department of Civil Engineering, Curtin University, Perth, Western Australia. Details of the type, sources, and sampling of the testing materials are presented.

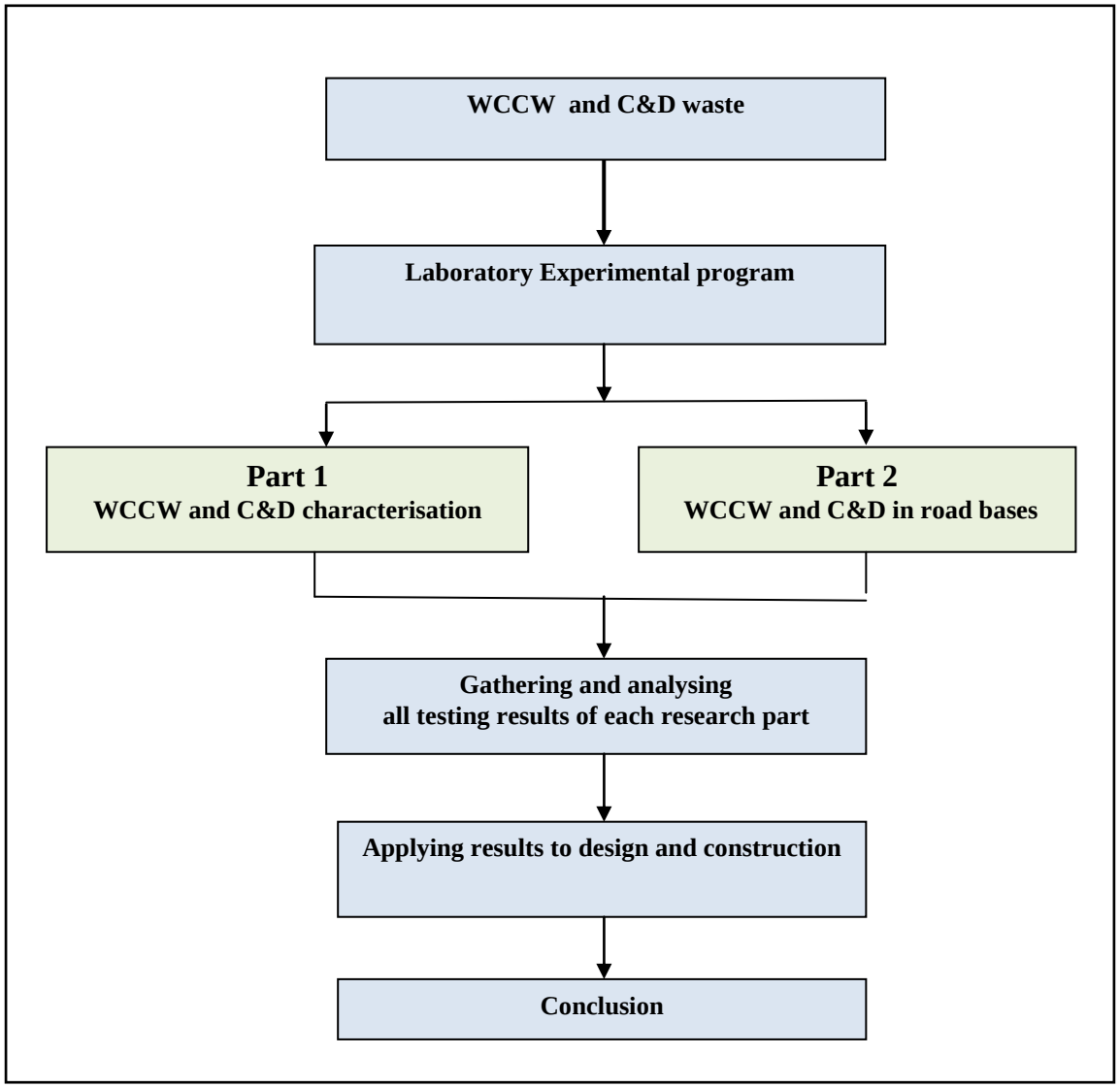


Figure 3.1 Overall research plan of the study

3.2 Experimental materials

The study involved two types of recycled crushed concrete waste in Western Australia: Construction and Demolition (C&D) waste and washed and crushed concrete waste (WCCW).

Construction and Demolition materials (C&D)

In this study, Construction and Demolition materials were collected from three producers of recycled material operating in the Perth Metropolitan Area, Western Australia: All Earth, C&D Recycling, and Capital Demolition and Earthworks.The main activities of these companies are: collecting construction and demolition waste from construction and earth-working companies, separating these into categories and producing recycled products for clean fill, road bases, and drainage aggregates.

A general description of the step undertaken by the Recycling companies to produce recycled material is illustrated in five steps described in Figure 3.2.

Step 1. C&D waste is collected from clients and taken to a recycling area

Step 2. Timber, paper, steel, and green waste are removed

Step 3. Crushing

Step 4. Screening

Step 5 Receiving uniform aggregate and recycled rubble material

Figure 3.2 The C&D waste producing process

Washed and Crushed Concrete Waste (WCCW)

Washed and crushed concrete waste from the ready mixed batching plants of Holcim (WA) Pty Ltd. was collected from a limestone quarry at Postans in WA for use in this study.

Approximately 30,000 tons of washed and crushed concrete waste are produced annually. Currently, there is a stockpile of over 80,000 cubic metres of unused washed and crushed concrete waste, an amount that is increasing every year.

WCCW is produced by the following procedures shown in Figures 3.3 and 3.4. Generally, the WCCW is collected from concrete mixer drums after washing with water at a batching plant. It is common practice in the ready-mixed concrete industry to thoroughly clean the inside of truck drums at the end of each day. The concrete trucks are cleaned with water and the resulting residue is placed in a wash pit. When the concrete residue settles, the water is removed. Finally, the settled waste is removed from the wash pit and transferred to a limestone quarry at Postans where it is put into a two-step mobile crusher to create the final washed and crushed concrete waste.

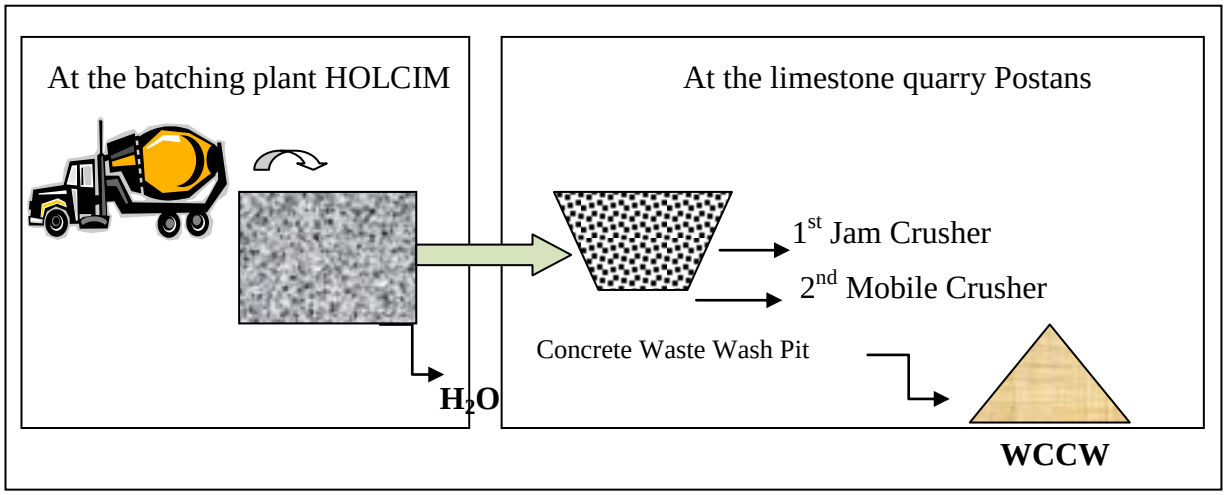


Figure 3.3 Schematic diagram of the WCCW production process

15 to 20kg WCCW samples from various storage piles (see step 4, Figure 3.4) were randomly sampled by the plant manager at Postans quarry. Approximately 100 samples were delivered to the Geotechnical Laboratory at Curtin University. The C&D waste from three companies was also delivered to the laboratory. Samples were kept in lidded plastic buckets in the laboratory area during the experimental process.

3.3 Part 1: WCCW and C&D waste characteristics

In this part, the geotechnical characteristics of both materials were investigated. The geotechnical characteristics of construction material are significant in evaluating structural qualities and performance and these have to be determined with regard to the possibility of their use. Figure 3.5 shows the methodology of WCCW and C&D Recycling characteristics.

Step 1. Concrete mixer truck

Step 2. Wash pit with concrete waste at Holcim

Step 3. Concrete waste crushing and the Postans quarry

Step 4. Ready-made WCCW at screening process at Postans quarry

Figure 3.4 The WCCW production process

The following series of laboratory tests were carried out to determine characteristics in accordance with Australian Standard Methods of testing soils for engineering purposes - AS 1289 (Australian Standard 2000) as follows:

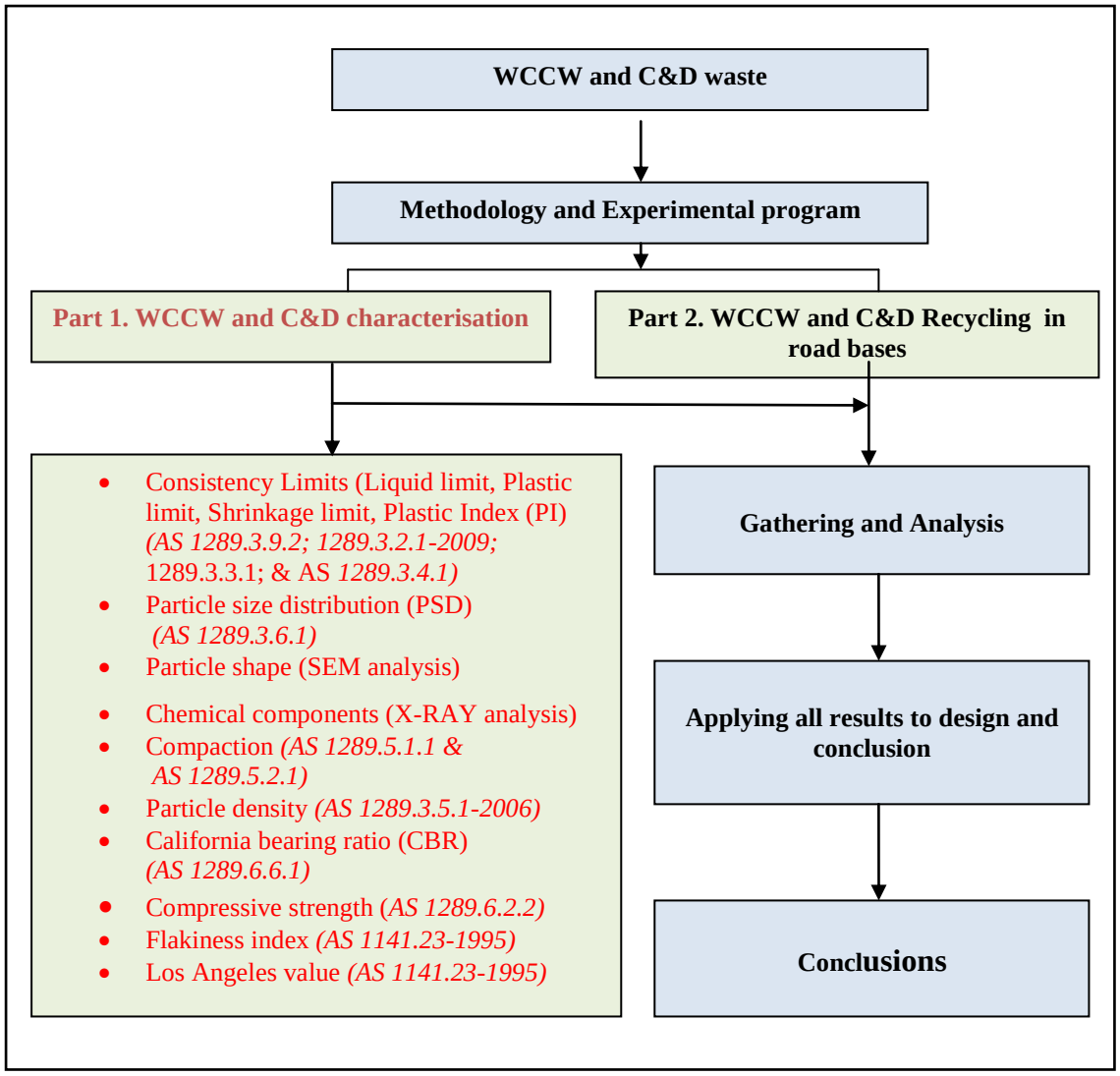


Figure 3.5 The methodology of WCCW and C&D waste characteristics

- Consistency Limits (Liquid limit, Plastic limit, Shrinkage limit, Plastic Index (PI) *(AS 1289.3.9.2; 1289.3.2.1-2009;* 1289.3.3.1; & AS *1289.3.4.1)*
- Particle size distribution (PSD) *(AS 1289.3.6.1)*
- Particle shape (SEM analysis)
- Chemical components (X-RAY analysis)
- Compaction *(AS 1289.5.1.1 & AS 1289.5.2.1)*
- Specific gravity *(AS 1289.6.7.2)*
- California bearing ratio (CBR) *(AS 1289.6.6.1)*
- Compressive strength (*AS 1289.6.2.2)*
- Flakiness index *(AS 1141.23-1995)*
- Los Angeles value *(AS 1141.23-1995)*

3.3.1 Consistency limits

The consistency limits test is a soil classification test provided under Australian Standard AS 12893.9.2-2006 to determine soil behaviour dependent on water content as shown in Figure 3.6. Depending upon its water content, a cohesive soil can be in four states: solid, semi-solid, plastic and liquid. The water content limits at the boundaries between the states are named respectively: liquid, plastic and shrinkage.

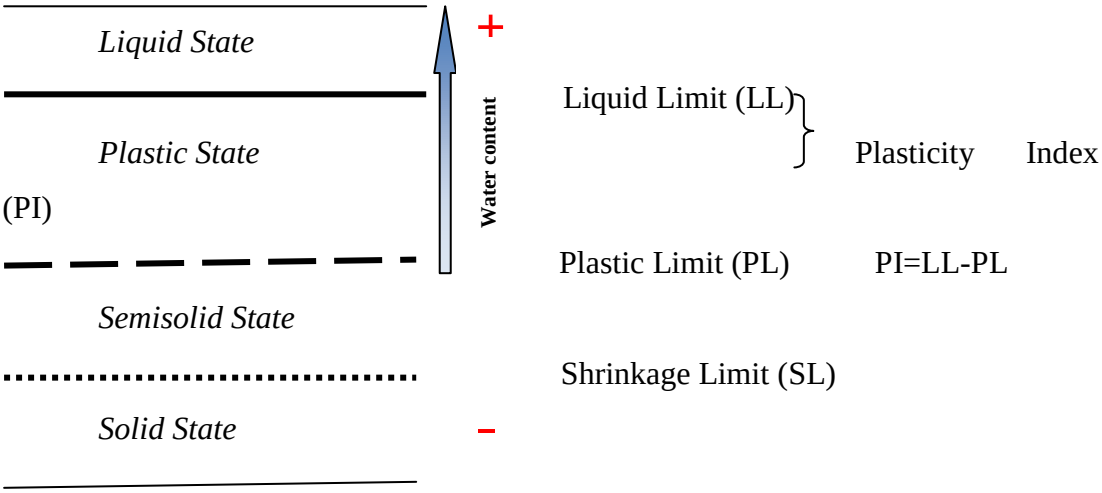


Figure 3.6 Consistency limits

These limits are determined by standard test procedures.

Liquid limit

The liquid limits of C&D Recycling and WCCW were determined by using a cone penetrometer one-point method, in accordance with the Australian Standard-AS 1289.3.9.2-2006 (Australian Standard 2006).

The liquid limit (LL) is the threshold at which material tranforms from a plastic to a liquid state. Moreover, it defines the moisture content at which a soil will become liquid and flow under its own weight, but the LL is only applied to a fine fraction of

the sample. In this study, a total of 70 samples of construction demolition and recycled crushed concrete were analysed for liquid limits.

In accordance with the standards, samples of approximately 100g of WCCW and C&D waste were passed through a 425μm sieve without any additional preparation. Between15mm and 25mm of distilled water was added to correlate to the penetration of the cone penetrometer. A pallette knife was used to fill the cup to capacity with part of the mixed material and it was then levelled and smoothed over. Finally, the cup with the material was installed under the cone with its tip touching the surface of the material in the cup (shown in Figure 3.7). It was released for 5±1 s and the dial gauge reading noted. The process was repeated until two tests came within the range of 15mm to 25 mm of cone penetration. The readings were within 0.5mm of each other. The material from the cup was removed and the moisture content was recorded (in accordance with AS 1289.2.1.1 specifications).

Figure 3.7 Cone penetrometer

Plastic limit

The plastic limits of C&D waste and WCCW were determined in accordance with Australian Standard-AS 1289.3.2.1-2009 (Australian Standard 2006).

The plastic limit (PL) is the threshold at which the material transforms from a semi-solid state to a plastic state. It contains less water than in its liquid limit state. The main aim of this experimental work was to determine the moisture content of the granular material when exhibiting homogeneous and plastic behaviour respectively and after being mixed with distilled water. A test was conducted in accordance with AS 1289.3.2.1-2009. The apparatus selected consisted of: a mixing bowl, a glass plate for rolling the material and a container (see Figure 3.8) and an oven heated to 105-110^{0}C .

Figure 3.8 Tools for testing soil plastic limit characteristics

A sample of about 40g was obtained from the test material which was passed through a 425μm sieve. The sample was mixed thoroughly with water in the mixing bowl. Water was added incrementally and mixed well until the material became a homogenous paste that was plastic enough to be shaped into a ball. The paste was covered and allowed to cure for at least 12 hours at room temperature. About 8g of the soil mixture was then taken and moulded by hand into a ball. The ball was rolled into threads of approximately 3mm until the point at which they crumbled. If the soil thread crumbled before the diameter reached 3mm, more water was added and remixed and the thread was rolled again. If the soil thread reached 3mm in diameter

without crumbling, a small amount of soil was added and remixed and the thread was rolled again. The procedure was performed until the thread crumbled at 3mm in diameter. More threads were rolled until they crumbled at 3mm in diameter and the moisture content of these threads was determined. The Plastic limit was determined to be the amount of moisture content existing in a thread of 3mm in diameter, at the crumbling stage. If it was impossible to prepare a rolled sample by adding extra water, the material would be recorded as 'non-plastic material'.

Plasticity Index (PI)

The plasticity indexes of C&D waste and WCCW were determined in accordance with Australian Standard-AS 1289.3.9.2-2006 (Australian Standard 2006). The plastic limit of the material is determined by the difference between the liquid limit (LL) and the plastic limit (PL). This test was conducted in accordance with AS standard 1289.3.3.1-2009 and can be shown by the following equation:

$$I_P=W_L-W_P \qquad (3\text{-}1)$$

where

I_P = plasticity index , as a percentage

W_L= liquid limit, as a percentage

W_P = plastic limit, as a percentage

Material groups ranging from low plasticity to extremely high plasticity, according to the plasticity index, depend on the properties of granular materials. However, material could be PI=0 in conditions $W_L=W_P$ or $W_L<W_P$ and non-plastic in conditions when neither or only one of the W_L and W_P can be determined.

Shrinkage Limit

The shrinkage limit index determines the water content which could influence volume change in the material. Tests were conducted in accordance with AS 1289.3.4.1-2008 for both materials.

A brief account of the procedure of this test is as follows: a sample was put into a shrinkage mould of 250mm internal length, and with an internal diameter of 25mm.

The initial length of the sample was measured directly and dried under different conditions: (a) 25 hours at room temperature and (b) in an oven at 105^0C to 110^0C) until shrinkage ceased. The final length of the sample was then measured and the shrinkage limit was calculated using the following equation:

$$LS= (L_S/L) x100 \qquad (3\text{-}2)$$

where

LS = linear shrinkage of the sample

L_S = longitudinal shrinkage of the sample in millimetres

L = length of the mould in millimetres

The experiment tools used in this test are shown in Figure 3.9.

Figure 3.9 Mould for testing soil shrinkage limit

3.3.2 Particle size distribution (PDS)

The particle size distributions of C&D waste and WCCW were investigated using a sieve analysis test as per standard AS 1289.3.6.1 (Australian Standard 1995). According to this test, it is possible to use sieves of dimensions between 63mm and 75µm, depending on the grain size of the material. The grain sizes used in this study were 19mm, 13.2mm, 9.5mm, 6.7mm, 4.75mm, 2.36mm, 2.36mm, 1.18mm, 600 µm, 425 µm, 300 µm, 150 µm and 75 µm.

Figure 3.10 Particle sieves and the sieve shaker machines

Small amounts from 3000g of materials were washed through the 75µm (micrometer) sieve. This process involved the addition of water, then agitating and washing the contents in the sieve until the water became clear. Most of the finer materials (less than 75µm) were washed through. The coarser parts of the material (larger than 75µm) were collected and then placed in an oven at 105^0C to dry overnight. The oven-dried cooled material was put into a set of sieves. Two types of sieve were used: one for coarse particles of of 19mm to 2.36mm and one for finer particles of 2.36mm to 75µm. The sets of sieves were placed in a mechanical sieve shaker, as shown in Figure 3.10, for approxmately 15 minutes. The remaining mass of particles in each sieve were weighed and determined. The grain-size distribution curves for the results of the test were plotted on a PSD sheet as shown in Figure 3.11.

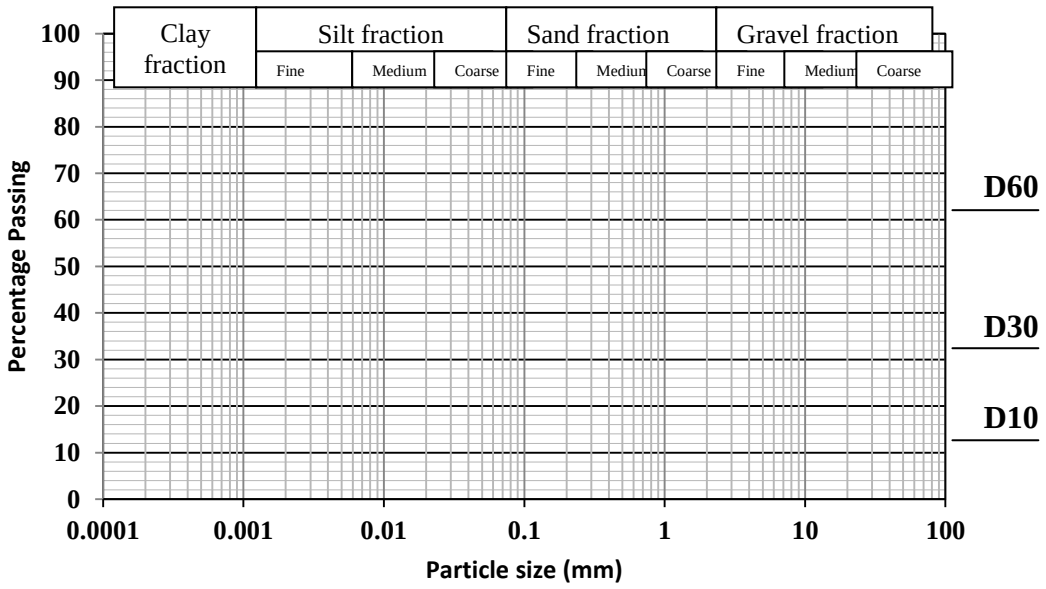


Figure 3.11 Particle size distribution sheet

Based on the PSD testing, coefficients of uniformity and curvature were determined in order to classify the soil material. These characteristics were obtained using the following equations:

$$C_u = D_{60}/D_{10} \quad \text{and} \quad C_c = (D_{30})^2/D_{60}D_{10} \qquad (3\text{-}3)$$

In total, 97 C&D Recycling samples and 10 WCCW samples were analysed for particle size distribution.

3.3.3 Particle shape and surface texture (SEM analysis)

The particle shape and surface texture of WCCW samples[3] were examined at the Centre for Material Research (CMR) in the Department of Physics, Curtin University by using Scanning Electron Microscope (SEM) analysis. A modern optical microscope, which has a digital camera, the Ziess Evo 40 XVP was used. The microscope has the significant advantage of digital image capture, allowing data

[3] But not the C&D samples.

transfer and the added convenience of further analysis by using image processing software installed on the microscope's computer. Before scanning with the electron microscope, samples were mounted on slubs, using carbon paint and gold coating to make them conductive. During SEM analysis, the X-Ray spectrums were determined, that is the elemental composition of the sample. X-Ray images were produced which mapped where particular elements occurred on the surface of the sample.

3.3.4 Chemical components (X-Ray analysis)

To determine the mineral and chemical components of WCCW, quantitative phase analysis was performed at Curtin's X-Ray Analytical Science Laboratory in the Department of Imaging and Applied Physics. The sample was ground using a mortar and pestle and then mounted in a standard steel sample holder. The XRD pattern was collected on D8 Advance with a Lynx Eye detector using Cu-radiation over a two-theta angular range of 7.5 - 80° at 1s/0.02°. The measured diffraction pattern was interpreted using PDF Database Sets 1-52, Jade 6.0 and EVA search/match software. The presence of the chemical elements H, C, Mg, Ca, Fe, Al, Si and O were assumed at commencement and used for searching and matching.

3.3.5 Modified Compaction

Compaction is a significant process that removes air content from a soil. The increase in soil density improves soil properties through increased shear strength and decreased settlement and permability. Compaction is an effective and cheap way to improve the properties of a soil.

Two methods of compaction are used for engineering purposes: the standard and the modified compaction test. In this study, tests were performed in accordance with AS 1289.5.2.1 (1998) (Australian Standard 2003). As pavement sub-base is subjected to

very heavy loading, modified compactive effort is used to find maximum dry density and optimum moisture content.

The aggregates used in this study were a maximum size of 19 mm. A mould and a hammer were the main tools used, as shown in Figure 3.12. The mould was 105mm in diameter and 115.5mm in height.The hammer had a 50mm diameter and a weight of 4.9kg. The material was placed in a mould in 5 layers and each layer was compacted 25 times by the hammer falling from a height of 450mm. At this time, the delivering compaction effort was 21.62 joules per impact.

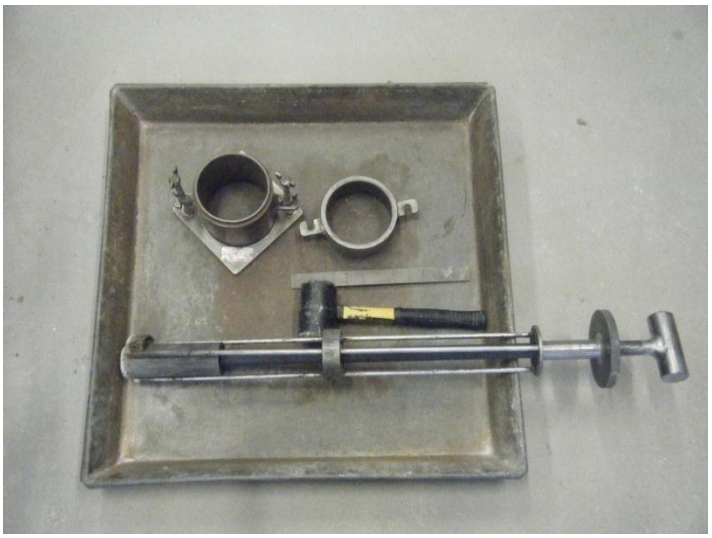


Figure 3.12 Tools for testing soil compaction properties

The test process involved the following steps: the material was mixed with water up to four times and the samples prepared in 5 layers for compaction. A sample was weighed, put into a container, weighed again and placed in an oven at a temperature of 105-110^{0}C for around 24 hours. The sample was weighed after oven-drying and the dry density was calculated. The plot curve illustrates the correlation between the material's maximum dry density and the added water content. The procedure was repeated, increasing the water content several times.

3.3.6 Particle density

The particle density test was performed in accordance with Australian Standard 1289.3.5.1 (Australian Standard 2006). The test for WCCW was conducted by using a density bottle for the fine fraction of material and by weighing it in water for material particles retained on a 2.36mm sieve. Standard preparation was used. Before determining the soil particle density, the densities of material passing through and retained in the 2.36mm sieve were examined to ensure they conformed to the standard.

To determine the particle density of WCCW passing through the 2.36mm sieve, the material was completely washed with water, then soaked for about 24 hours in a bottle filled with water. The material was then removed from the bottle and dried in an oven at 105^0C to 110^0C. During the test procedures, the mass of both the empty bottles and the bottles with material and water were recorded. Based on the measurements of mass, the particle density was determined using a standard equation.

Of the WCCW that remained on the 2.36mm sieve, subsamples were prepared from the retained particles. The material was washed and immersed in water at room temperature for 24 hours. It was then placed into a wire basket and immersed in water until the mass had been measured. This was followed by oven drying at 105^0C to 110^0C and the mass determined after cooling. Based on the measurements of mass, particle density was determined using a standard equation.

Finally, the particle density of the total material was determined based on the particle density measurements of the WCCW passing through and retained in the 2.36mm sieve.

3.3.7 The California Bearing Ratio (CBR)

Construction demolition and washed and crushed concrete samples were subjected to the CBR test procedure in accordance with AS 1289.6.1.1 (Australian Standard 1998) for unsoaked and soaked methods.

The aim of the CBR test is to determine the strength of materials used in road construction. This method, founded around 1930 at the California Division of Highways has become the most widely used test method in geotechnical engineering around the world. The index obtained from the experiment is used in the calculation of the thicknesses of flexible pavements.

A total of 30 samples were analysed in this research to obtain the California Bearing Ratio. The apparatus consisted of: a cylindrical metal compaction mould with an internal diameter of 152mm and a height of 178mm, a metal collar and a plate containing holes, a loading compression machine, displacement measuring devices, dual gauges with an accuracy of 0.01mm, a modified compaction hammer, mixing bowl, scales, soaking container, and an oven, as illustrated in Figure 3.13.

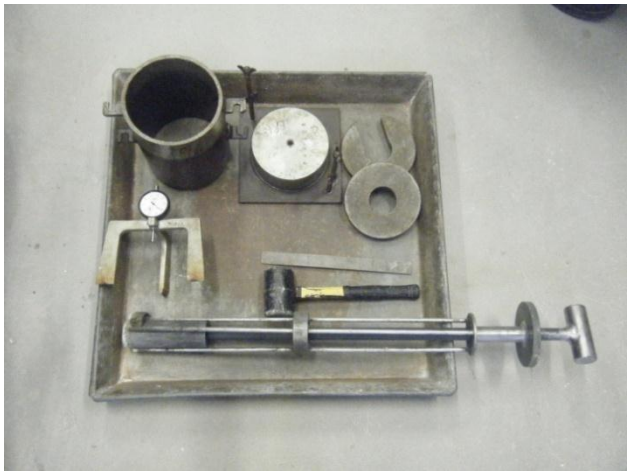


Figure 3.13 Tools for testing soil CBR

Before conducting the test, the MDD and OMC were examined in accordance with the procedure prescribed in AS 1289. These indexes were used in the compaction process. The prepared material was compacted in the experiment mould. Material was compacted at 95% MDD and 100% OMC in five layers in a modified compaction effort. The following method was used for both materials.

After the preparation of two samples, one was placed in a container of water and soaked for 4 days, the swell was measured and the penetration test was conducted.The unsoaked sample was placed in the compression machine for the penetration test. The sample's displacement was measured by the penetration of the piston in the displacement measuring device. The force measuring device measured the applied load during the penetration tests at 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 7.5, 10.0 and 12.5 sec, and the load from the force measuring device was noted as seen in Figure 3.14. Finally, the moisture content was determined in each sample.

Figure 3.14 The soaked CBR setup in the soaking container

The load penetration curve was plotted by using the load on the piston and penetration. The bearing ratios for loads at penetrations of 2.5mm and 5mm were calculated by the following equations:

$$\text{CBR= Load (kN) at 2.5mm x } 100/13.2 \qquad (3\text{-}4)$$

$$\text{CBR= Load (kN) at 5.0 mm x } 100/19.8 \qquad (3\text{-}5)$$

According to the Washington Department of Transportation (WSDOT), in the case of high-quality crushed stone material, the CBR is 100%. In other sources of material such as coarse grained soils, the CBR maximum is 80%.

Figure 3.15 The penetration test at the compression machine

3.3.8 Flakiness Index

Only the WCCW material flakiness index was determined in accordance with test method WA 216.1. The flakiness index represents the percentage of particles with the least dimensions that is, less than three-fifths of the mean dimension.

The main stage of this test was to determine particle size distribution, and after sieving, to keep the 26.5-19.0mm, 19.0-13.2mm, 13.2-9.50mm, 9.50-6.70mm and 6.70-4.75mm sieve fractions separate. Materials over 26.5 mm and those that passed through the 4.75 mm sieve were excluded from the test. Each sieve fraction was passed separately through the appropriate slot by hand and then the particle mass passing through the appropriate slot for each of the sieve fractions was measured.

3.3.9 Los Angeles value test

This test was conducted under standard AS 1141.23-1995 using WCCW material. The test, using a Los Angeles Abrasion testing machine as shown in Figure 3.17**,** determines mass loss of the aggregate particles on abrasion.

The test material, prepared from WCCW, contained a combination of the aggregate fractions which remained in sieves. The fractions measured from 19.0mm to 13.2 mm, 13.2mm to 9.5mm, and 9.5mm to 4.7mm. The desired mass for the first two fractions cited was 2500g and for the last fraction 5000g. Fractions were prepared via the following steps: sieving to obtain the appropriate fractions, washing to remove clay particles and dust, drying and cooling, loading the material and allocating abrasion balls in the Los Angeles abrasion testing machine.

According to the standard, fractions from 19.0mm - 13.2mm and 13.2mm - 9.5mm need 11 steel balls with a 5000g mass. For 9.5mm - 4.75mm, 7 steel balls with a 5000g mass are needed. After the material and the balls were put into the machine, the revolution counter was set to 500. On completion, the material and balls were removed from the drum and the material split from the steel balls. After separation, the material was put through a 1.70mm sieve and weighed and the material that passed through was retained.

Figure 3.16 The Los Angeles machine and steel balls

The material that was coarser than 1.70mm was washed and oven-dried at 105^0C to 110^0C for minimum period of 16 hours. The Los Angeles value can be calculated using the following equation:

$$\text{Los Angeles} = \frac{m_t - m_w}{m_t} \text{ x } 100 \qquad (3\text{-}6)$$

where : m_t – total mass in grams of the washed and dried material before abrasion

m_w – mass of material in grams retained on the 1.70mm sieve after abrasion, washing, drying and re-sieving.

3.4 Part 2: WCCW and C&D Recycling for road bases

3.4.1 Outline

The research methodology, as shown in Figure 3.17, can be divided into two parts. The first part was the mechanical stabilisation of WCCW. Based on particle content, the particle re-grading process was investigated. The objective of this part was to establish the particle content in the range of road-base material specifications for Western Australia with the aim of improving its material properties. WCCW stabilisation is explained in section 3.4.2.

In the second part, the bulk of the laboratory work involved testing the original and re-graded WCCW and C&D waste in i) a repeat load triaxial apparatus to determine the resilient modulus and permanent deformation characteristics and ii) a conventional triaxial apparatus to determine the strength characteristics. The results were compared with conventional material to evaluate their suitability. The commonly used base course material, crushed rock, which satisfied Western Australia Main Roads specifications, was used as a reference material.

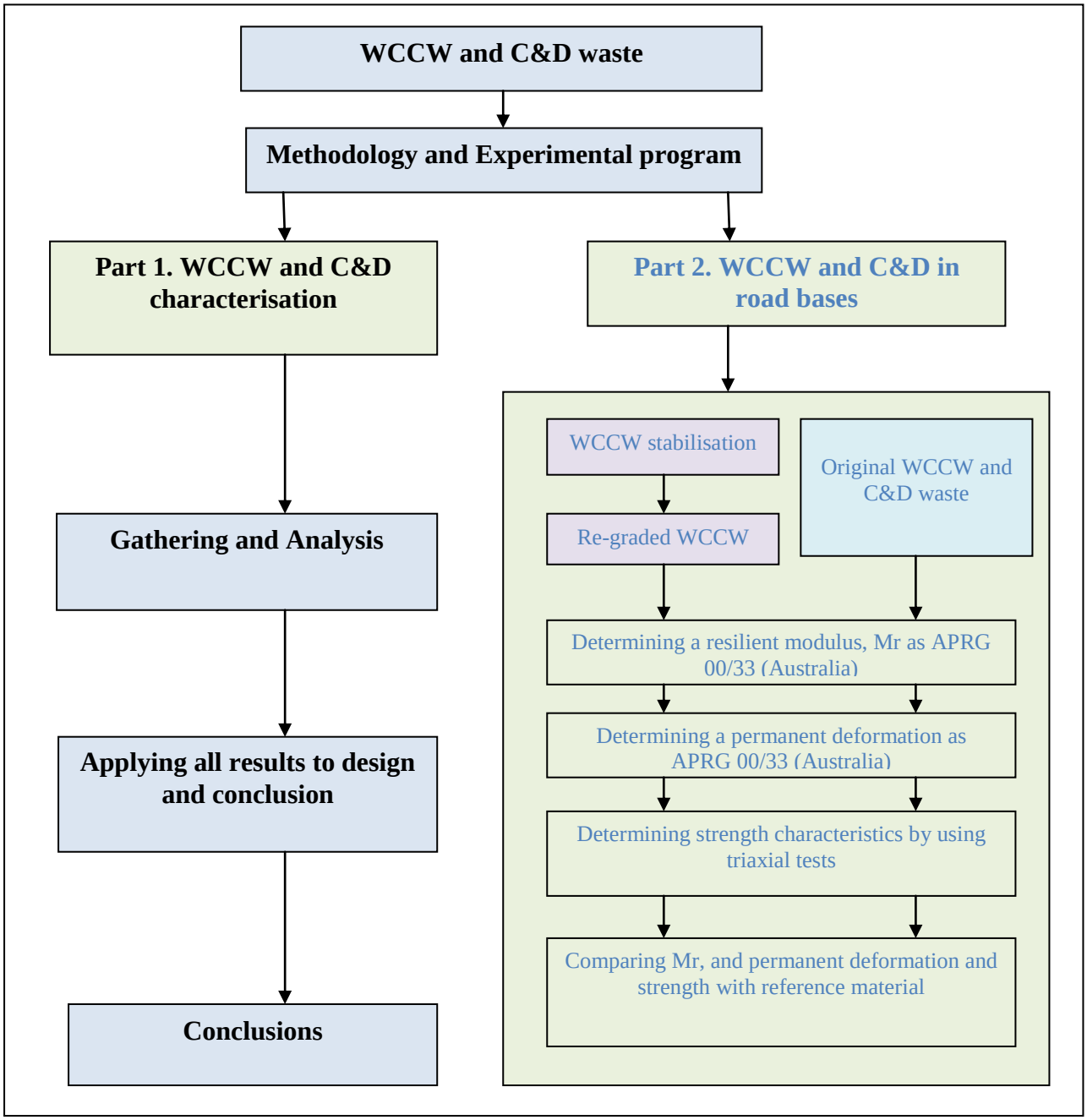


Figure 3.17 The methodology of WCCW and C&D Recycling for road bases

3.4.2 Stabilization of WCCW (Re-grading process)

According to the particle size distribution results for the WCCW material, the amount of sand-sized fraction[4] is higher than the coarser fraction. After compaction, the fine fraction increased significantly, a content change that should have a negative

[4] The sand –sized fraction is between 1180mm and 37.5mm.

influence on the performance properties of a pavement. To improve performance properties, mechanical stabilisation was provided in this study.

In terms of the washed and crushed concrete waste, mechanical stabilisation was provided, based on the re-grading process of the original WCCW which resulted in renewed particle content of the material. The experimental plan is illustrated in Figure 3.18

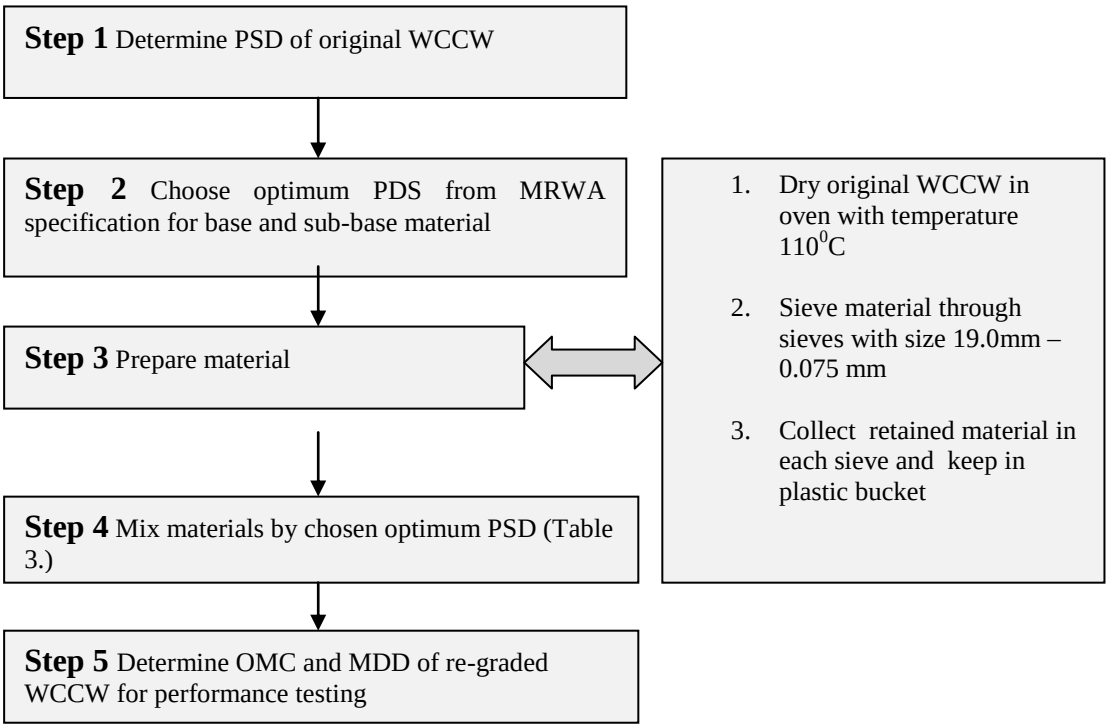


Figure 3.18 Experimental plan for the stabilisation of WCCW

Before stabilisation, the particle size distribution of the WCCW was determined before and after compaction. Based on the results from the stabilisation method, it was decided to use re-graded particles. This involved modifying the particle size distribution from that of the original material. The particle size distribution curve of re-graded WCCW would then fall within the range of the road-base material specifications for Western Australia (as per the allowed specification area in Figure 3.19). The desired re-graded WCCW curve is illustrated below by a red dotted line. The particle size distribution required for re-graded WCCW is shown in Table 3.1.

For material preparation, firstly the original WCCW was sieved on 19.0mm,13.2 mm, 9.5mm, 6.7mm, 4.75mm, 2.36mm, 1.18mm, 600µm, 420µm, 300µm, 150µm and 75µm meshes and the retained particles on the sieve kept in plastic buckets, as shown in Figure 3.20. Particles were then selected, as shown in column 2 in Table 3.2, and mixed with an automatic mixer. After mixing, OMC and MDD parameters were examined in the re-graded WCCW, for the purpose of performance testing.

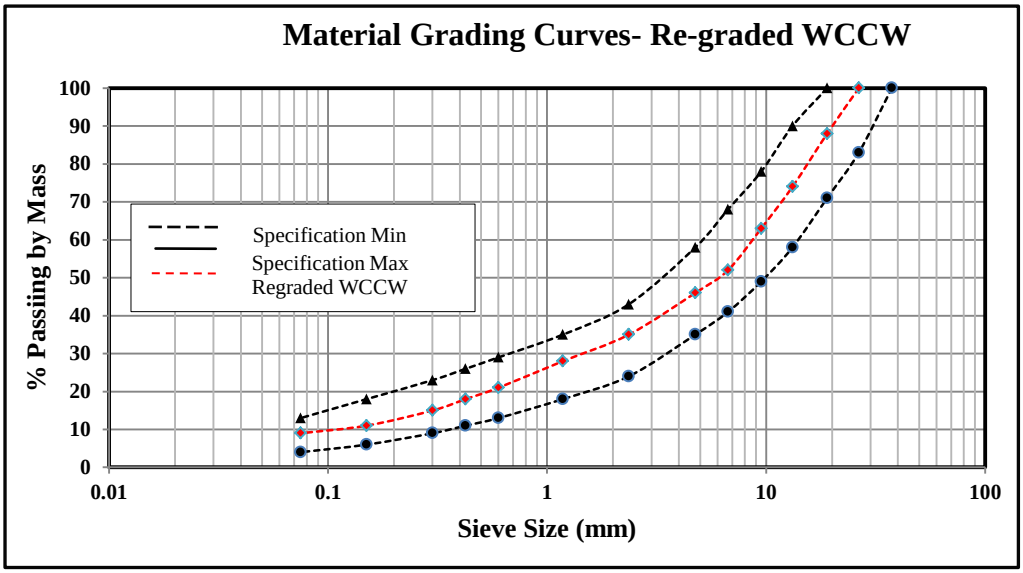


Figure 3.19 Chosen particles content curves

Figure 3.20 Sieved and retained WCCW in plastic buckets

Illustrations of the particle content of original and re-graded WCCW are shown in Figure 3.21.

Table 3.1 Target grading proportions of WCCW

Particle Size Distribution		**Target Retained,% (1)**	**Target Passing,% (2)**
Test Method	**MRWA:115.1**		
Specification	**Due to plot**		
Sieve Size (mm)	**Passing,%**		
19.0	72-100	12	88
13.2		14	74
9.5	50-78	11	63
6.7		11	52
4.75	36-58	6	46
2.36	25-44	11	35
1.18	18-35	7	28
0.600	13-28	7	21
0.425	11-25	3	18
0.300	9-22	5	13
0.150	6-17	2	11
0.075	4-13	2	9

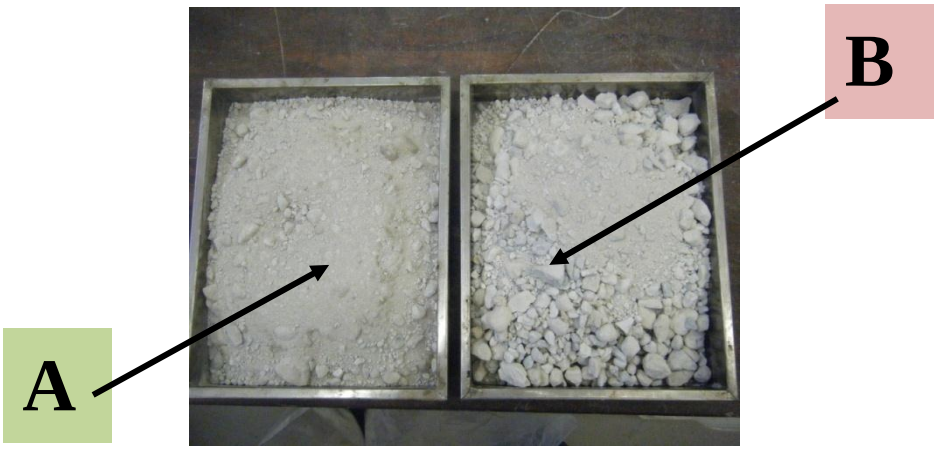


Figure 3.21 (A) Original material grade (WCCW) and

(B) Re-graded material (WCCW)l

3.4.3 Performance testing on original and re-graded WCCW and C&D waste

Laboratory work in this stage involved testing original and re-graded WCCW and C&D Recycling in a repeat load triaxial apparatus, to determine their resilient modulus, permanent deformation, and shear parameters, compared to the characteristics of conventional road-base materials used in Western Australia.

In this study, two main laboratory performance tests were selected:

1. A one-dimensional repeat load triaxial test (RLT) test to determine the resilient modulus and permanent deformation under repeated loading
2. A static triaxial shear (STS) test to determine shear strength (stress at failure).

Sample preparation

Experimental materials comprising original and re-graded WCCW and C&D Recycling were firstly oven-dried at 110 ^{0}C for 24 hours to control the accurancy of their dry mass. They were then allowed to cool before being mixed with the appropriate optimum water content. The mixing procedure consisted of adding water with an optimum water content percentage, based upon the dry mass of the nominated materials. The samples were then compacted using a modified compaction method in a standard mould of 100mm in diameter and 200mm in height. Compaction was achieved with 25 blows of a 4.9kg hammer at a 450mm height drop to form 8 layers. To ensure a good bond between the layers, each layer had to be scored to a depth of 6mm before the next layer was compacted. After compacting, the weight of each sample and mould was determined and the sample was removed from the mould.

The samples prepared from the original WCCW for the unified compressive strength tests, were wrapped in plastic to prevent loss of moisture and then stored at room temperature conditions for a 7-day curing period.

The permanent deformation, resilient modulus and shear parameters of WCCW were tested on samples at 100% OMC and MDD. The relationship between the modulus

and normal stress for the C&D Recycling materials was tested on samples at 60% and 80 % OMC with 100% MDD.

In order to access the potential changes of the modulus over time, material from All Earth was chosen for resilient modulus testing at 60% OMC over a period of 1, 7 and 28 days curing time at room temperature. To prevent loss of moisture, samples for this test were wrapped in plastic directly after removal from the mould.

3.4.4 The resilient modulus

The standard method of Austroads APRG 00/33-2000 (Voung and Brimble, 2000) for the repeat load triaxial test was followed for resilient modulus testing and permanent deformation testing. The UTM-14P digital servo control testing machine, which has an ability to conduct both resilient modulus testing and permanent deformation testing, was used in the Geomechanics Laboratory, in the Deparment of Civil Engineering, Curtin University of Technology. Figure 3.23 shows the apparatus used to perform the tests.

The samples used in the resilient modulus test were prepared in the same way as the triaxial test, with a standard mould, 100mm diameter and 200mm in height. The height to diameter ratio was 2 and 2.5, as can be seen in Figure 3.23.

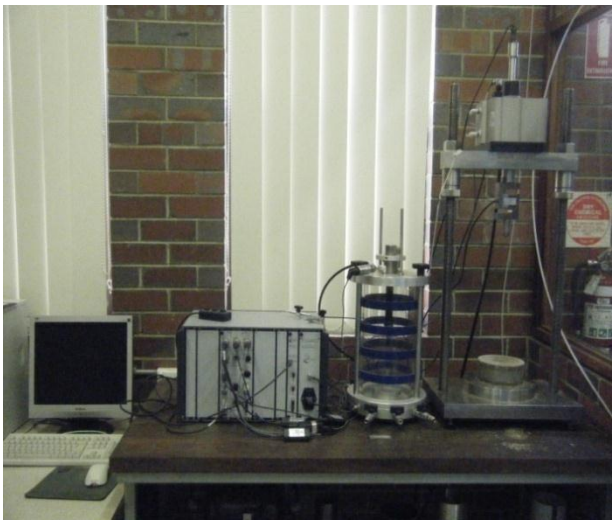


Figure 3.22 Triaxial test apparatus in the laboratory

Figure 3.23 The triaxial chamber with a rubber membrane covering the cylindrical sample

The samples were placed within the triaxial cell and positioned between the base plate and crosshead of the testing machine. The dynamic axial stress came from a feedback controlled high-pressure air actuator, capable of accurately applying stress pulses following the acting stress of the standard. Confining pressure was generated by a closed loop controlled actuator, to simulate lateral pressure acting on the surrounding materials, as would occur on a road. Confining pressure was applied by air pressure. The machine conveyed a vertical dynamic force in a rectangular waveform over a time period of 3 seconds and a load pulse of 1 second in duration, in accordance with the standard requirements (shown in Figure 3.27).

The load cell, confining pressure, and external linear variable differential transducer (LVDT) were placed on the top of the triaxial cell. This was used to measure deformations over the entire length of the sample, by a control and data acquisition system (CDAS) which provided control signals, signal conditioning, and data acquisition. The CDAS communicated with a computer which provided interfacing with the testing software and stored the raw test data. This enabled the resultant stress and strain in the sample to be determined.

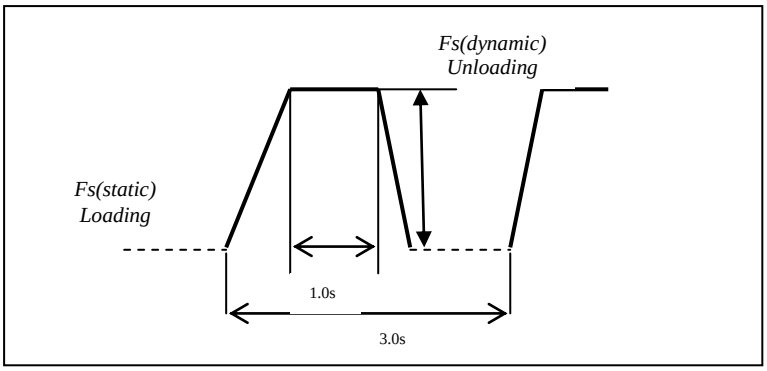


Figure 3.24 Illustration of the vertical force waveform

Following this standard, the samples were used sequentially in a series of 65 stress stages (Figure 3.25) to check the elastic condition of each one throughout multiple loading stress stages. Before performing the resilient modulus process, a pre-conditioning stage was carried out to allow the end caps to bed into the specimen and to allow applied stresses and resilient strains to stabilise under the imposed stress conditions. 1000 loading cycles of pre-conditioning were used and for each stress stage after pre-conditioning, 200 loading cycles were applied to the samples.

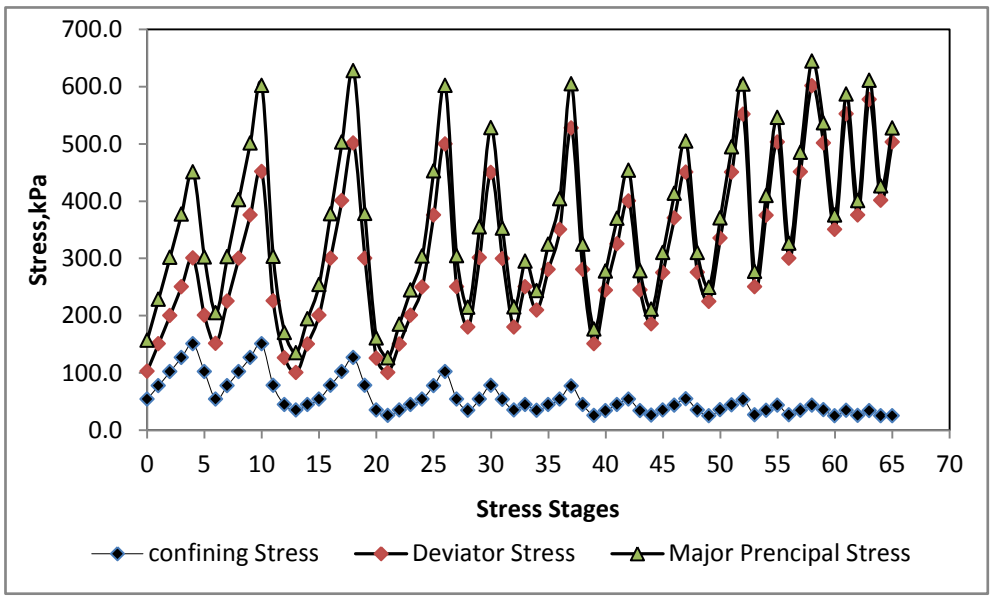


Figure 3.25 Applied stresses and stress stages of the resilient modulus test

3.4.5 Permanent deformation

This test was used to determine the permanent strain of the material depending on different stress values. New samples were prepared, following the same method used for the resilient modulus samples described in the sample preparation item. Permanent deformation testing was calculated in accordance with the Austroads - APRG 00/33 standard. Specimens were loaded in three stress stages, each involving 10,000 cycles (Figure 3.26) at a stress condition of specified repeated deviator stress and static confining stress as shown in Table 3.2.

Table 3.2 Stress levels for permanent deformation of base materials

Permanent deformation stress levels		
Stress Stage Number	**Base**	
	Confinning pressure, σ_3 (kPa)	**Cyclic deviatore stress,σ_d (kPa)**
1	50	350
2	50	450
3	50	550

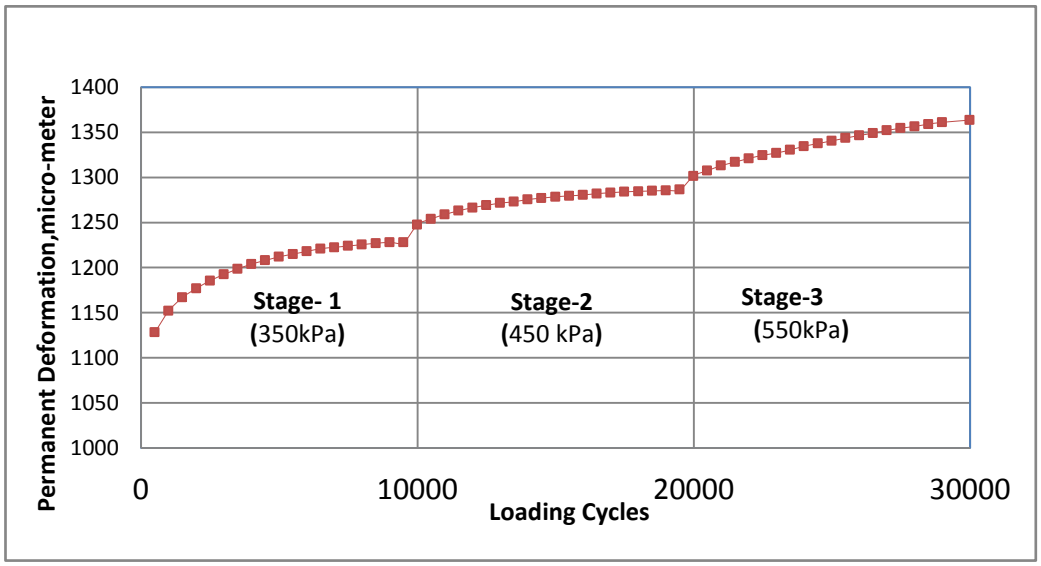


Figure 3.26 Permanent deformation in stress stage levels and loading cycles

3.4.6 The Static Triaxial Shear (STS) Test

The objective of the static triaxial shear test (STS) is to determine the shear strength parameters (cohesion c and internal friction φ) of a cylindrical soil sample covered by rubber membranes, by plotting Mohr circles and investigating the stress-strain relationship in selected stress conditions. Generally, it is a compressive test using confining lateral pressure in the dedicated triaxial test apparatus.

Research materials in this study were investigated using triaxial tests in accordance with AS 1289.6.4.1(Australian Standard 1998). The UTM-14P digital servo control testing machine which has the ability to conduct triaxial testing, resilient modulus testing and permanent deformation testing, was used in the Geomechanics Laboratory, in the Deparment of Civil Engineering, Curin University of Technology, as shown in Figures 3.22 and 3.23.

There are three types of triaxial tests used, depending on the following drainage conditions: unconsolidated undrained (UU), consolidated undrained (CU), and consolidated drained (CD). In this study, the consolidated undrained method was

chosen for the determination of shear parameters of washed and crushed concrete materials (WCCW).

In the test, horizontal stresses were kept constant, whilst vertical stress was increased at a rapid rate to produce failure. The horizontal stresses or confining stresses were 40kPa, 80kPa, and 120kPa. Generally, the stress and strain curve resulting from this test may not fully represent those strains occuring at a single failure wheel load in the field. However, the test identifies the maximum stress limit (failure limits or shear strength) that the material can sustain, beyond which the stress state cannot exist in the material.

In the consolidated drained (CU) test, the drainage valve was opened during the consolidation process of the sample in the chamber with confining pressure, and closed when axial stress occurred.

The triaxial test on material in the CU condition was conducted in accordance with AS 1289.6.4.1 (Australian Standard 1998). The triaxial chamber, significant in the testing process, is shown in Figures 3.22 and 3.23. As shown in Figure 3.23, the triaxial chamber consists of a loading piston, a loading cap which induces vertical stress, drainage, and chamber pressure measurement. Samples must be cylindrical, with a height to diameter ratio of 2 and 2.5. They must measure 100 mm in diameter and 200 mm in height.

For the plotting of Mohr circles and to determine the shear strength parameters of the soil, minor and major principal stresses are measured by triaxial tests. These stressses are represented in Figure 3.27.

After placing a sample in the chamber, lateral pressure (σ_3) is applied along with load (axial stress σ_1) from the testing apparatus. The deviator stress (σ_d) is the axial stress (σ_1) minus the confining stress (σ_3) (See Equation 3). Repeated stress is applied to the sample until it fails. The process is then repeated with the other samples at other confining pressures. Triaxial test results were used for plotting Mohr cycles and from this, the shear parameters of the investigated material were determined.

$$\sigma_d = \sigma_1 - \sigma_3 \quad \text{or} \quad \sigma_1 = \sigma_d + \sigma_3 \qquad (3\text{-}7)$$

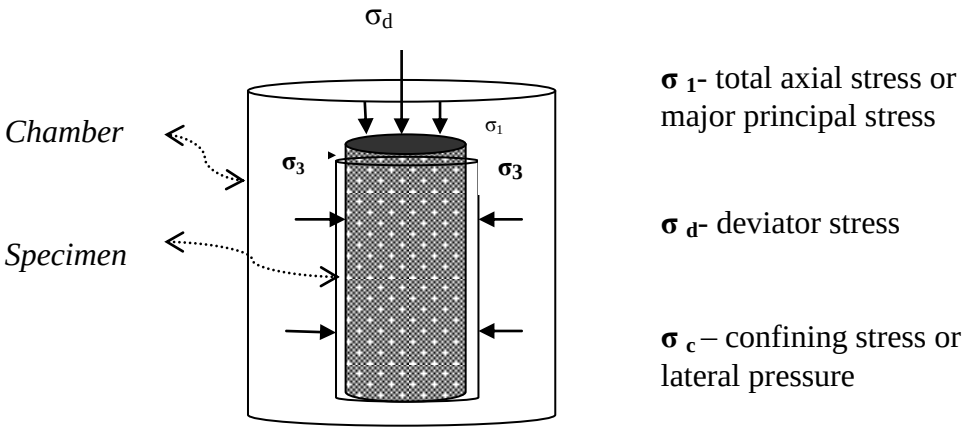


Figure 3.27 Stresses acting on a triaxial sample

3.4.7 Reference material

In the verification stage of this study, crushed rock base (CRB) was used as the baseline reference, having characteristics in accordance with Main Road Specification 501. One part of this specification demonstrates that appropriate products and materials can be produced which are suitable for base and sub-base layers and that they exhibit acceptable limits for use in road construction in Western Australia.

The following table illustrates the important characteristics of crushed rock as specified in Main Road Specification 501. The experimental results from Part 1, in terms of the nominated materials - construction and demolition materials and washed and crushed concrete waste - were compared with the limits of conventional crushed rock shown in Table 3.3.

Test	Limits	Test Method
Liquid Limit, LL	25.0 % max	WA 120.2
Plastic Limit, PL	N/A	WA 121.1
Plasticity Index, PI	6.0% max	WA 122.1
Linear Shrinkage. LS	2.0% max 0.4 % min	WA 123.1
Flakiness Index, FI	30 % max	WA 216.1
Los Angeles Abrasion Value	35 % max	WA 220.1
Max.Dry Compressive Strength, MDCS	1.7 MPa min	WA 140.1
California Bearing Ratio, (CBR) (Soaked 4 days)	100 % min	WA 141.1
Modified Compaction	N/A	WA 133.3

Table 3.3 The acceptance limits of crushed rock base (CRB) in accordance with Main Roads Specification 501

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Overview

This chapter presents the results and discussion of laboratory experiments performed on construction and demolition materials and washout crushed concrete waste (WCCW) from the company Holcim, in Western Australia. The results are produced from the utilisation of the methodologies and experimental programs mentioned in Chapter 3. In terms of the construction demolition waste materials, the experimental process was undertaken by the Curtin Pavement Research Group (CURTIN-PRG) at Curtin University. This chapter presents the testing results of all investigated materials. Figure 4.1 illustrates the testing plan.

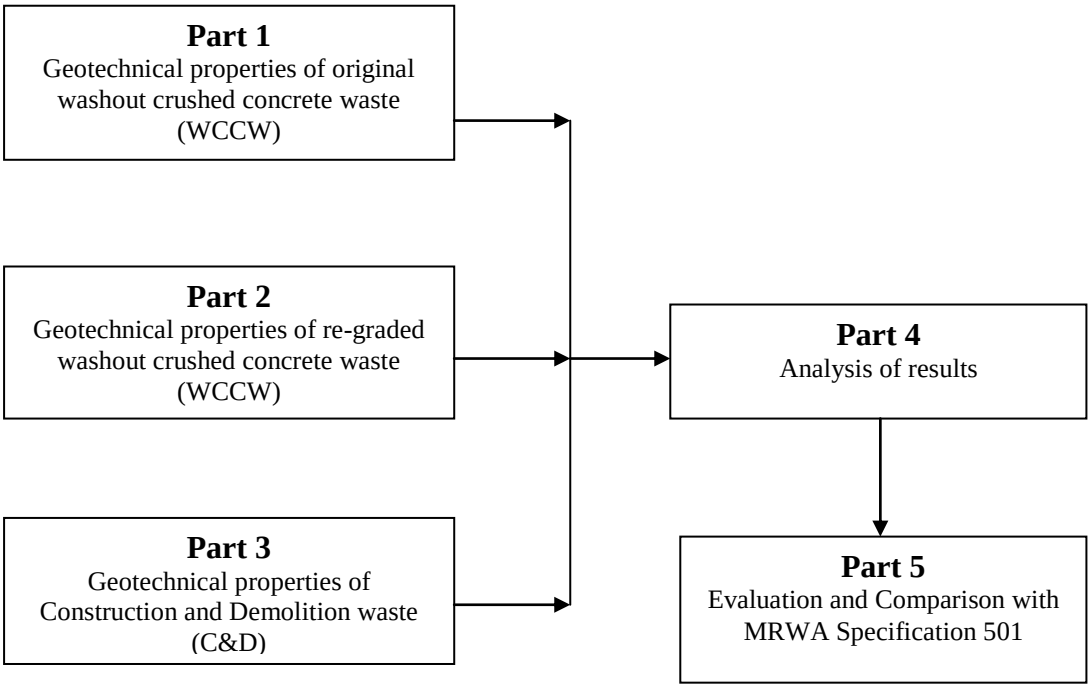


Figure 4.1 Methodology results and discussion of nominated materials in Chapter 4

4.2 Part 1: The geotechnical properties of original WCCW

4.2.1 Consistency limits

Liquid Limit (LL)

In accordance with test AS 1289.3.9.2-2006, the liquid limit of washout crushed concrete waste had a mean value of 22%. Bowman (2009) reported that for recycled products produced in Perth, the liquid limit mean value is 34.5%. This value is related to the absorption and moisture holding ability of cement based fines generated during the crushing process, or the amount of the flaky, fibrous or organic particles present.

Plastic Limit (PL)

In accordance with AS 1289.3.2.1-2009, the plastic limit of original WCCW was 20%. However, for pavement materials, a high plastic limit may indicate the presence of an undesirable amount or type of clay.

Plastic Index (PI)

In accordance with AS 1289.3.3.1-2009, the plastic limit of the original WCCW is 2.0 %.

Linear Shrinkage

In accordance with test method AS 1289.3.4.1-2008, the linear shrinkage of original WCCW was nearly zero.

4.2.2 Particle distribution

Particle size distribution of the original WCCW, before and after modified compaction is shown in Figure 4.2. It was found that for the original WCCW, before compaction, the coarse and sand fraction ratio was approximately 1:1. After compaction, this ratio changed slightly. The grading curves indicate that breakdown certainly occurs in the compaction process. The amount of coarse fraction in the original WCCW is reduced by 4-10 %, whereas, the amount of sand fraction is

increased by 3-7 %.The curve in Figure 4.2 shows a small number of particles before compaction, of diameters between 1.180 and 2.36mm. In this range, the distribution is not normal and the original WCCW may be gap graded where some particle sizes are missing.

Grading characteristics such as uniformity and curvature coefficients have been calculated using Equation (3) as mentioned in Chapter 3. Cu and Cc coefficients before and after compaction are demonstrated in Table 4.1. These parameters are significant to determine soil material classification.

Table 4.1 Grading characteristics of original WCCW before and after compaction

Property	Before compaction	After compaction
D_{60}	6.7	4.75
D_{30}	0.425	0.60
D_{10}	0.300	0.300
Coefficient uniformity (Cu)	22.3	15.8
Coefficient curvature (Cc)	0.09	0.25

Generally, Cu < 3 indicates uniform grading and Cu > 3, a well graded soil. (Roy Whitlow, 2001).

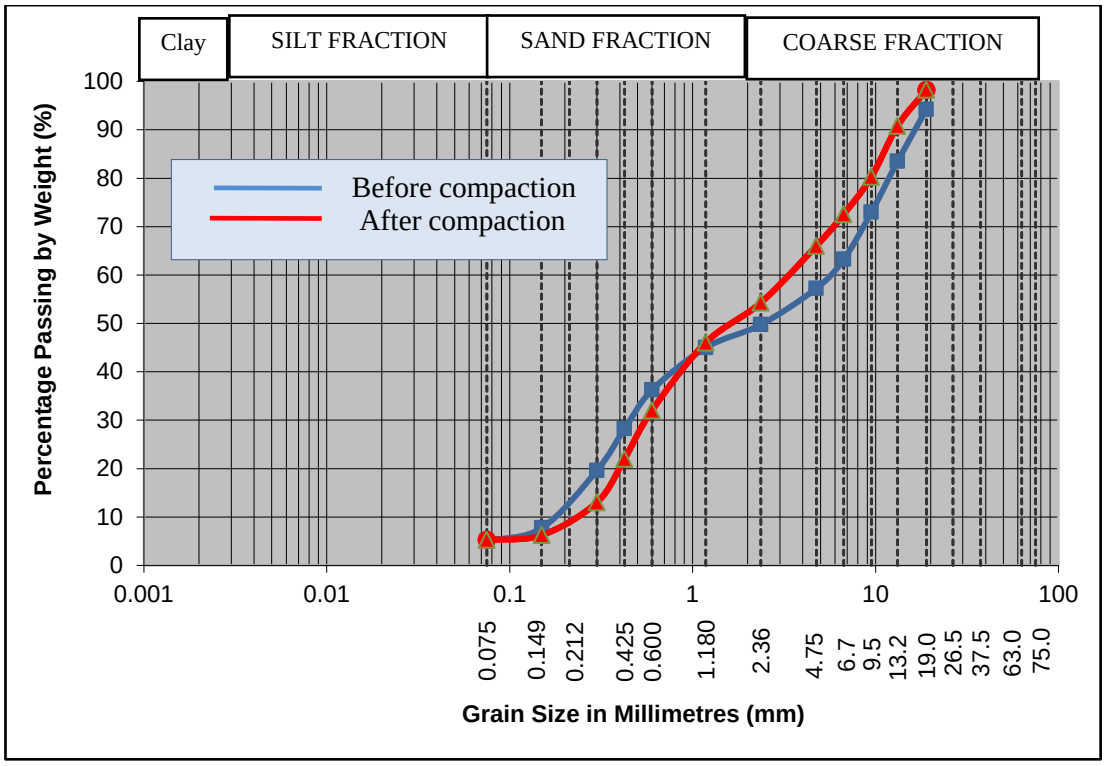


Figure 4.1 Comparison of before and after modified compaction grading curves for original WCCW

Before compaction, Cu and Cc were 22.3 and 0.9 respectively. After compaction, these values were reduced to Cu =15.8 and Cc = 0.25. These results show that the original WCCW material was poorly graded either before or after compaction. The compaction process influences material gradation. By characterising the gradation curves with the help of Cu and Cc after compaction, the washout crushed concrete waste can be classified into soil groups, GP, as poorly graded gravel with sand and little fines, based on the Unified Soil Classification System (USCL) (B.H.C 1993) .

Main Roads Western Australia has established the particle size distribution specifications of base and sub-base courses. Figure 4.3 shows the comparison between base and sub-base material specifications and original WCCW grading curves.

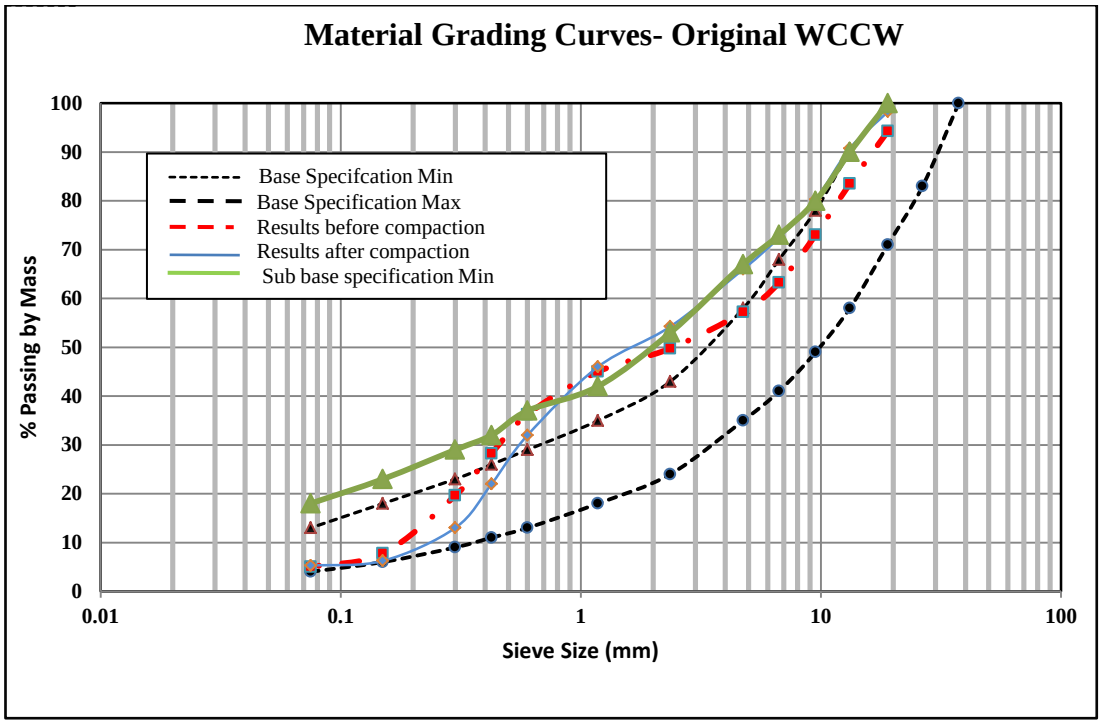


Figure 4.2 Particle size distributions of original WCCW before and after compaction

The grading curve of the original WCCW prior to compaction was near to and over the upper specification limits of the base material on the fine side. In particular, the amount of fraction passing through sieve sizes 0.425 - 4.75 mm, was well outside the specifications for the fine side. After compaction, the amount of material passing through sieve sizes bigger than 0.600 mm, lay outside the base material range. Therefore, the original WCCW before and after compaction, could not be used as base material by itself, from the perspective of particle size. However, compared with sub-base specifications, the original WCCW grading came within the specifications with the exception of the amount of particles passing through sieve size 1.180 mm.

After compaction, the amount of the fraction passing through the sieve sizes was increased and only material passing through sizes 0.075-0.425 mm was within the specification area. In both cases, material content was mostly of a finer fraction than the coarser fractions, as seen in Figure 4.3.

4.2.3 Particle shape

Particle shape and texture are significant factors affecting a particle's material packing ability and these factors influence the mechanical behaviour of the material. An image analysis of photographs, using a SEM (Scanning Electron Microscope), was undertaken on the washout crushed concrete waste samples from Holcim and on grains of gravel and sand with fractions between 19.0mm- 2.36mm and 2360µm- 75 µm. Images of coarse and sand fractions are shown in Figure 4.4 and 4.5, in different magnifications.

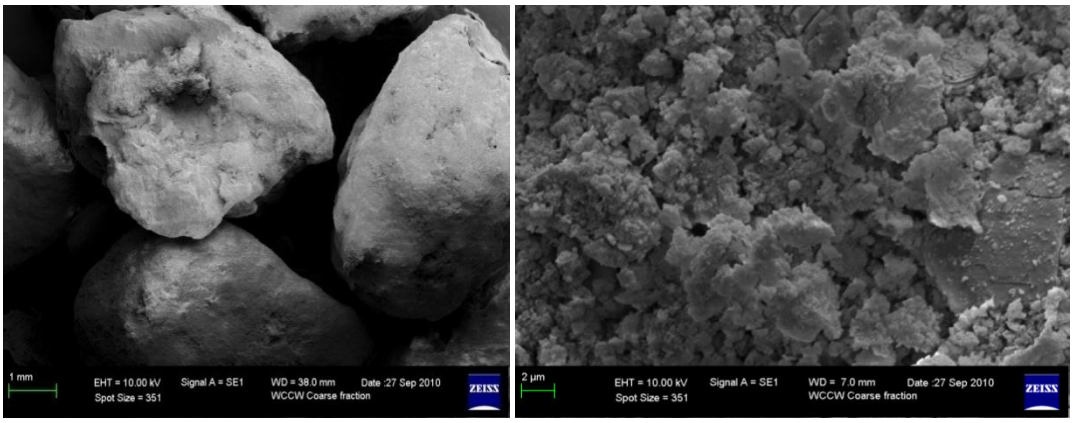


Figure 4.3 Coarse fraction particle shape and surface in 1 mm and 2 µm

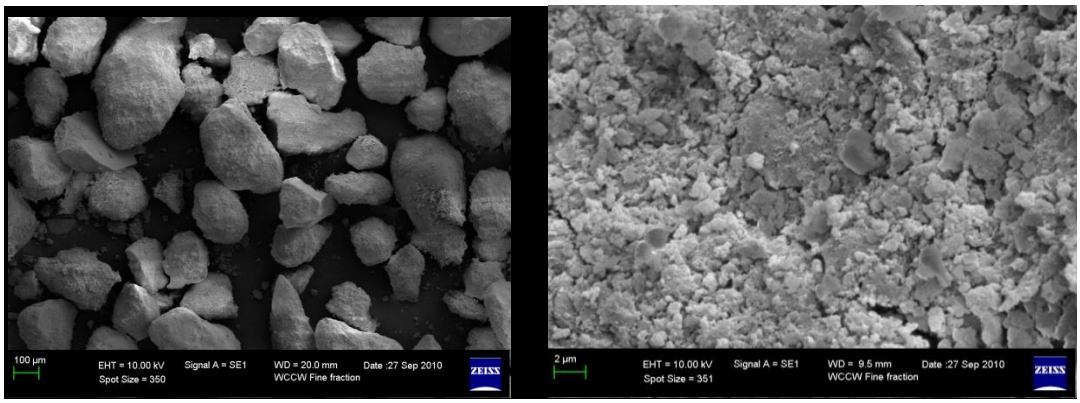


Figure 4.4 Sand fraction particle shape and surface in 100 µm and 2 µm

As shown in the SEM photos, coarse sand particles are triangular and almost sub-rounded according to Powers' scale of roundness, and surfaces have partial porosity,

which influences small strain deformation behaviour. According to Human (1992) and Leung (1996), the angular particles improve the material's mechanical properties under static loads.

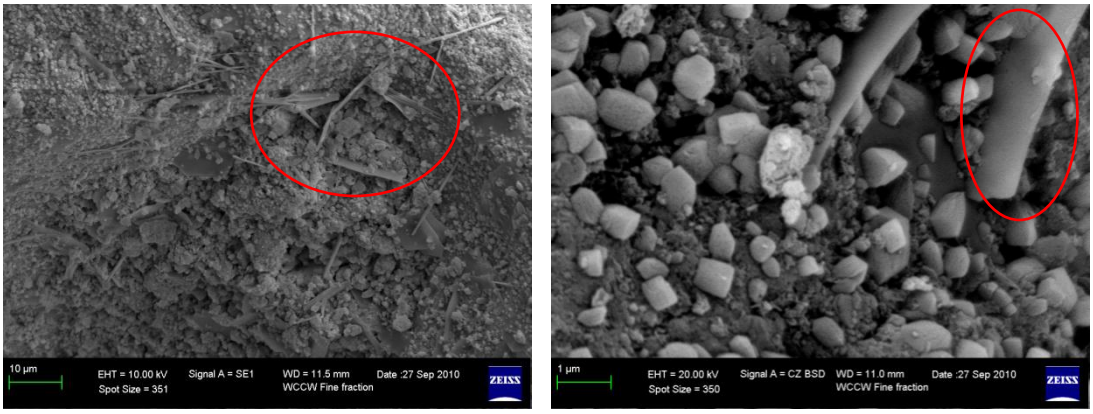


Figure 4.5 Crystal minerals in WCCW

Crystals settled on top of some parts of the sand particle surfaces. These crystal images are matched with sand fraction images in 10 µm and 1 µm magnifications as shown in Figure 4.6. According to SEM analysis, generally, the elements in crystals are Ca, Si, Au.

4.2.4 Chemical components

Table 4.2 indicates the mineralogical composition of original washout crushed concrete waste (WCCW) identified from an X-Ray spectrum analysis. Its main components are quartz, calcite, portlandite, orthoclase, and albite. Among these, quartz has the higher mineralogical content of 64.2%, followed by calcite with 21.3 %.

Phases	Percentages
Quartz (SiO_2)	64.2
Calcite ($CaCO_3$)	21.3
Portlandite ($Ca(OH)_2$)	0.7
Orthoclase ($K(Al,Fe)Si_2O_8$)	1.6
Albite ($Na(AlSi_3)O_8$)	6.0
C2S	6.2

Table 4.2 XRD results of original WCCW

4.2.5 Modified Compaction

Maximum dry density (MDD) and optimum soil moisture content (OMC) are significant factors in understanding the shear strength, resistance to future settlement, and permeability characteristics of soil. In relation to washout crushed concrete waste those properties have not been established, therefore the modified compaction test was performed several times to ensure an accurate result.

In accordance with the standard method AS1289.5.2.1-2003, the maximum dry density and optimum moisture content of the original washout crushed concrete waste is 1.82 ton/m^3 and 15.5%, respectively, as shown in Figure 4.7. Furthermore, the natural moisture content in washout crushed concrete waste (WCCW) is approximately 17%.

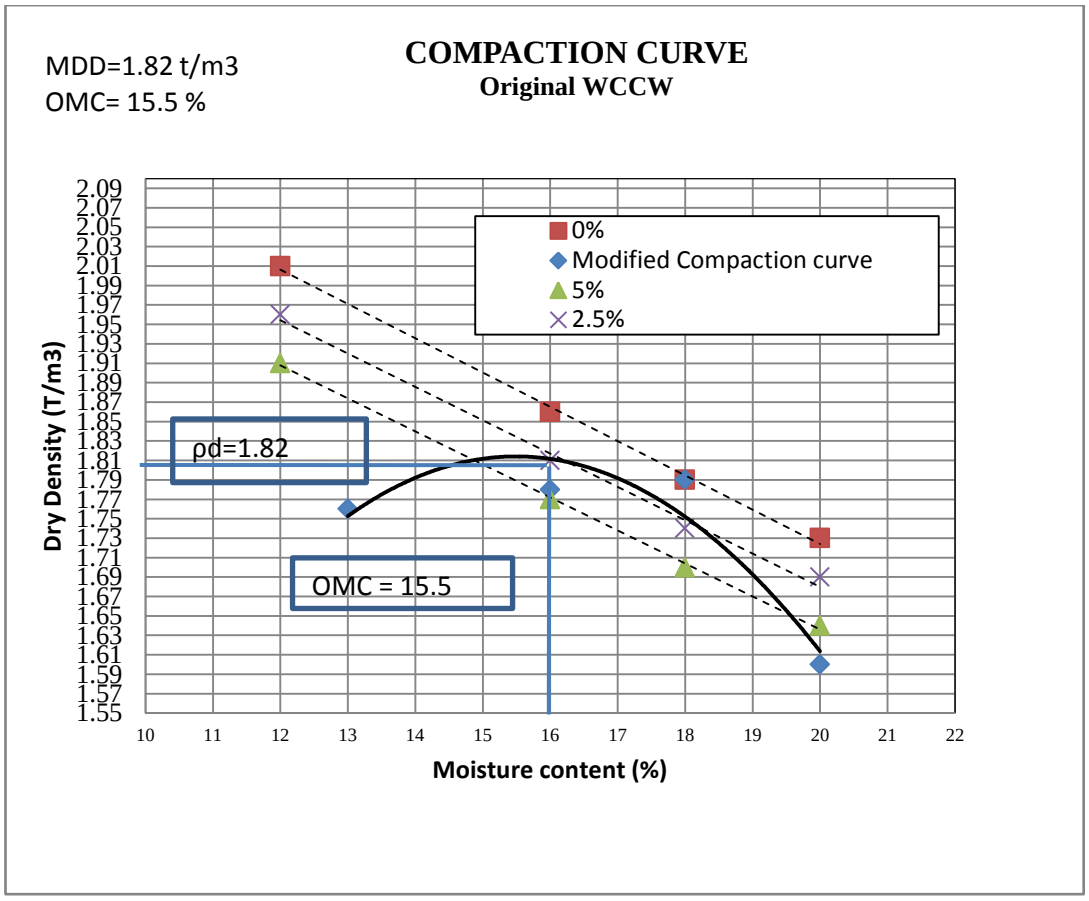


Figure 4.6 The original WCCW compaction curve

The washout crushed concrete waste had a particle density value of 2.65 t/m^3, but produced a low MDD $_{modified}$ value of 1.82 t/m^3 and a high OMC $_{modified}$ value 15.5%, because of its high water absorption ability.

4.2.6 Particle density

In accordance with AS 1289.3.5.1-2006, the particle density of the washout crushed concrete waste is 2.65 t/m^3. This measurement was obtained from calculations based on the average apparent particle density of fractions passing through and remaining in a 2.36 mm sieve.

4.2.7 California Bearing Ratio (CBR)

As the California Bearing Ratio test for WCCW has not yet been performed, this test was conducted three times using unsoaked and soaked methods in modified compaction conditions with 95% MDD and 100% OMC. Table 4.3 shows the results of the CBR from this study and the specifications of Austroads (Austroads 2004).

California Bearing Ratio		
Test methods	*Soaked*	*Unsoaked*
Washout crushed concrete waste (original)	100	90
CBR values (%) for Austroads minimum specifications (Austroads, 2004)		
Recycled concrete subbase	50	N/A
Recycled concrete base course	100	N/A
Gravel base course	80	N/A
Ferricate base course	80	N/A
Crushed rock base course	100	N/A

Table 4.3 California Bearing Ratio (CBR) results and specifications

The CBR for original washout crushed concrete samples was prepared by a modified compaction effort under four days of soaked conditions corresponding to a density of 1.82 t/m^3. This is around 100% which complies with the specifications of road base materials. In terms of unsoaked conditions, it is 90%. This is an expected result as hard rock is similar to compacted crushed limestone.

4.2.8 Maximum Dry Compressive Strength (MDCS)

The main significance of the MDCS value is as a way of determining the material's ability to withstand traffic and weathering on the shoulder. As a result of test method WA 140.1, the MDCS of the washout crushed concrete waste is 1.3MPa.

4.2.9 Unconfined Compressive Strength (UCS)

UCS tests were conducted over 7 days on the washout crushed concrete waste sample with an MDD of 1.82t/m^3 and an OMC of 100%. The UCS of a soil represents its capability to resist a compressive load in the absence of lateral restraint; this is ultimately a test of strength.

Three samples were prepared for testing. As can be seen in Figure 4.7, the mean compressive strength value was 326kPa after sample preparation and 956kPa after seven days with the sealing in normal condition. This value increased over 1.5 times after seven days. This improvement may well relate to the rehydration of cement particles remaining in the waste material. This property is not mentioned in MRWA Specification 501. However, Leek (2010) recommended that unconfined compressive strength tests be used as index tests with upper and lower limits for each category of material used in road construction.

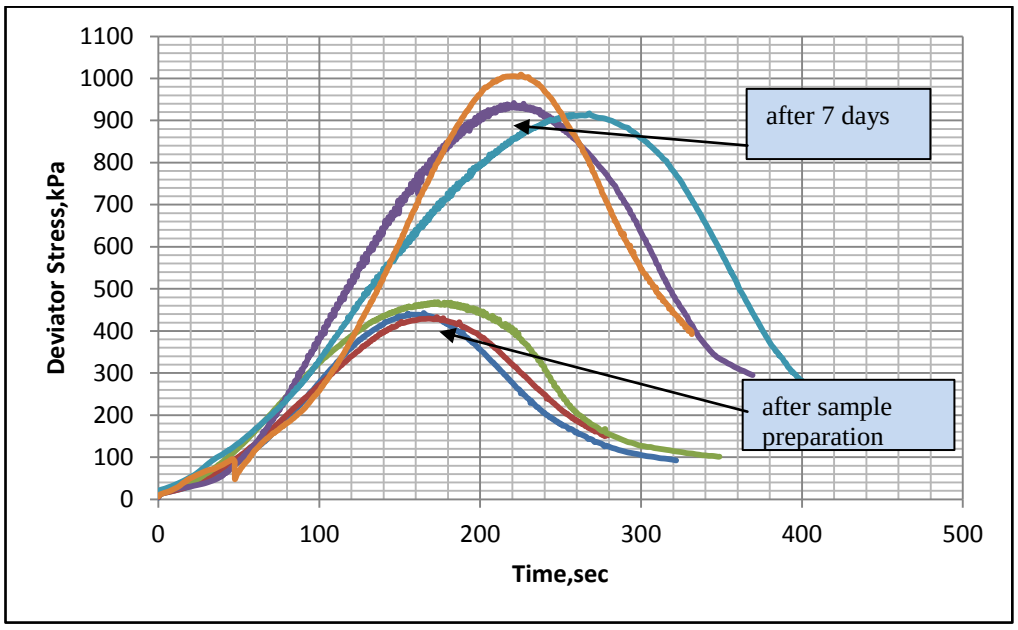


Figure 4.7 UCS test result of WCCW material

4.2.10 Flakiness index

The result of test method WA (Western Australia) 216.1 showed the flakiness index of the washout crushed concrete waste as 15 %.

4.2.11 Los Angeles (LA) value

This value presents the loss of the aggregate particles during the abrasion process in a Los Angeles testing machine. The test was conducted under test method AS 1141.23-1995 and the mean LA value for the washout crushed concrete waste was 29.5%.

4.2.12 Static triaxial test

This section presents the results of the shear test parameters of washout crushed concrete waste that was compacted at 100% maximum dry density and optimum moisture content derived from the compaction curve. The test is used to examine strength characteristics and to determine shear parameter cohesion (c) and friction angle (φ) of original washout crushed concrete waste under a triaxial shear test by plotting the Mohr-Coulomb failure envelope, from experimental results. This test also established the failure line of the material to determine the maximum stress level, which could be applied. Confining pressures of 40kPa, 80kPa, and 120kPa were applied to the samples in each test.

Table 4.4 presents the test results of the original WCCW from triaxial shear tests. Figures 4.10 and 4.11 have been plotted from data in Table 4.4. Values of lateral confining stress (σ_3) and total vertical stress (σ_1) at failure were plotted and circles drawn through these points. A line that is tangential to circles plotted in this manner is named the failure envelope and the parameters of cohesion and friction angle are determined from this line as indicated.

Table 4.4 Shear test results of the original WCCW

Original WCCW				
σ_3 *(kPa)* (1)	σ_1 *(kPa)* (2)	$q = \sigma_d$ *(kPa)* (3)	$q = \sigma_d/2$ *(kPa)* (4)	$p = (\sigma_1 + \sigma_3)/2$ *(kPa)* (5)
40	1062.6	1022.6	511.3	551.3
80	1243.0	1163.0	581.5	661.5
120	1374.0	1254.0	627.0	747.0

From Figure 4.8, the cohesion and friction angles of the original WCCW are 231.1 kPa and 36^0. These parameters are not used as direct inputs in pavement design but they can give useful information regarding the material's performance. Practically, a friction angle greater than 45^0 indicates a usable material, and cohesion between 20kPa to 150kPa is within a favourable range. Material is likely to ravel below this range and would be brittle above the range. From the results, WCCW is shown to be the more brittle material.

Figure 4.10 shows the relationship between deviator stress and vertical strain at the three different effective confining stress levels for WCCW samples. It can be seen that deviator stress increases with vertical strain until it reaches peak strength. It seems that at higher confining pressures, peak strength becomes higher and the strain corresponding to peak strength also becomes higher.

The material is more stable in low confining stress conditions at 40kPa than at 80 kPa and 120kPa. After reaching peak strength, a sharp drop is matched within a range of 2-3% vertical strain at 80kPa and 20kPa.

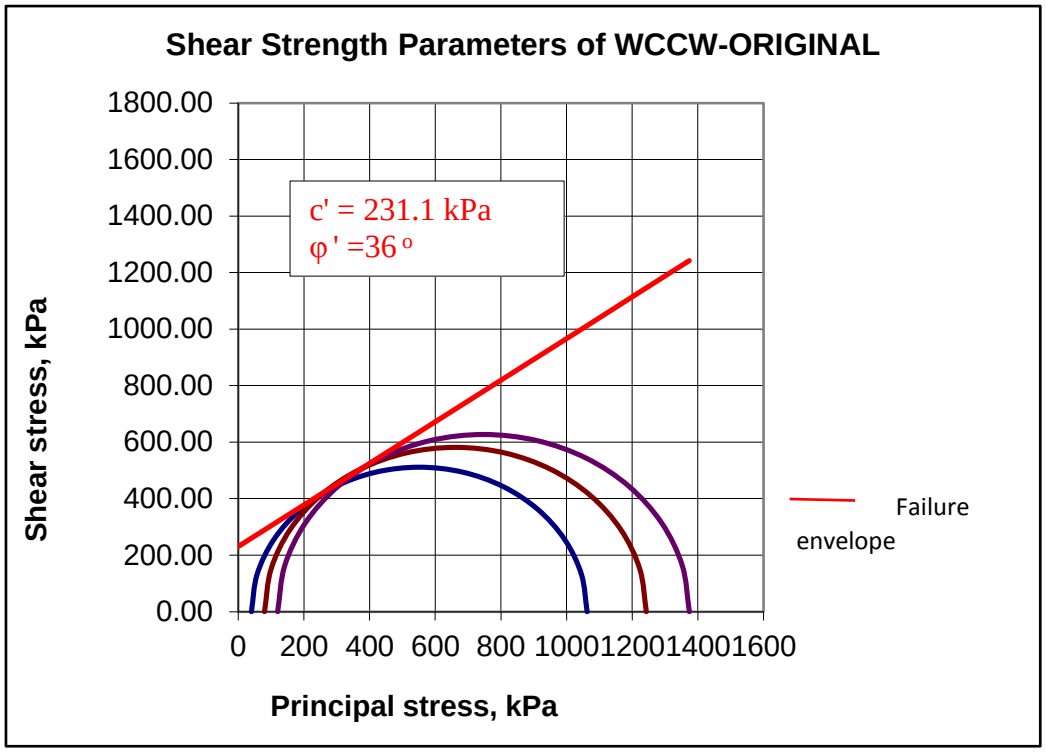


Figure 4.8 Mohr's circles and failure envelope for original-WCCW

In principle, a material having a higher friction angle value is more stable under high confined stress conditions whereas one having a higher cohesion value is more stable under low confined stress conditions.

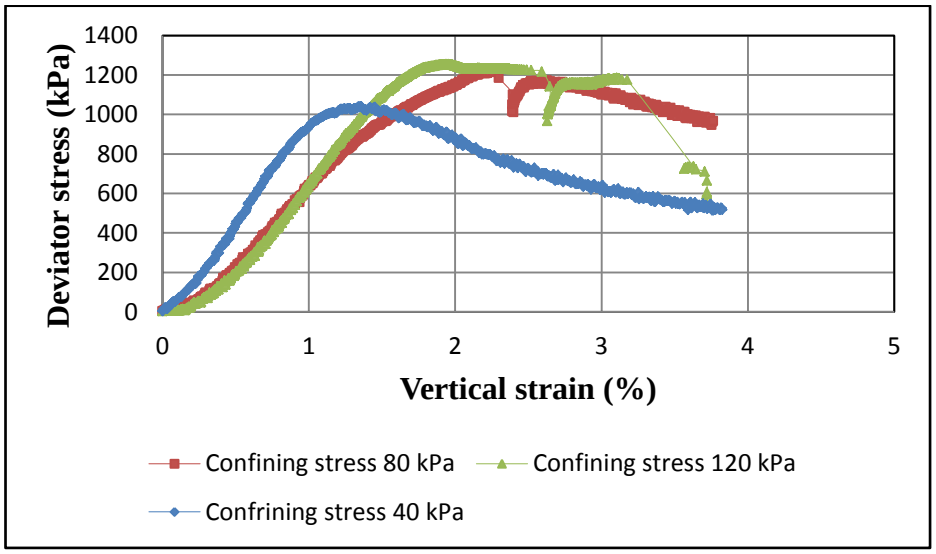


Figure 4.9 Deviator stress- vertical strain curve

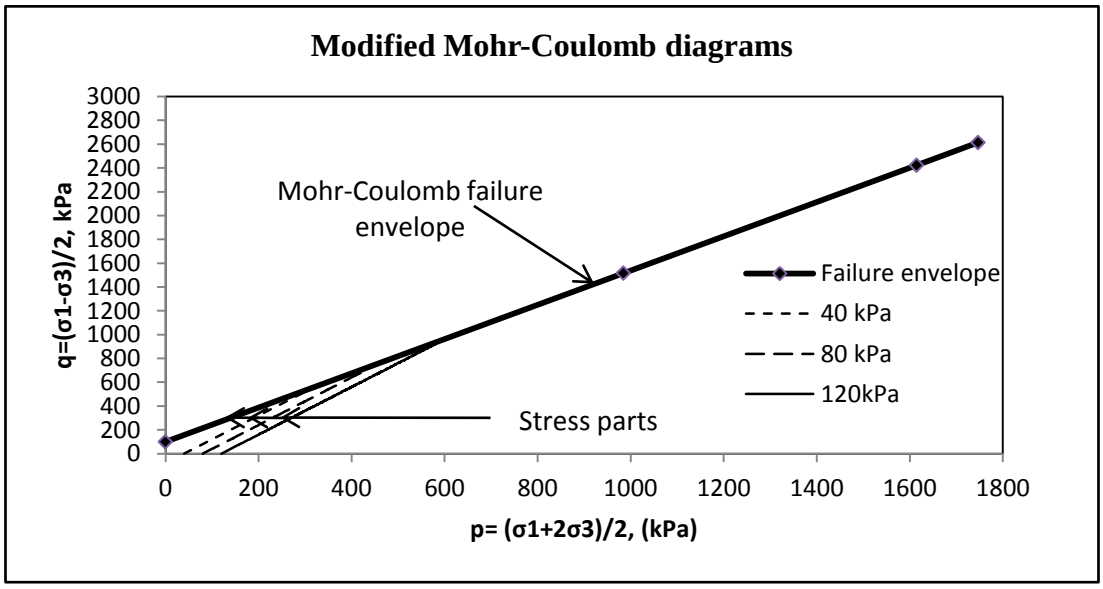


Figure 4.10Triaxial test results of original WCCW in p-q stress spaces

4.2.13 Repeat load triaxial test

Permanent deformation and resilient modulus, stress-dependent characteristics of nominated materials are determined by the repeat load triaxial testing standard method, Austroads APRG 00/33-2000. These tests were carried out in the Geomechanics Laboratory, at the Department of Civil Engineering, Curtin University.

4.2.14 The results of permanent deformation characteristics

Pavement deformation testing was performed to obtain the plastic strain response at one stress level over a large number of repetitions. The tests were conducted at deviator stress pressures of 350kPa, 450kPa, and 550kPa with a confining stress of 50kPa. Permanent deformation testing was calculated in accordance with Austroads-APRG 00/33 standard.

Experimental samples prepared at a target density of 98% $MDD_{modified}$ and 100% $OMC_{modified}$ for original WCCW were loaded in three stress stages, each involving 10,000 cycles.

From the test results shown in Figure 4.12, it is clear that permanent deformation occuring in the original recycled concrete was high. In the first stage, it increased remarkably and in second and third the increase was gradual. After 30,000 cycles the permanent deformation of the original recycled crushed concrete was approximately 2,100 micrometers.

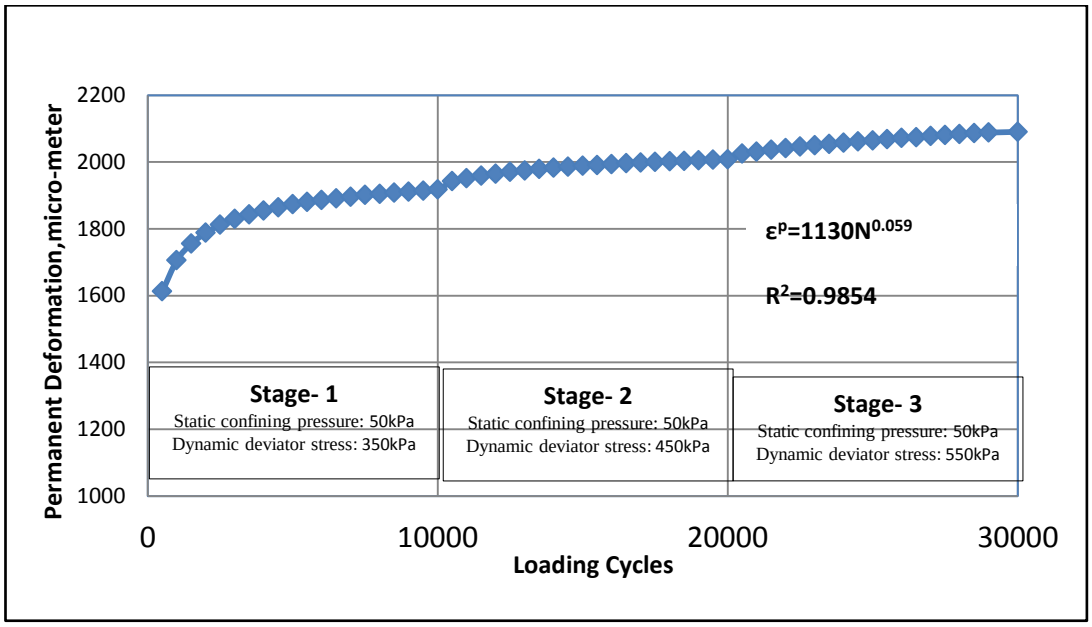


Figure 4.11 Permanent deformation of original WCCW

For most base materials, the failure condition, where permanent deformation and resilient strain rates increase with increased loading cycles, was often found when the total permanent strain exceeded 20,000 micrometers (Vuong 1999). In this case, the permanent deformation of the original WCCW would be around 10% of the failure permanent strain measure of 20,000 micrometers.

The permanent deformation characteristics of re-graded WCCW can be modelled using Sweere, G.T.H's model from SAMARIS (2004) as $\varepsilon^p=1130N^{0.059}$.

4.2.15 The results of resilient modulus characteristics

Resilient modulus, an important material property and analogous to the modulus of elasticity, can be used to predict the response of a material to repeated impulses or moving loads, such as those imposed by vehicle tyres on a road surface. A resilient modulus value can be used with structural response analysis models to calculate pavement structural response to wheel loads and it can be used with pavement design procedures to design the pavement's structure.

The standard method Austroads APRG 00/33-2000 (Voung and Brimble, 2000), allows a suite of 65 stress conditions at various stress levels applied to a tested sample to characterise the vertical resilient (recoverable) strain under a combination of applied dynamic vertical and static confining stresses. Figure 4.13 shows the resilient modulus results of the original washout crushed concrete waste with applied loading sequences.

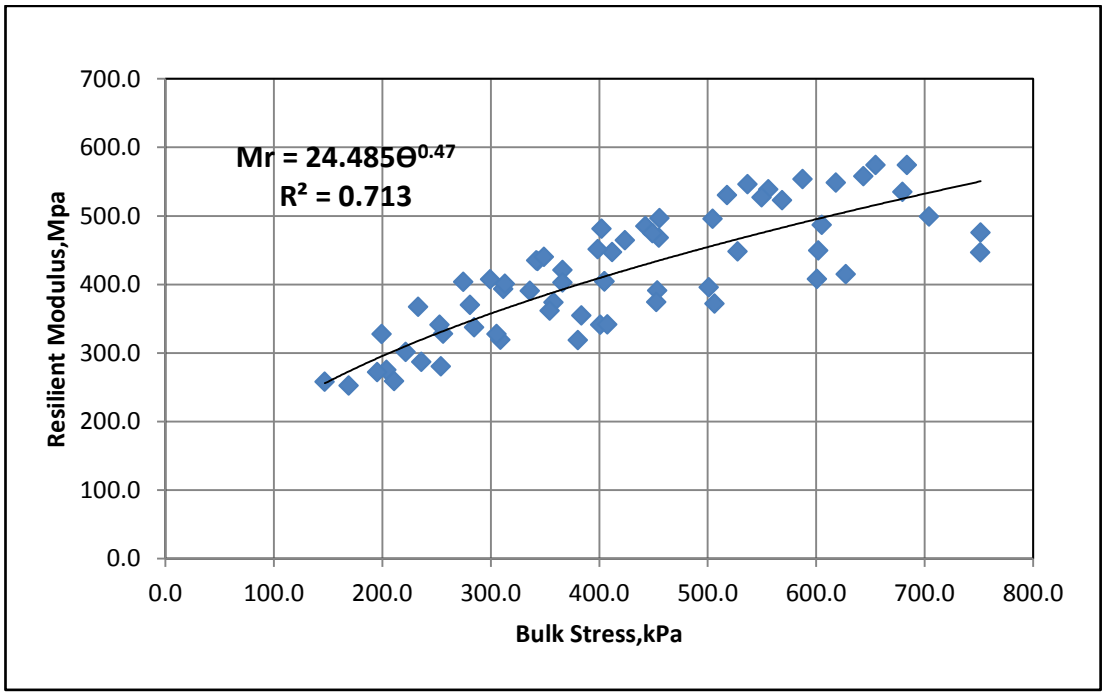


Figure 4.12 Mr vs bulk stress for original WCCW

The representative K-Θ modes of original WCCW are exhibited in equation

$$Mr = 24.485\Theta^{0.47}. \qquad (4\text{-}1)$$

4.3 Part 2: Geotechnical properties of re-graded WCCW

4.3.1 Particle size distribution

Correct particle size distribution is an important factor affecting the high density and mechanical strength of granular materials. A mechanical stabilisation method was used in this research for the improvement of evidence of mechanical and engineering properties of the original WCCW (Authorities 1970).

In Figure 4.13, the grading line of the original WCCW lies almost out of the base specification area before and after compaction.

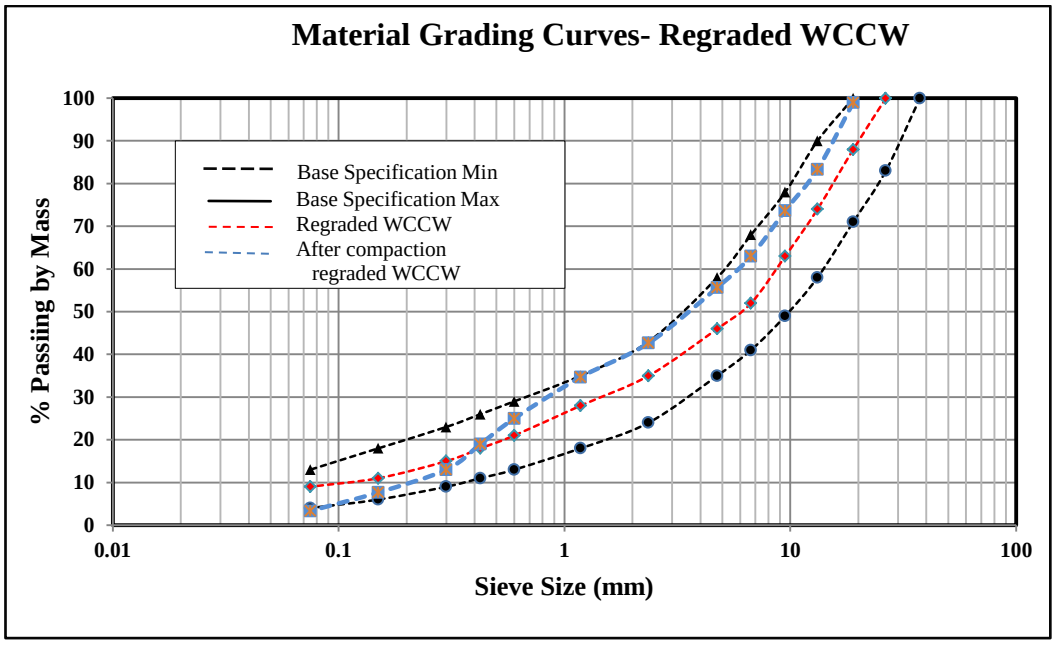


Figure 4.13 Particle size distributions of re-graded WCCW

Changing the amount of grain size distribution in original WCCW is one method used, other than mixing materials of various types. The new grading portion, a mixture with increasing amounts of the material's coarser fraction, can be seen in column (2) in Table 4.5 and is shown by a red dotted line in Figure 4.13.

Table 4.5 Target grading proportions for original WCCW

Particle Size Distribution		**Target Retained,% (1)**	**Target Passing,% (2)**	**After Compaction, Passing,% (3)**
Test Method	**MRWA:115.1**			
Specification	**Due to plot**			
Sieve Size (mm)	**Passing,%**			
19.0	72-100	12	88	96
13.2		14	74	86
9.5	50-78	11	63	75
6.7		11	52	63
4.75	36-58	6	46	54
2.36	25-44	11	35	42
1.18	18-35	7	28	34
0.600	13-28	7	21	24
0.425	11-25	3	18	19
0.300	9-22	5	13	13
0.150	6-17	2	11	8
0.075	4-13	2	9	4

As grading curves, the PSD of the re-graded WCCW lies within the specification area after compaction.

After re-gradation, the coefficients of uniformity and curvature were calculated for analysis of the improvement of particle contents in re-graded WCCW. According to the Unified Soil Classification Standard, based on the Cu and Cc values, the re-graded WCCW could belong to the CW soil type, being well-graded gravels, gravel-sand mixtures, and little fines. Table 4.6 presents Cu and Cc values of the original and re-graded WCCW.

Table 4.6 Cu and Cc values of WCCW

Materials	Classification values	Before compaction	After compaction
Original WCCW	**Cu**	22.3	15.8
	Cc	0.9	0.25
Re-graded WCCW	**Cu**	63.3	22.3
	Cc	3.9	0.7

4.3.2 Modified compaction

A second compaction test on re-graded WCCW revealed that the amount of coarse particles increased, fine particles were reduced, the maximum dry density was improved to 1.89t/m^3 and the optimum moisture content was reduced to 15%, as seen in Figure 4.15.

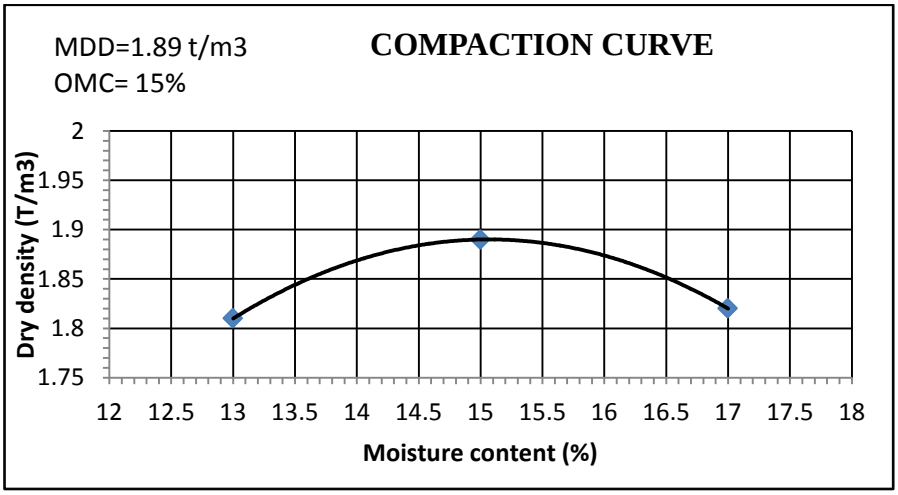


Figure 4.14 The Re-graded WCCW compaction curve

This improvement in the maximum dry density of the re-graded WCCW related to the new particle distribution in the material. Gap-graded particle distribution of the orginal WCCW became normal in particle distribution after re-gradation, which gave it a chance to obtain more dense particle packing. Reducing the amount of fine particles reduces the absorption properties of re-graded WCCW.

4.3.3 Shear strength

As result of re-gradation, the angle of friction of WCCW is improved and can give a friction angle as efficient as that of the dense sand and gravel, which is in the range of 40 to 60 degrees (Yoder E 1975).

Figure 4.15 shows the relationship between the deviator stress and the vertical strain for re-graded WCCW samples at the three different effective confining stress levels of 40kPa, 80 kPa, and 120kPa. It can be seen that deviator stress increases with vertical strain until it reaches peak strength. Moreover, the deviator stress increases with the growth of confining stresses. It seems that at higher confining pressures, peak strength becomes higher and the strain corresponding to the peak strength also becomes higher.

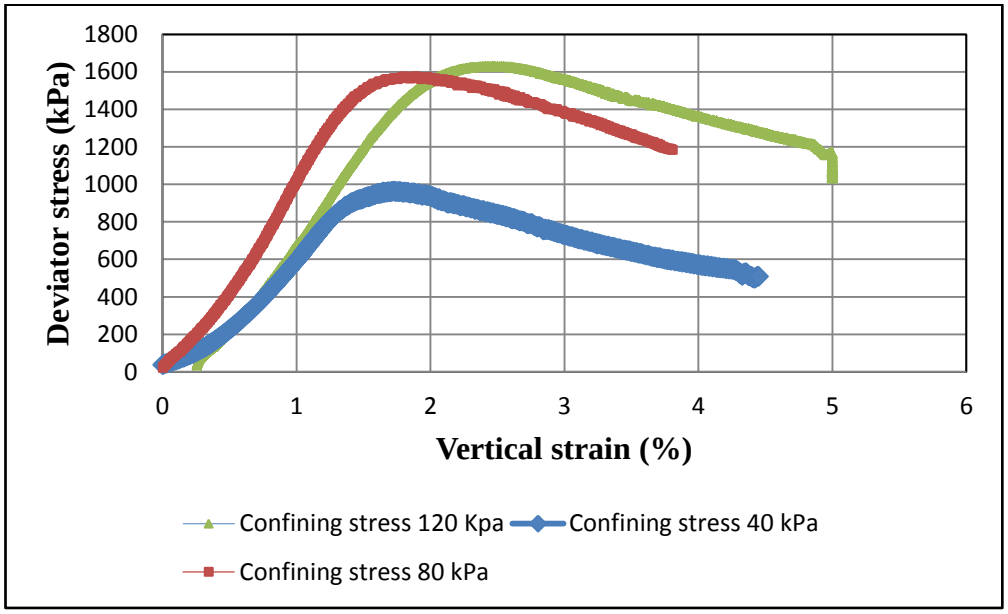


Figure 4.15 The deviator stress-vertical strain curve of re-graded WCCW

Figure 4.16 presents the cohesion and friction angle of the re-graded WCCW, 99.4 kPa and 55.2^0. Compared with the results of original WCCW, cohesion is reduced and the friction angle is markedly increased. These positive values suggest that after

re-gradation, WCCW could belong to a category of appropriate material that lies within the preferred specifications range.

The re-gradation process influenced the shear strength properties of the material. Table 4.7 shows that vertical and deviator stress improved significantly except at a confining stress pressure of 40kPa where the principal stress values are almost similar to those of the original WCCW.

Re-graded washout crushed concrete waste				
σ_3 *(kPa)* (1)	σ_1 *(kPa)* (2)	$q = \sigma_d$ *(kPa)* (3)	$q = \sigma_d/2$ *(kPa)* (4)	$p = (\sigma_1 + \sigma_3)/2$ *(kPa)* (5)
40	985.0	945.0	472.5	512.5
80	1615.0	1535.0	767.5	847.5
120	1747.0	1627.0	813.5	933.5

Table 4.7 Shear test results of re-graded WCCW

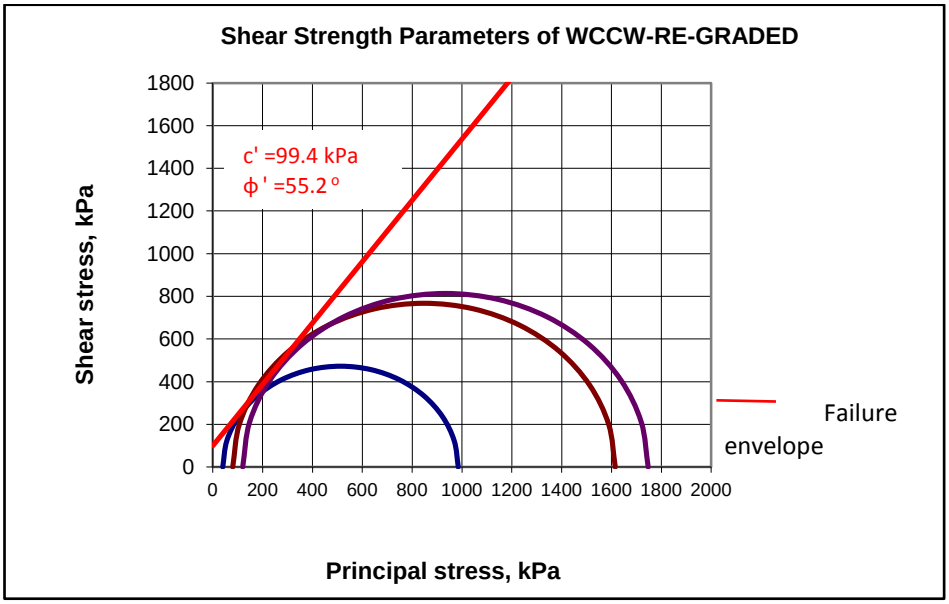


Figure 4.16 Mohr's circles and failure envelope of RCC-Re-graded

The modified Mohr-Coulomb diagrams, in particular, the 'p-q' diagrams, are used to represent the stresses at failure in each test by point plot. The 'p-q' diagram is based on the relationship between principal stresses and Mohr-Coulomb shear parameters c and φ. The 'p-q' diagrams of re-graded WCCW are shown in Figure 4.17. This figure is plotted from marked data in columns (4) and (5) in Table 4.9.

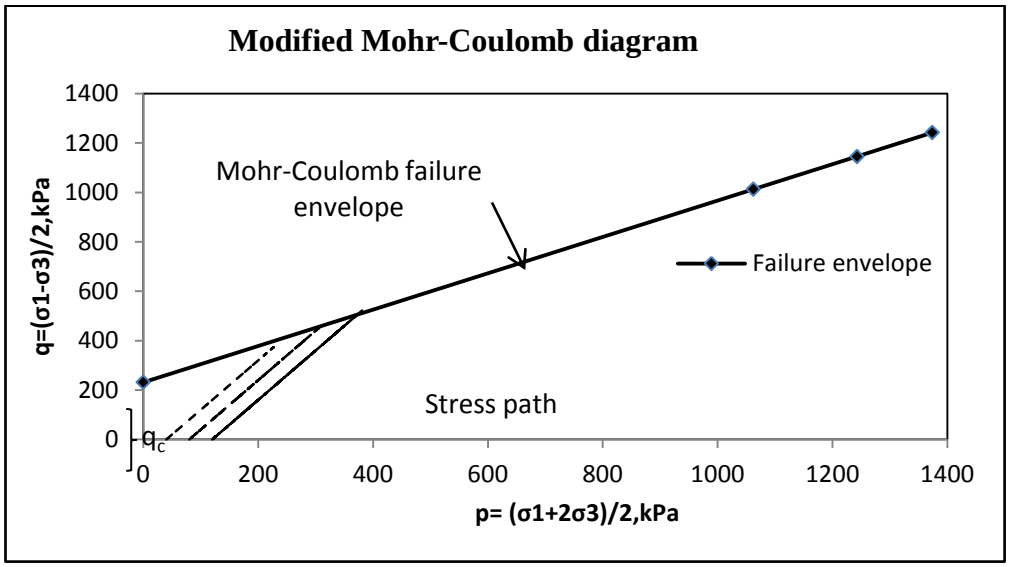


Figure 4.17 Triaxial test results of re-graded WCCW p-q stress spaces

4.3.4 Repeat load triaxial test

At Repeat Load Triaxial Test (RLT), resilient modulus and permanent deformation characteristics are determined.

4.3.5 The results of resilient modulus characteristics

Figure 4.18 shows the resilient modulus of re-graded WCCW. The straight line shown in the figure, is the linear regression of data points, obtained from the load sequences applied to the re-graded WCCW samples.

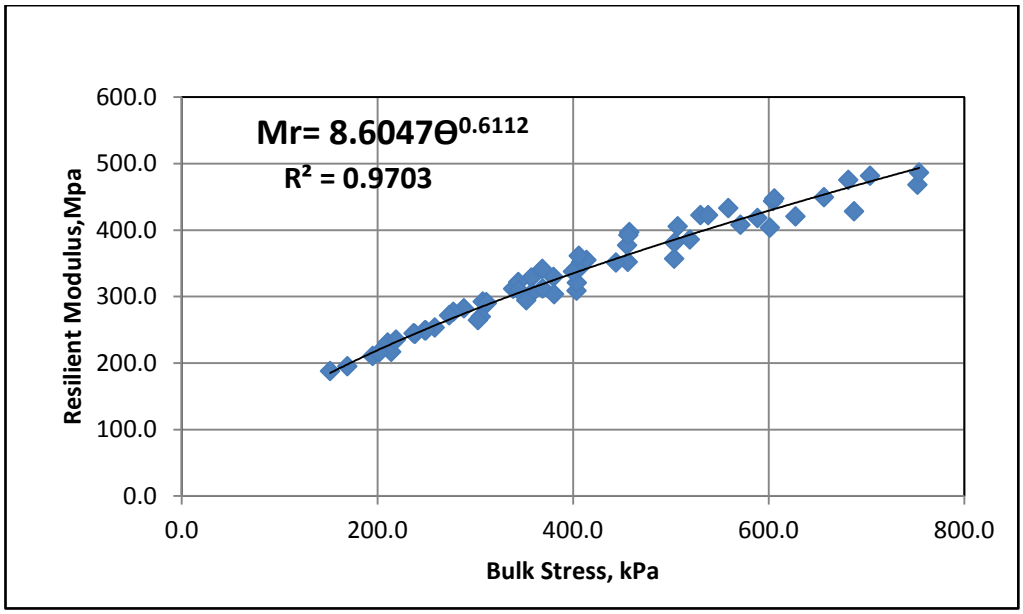


Figure 4.18 Mr vs bulk stress for re-graded WCCW

It confirms the theory of an increase in Mr with bulk stress for coarse materials. The representative K-Θ modes of re-graded WCCW are exhibited in equation

$$Mr = 8.6047\Theta^{0.6112}. \qquad (4\text{-}2)$$

4.3.6 The results of permanent deformation characteristics

After gradation, the permanent deformation of re-graded WCCW, as can be seen in Figure 4.19, was reduced and it was compared with the original WCCW. However, it increased dramatically by between 1,000-,1400 micrometers in every stage. In the case of the re-graded recycled crushed concrete, it measured approximately 1,380 micrometers after 30,000 cycles in the third stage. It seems that the number of loading cycles influenced its permanent deformation values.

The permanent deformation characteristics of re-graded WCCW can be modelled using Sweere,G.T.H's model from SAMARIS (2004) as $\varepsilon^p=799.37N^{0.0496}$.

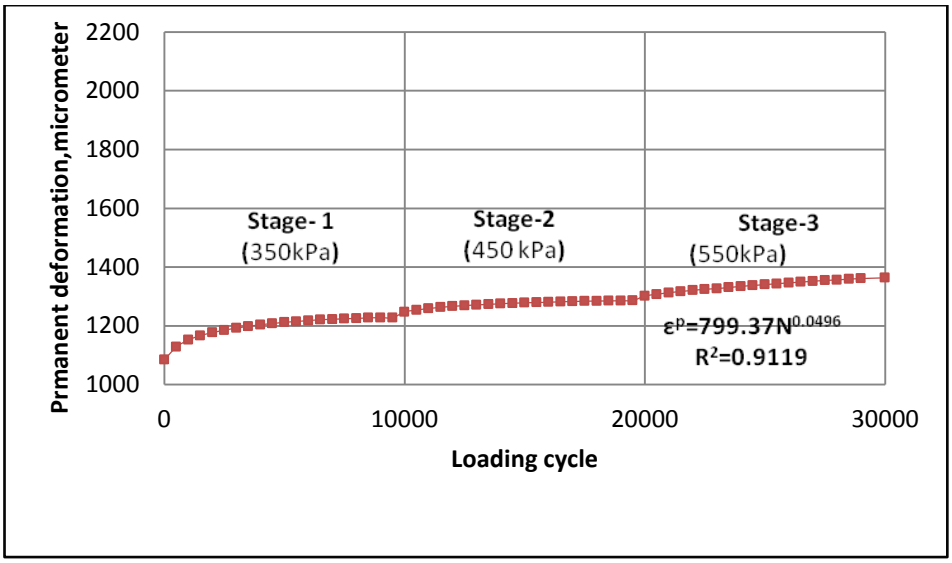


Figure 4.19 Permanent deformation of re-graded WCCW

4.4 Part 3: The geotechnical properties of Construction and Demolition (C&D) waste

4.4.1 Consistency limits

Liquid Limit (LL)

The average liquid limit of the construction and demolition material from All Earth, Capital Demolition and C&D Recycling is 34.5% compared to the MRWA specification limit of 35% for a base course.

Linear shrinkage

According to MRWA specification 501.94.03, the maximum linear shrinkage of crushed recycled concrete is allowed to be 3.0 %. In accordance with test method AS 1289.3.4.1-2008, the linear shrinkage of WCCW is zero. In the case of construction and demolition materials, it was generally low, with a median value of zero, and a mean of 0.27 %.

4.4.2 Particle size distribution

The grading of C&D Recycling materials (Figure 4.20) shows that all materials are low in fines and that for these samples at least, the grading of the All Earth material is well out of the specification on the fine side, and the grading for C&D Recycling is slightly out of specification on the coarse side. The coefficients of curvature and uniformity for each material are shown in Table 4.8.

Table 4.8 Grading properties of C&D Recycling materials

Property	**Results**		
	C&D	***All Earth***	***Capital Demolition***
D_{60}	10	3.5	5.6
D_{30}	1.5	0.65	1.8
D_{10}	0.3	0.23	0.425
Coefficient of Uniformity (Cu)	33.3	15.2	13.2
Coefficient of Curvature (Cc)	0.8	0.5	1.4

Whilst the grading is outside the specification for All Earth, the coefficients of uniformity and curvature for all materials are within a tolerable range.

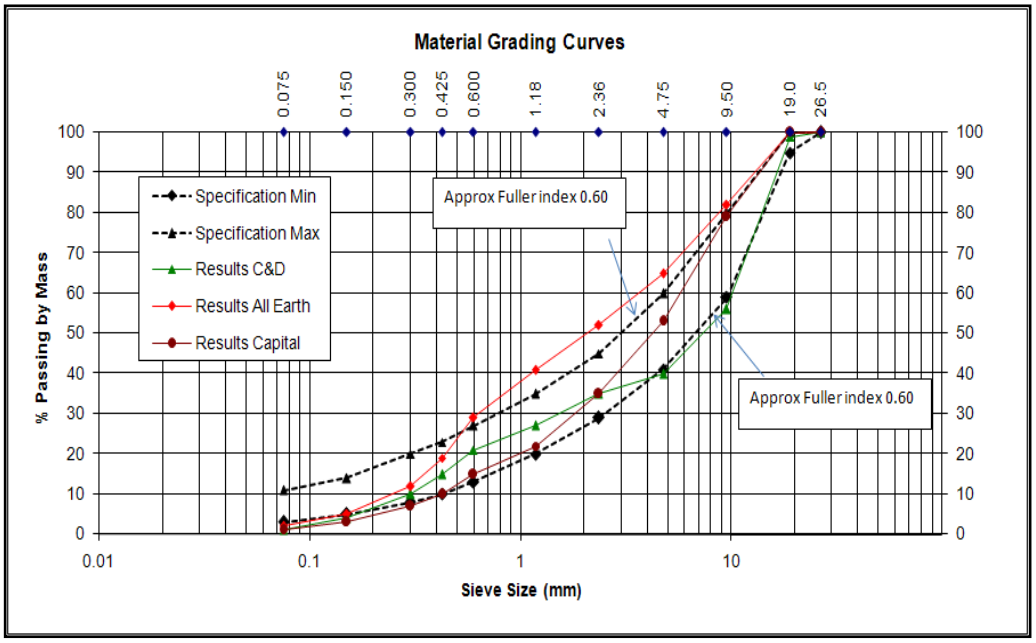


Figure 4.20 Particle size distributions for C&D Recycling materials

4.4.3 Modified compaction

Maximum dry density and optimum moisture content testing was undertaken at Curtin University. Compaction curves are shown for C&D Recycling in Figure 4.21, All Earth in Figure 4.22 and Capital Demolition in Figure 4.23. With regard to C&D Recycling, the maximum dry density and optimum moisture content were 1.96 t/m^3 and 11.3% respectively, for All Earth C&D Recycling material, 1.86t/m^3 and 10.9% respectively, and for Capital Demolition 1.91 t/m^3 and 11.3% respectively.

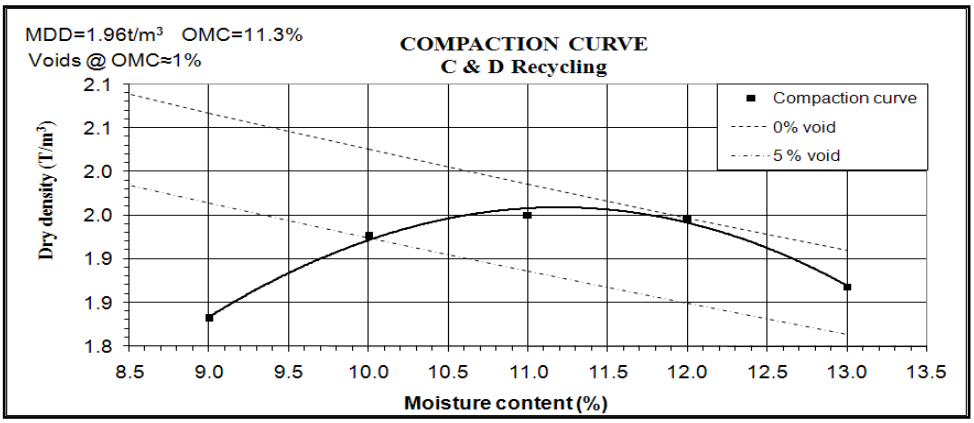


Figure 4.21 The C & D Recycling compaction curve

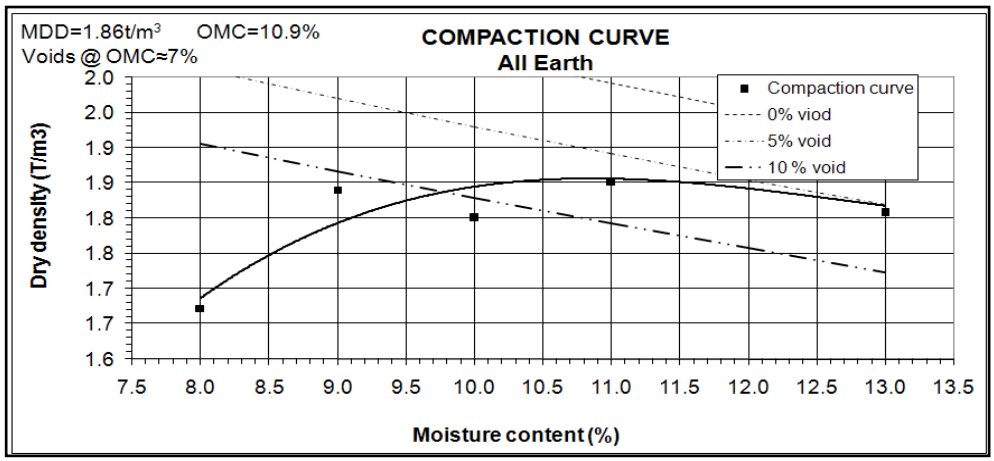


Figure 4.22 The All Earth compaction curve

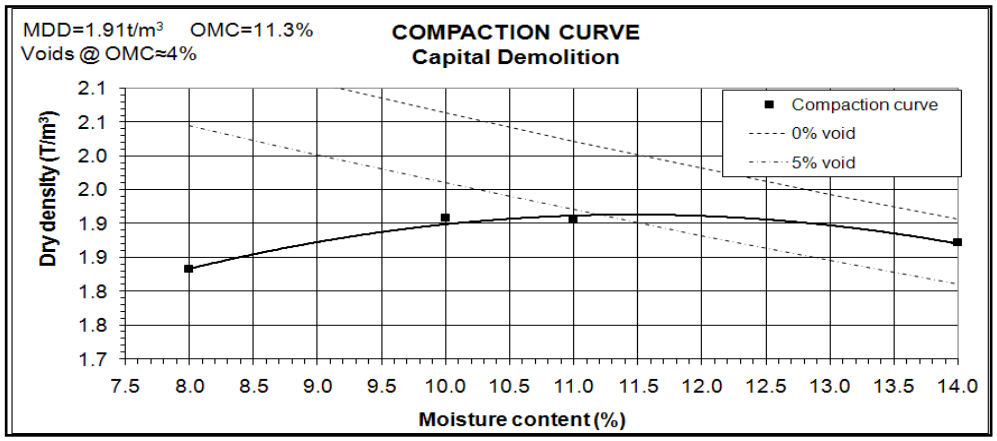


Figure 4.23 The Capital Demolition compaction curve

Table 4.9 demonstrates the values of maximum dry density (MDD) and the optimum moisture content (OMC) of the research materials.

Table 4.9 MDD and OMC results of research materials

Values	**Results**		
	C&D	***All Earth***	***Capital Demolition***
MDD (ton/m^3)	1.96	1.86	1.91
OMC (%)	11.3	10.9	11.3

4.4.4 Unconfined Compressive Strength (UCS)

Unconfined compressive strength values were evaluated on samples of Construction and Demolition waste material at 1 day and 28 days curing. The results in Table 4.10 show that there is some degree of cementing action for recycled materials.

Table 4.10 The results of Unified Compressive Strength Testing (UCS)

Supplier	UCS Un-cured (kPa)	UCS Cured (kPa)
Capital Demolition	668	1625
C&D Recycling	220	474
All Earth	541	1323

UCS tests for samples of All Earth material in Table 4.11 show that there was a gradual increase of strength over time. Should this strength gain be related to the rehydration of cement bonds as suspected, the strength gain will be extremely dependent upon the curing period.

Table 4.11 The results of Unified Compressive Strength Testing on All Earth material

Day	UCS (kPa)
1	625
7	99
28	1023

Capital Demolition sources its material from structural concrete only, whereas All Earth and C&D Recycling receive supplies from a wide range of sources, and much of the concrete is non-structural, such as house pads, paving, and the kerbing from road works. There is also a blend of other products, mainly brick, tile, sand, aggregates and asphalt.

MRWA Specification 501 requires a 7 day UCS value of 0.6 to 1.0MPa. Based on the results in Table 4.8 it is likely that a 7 day value for UCS will be potentially in range of 0.37 to 1.2MPa.

4.4.5 California Bearing Ratio (CBR)

The CBR's of the Construction and Demolition materials were between 121 % and 171 % compared to a specification minimum of 100%.

4.4.6 Shear strength

In order to assess changes in apparent cohesion over time, static triaxial testing was undertaken on All Earth materials at 1, 7, and 28 days. For these tests, a 'p-q' diagram as shown in Figure 4.25, was used to determine values for cohesion (c) and friction angle (φ) during 1,7 and 28 days curing. The results are presented in Table 4.12.

Curing period	**1 day**	**7 days**	**28 days**
Friction angle (φ^0)	56.9	49.9	62.6
Cohesion c (kPa)	58.4	146.7	86.5

Table 4.12 The values of cohesion and friction angles for All Earth materials at various curing times

The 1 and 28 day results show the trend expected of a product that has some rehydration of cement bonds, with an increase in apparent cohesion and friction angle. However, the 7 day results show much higher cohesion and a lower friction angle.

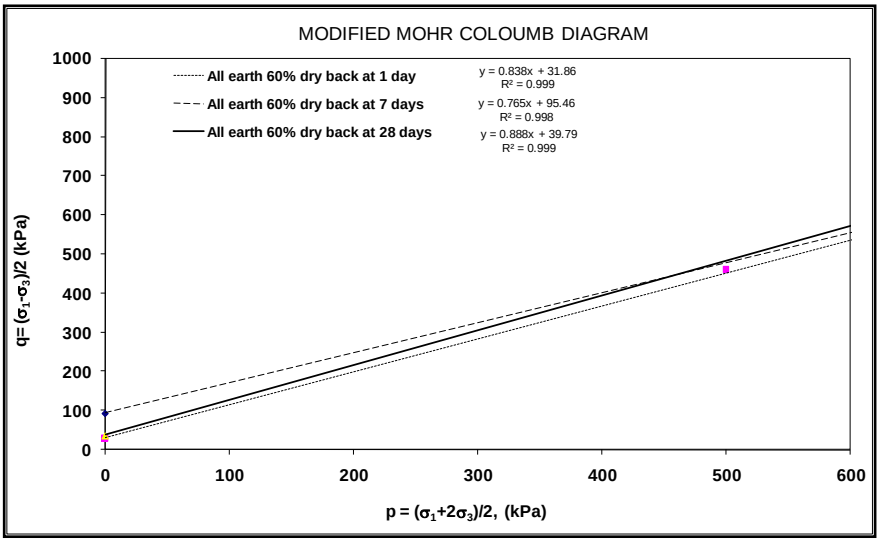


Figure 4.24 The p-q diagram for All Earth materials

4.4.7 The results of resilient modulus characteristics

The values of k_1 k_2 and k_3 for each material are shown in Table 4.13. This also shows the resilient modulus of the materials at 60% and 80% of OMC at specific vertical and confining stress ratios.

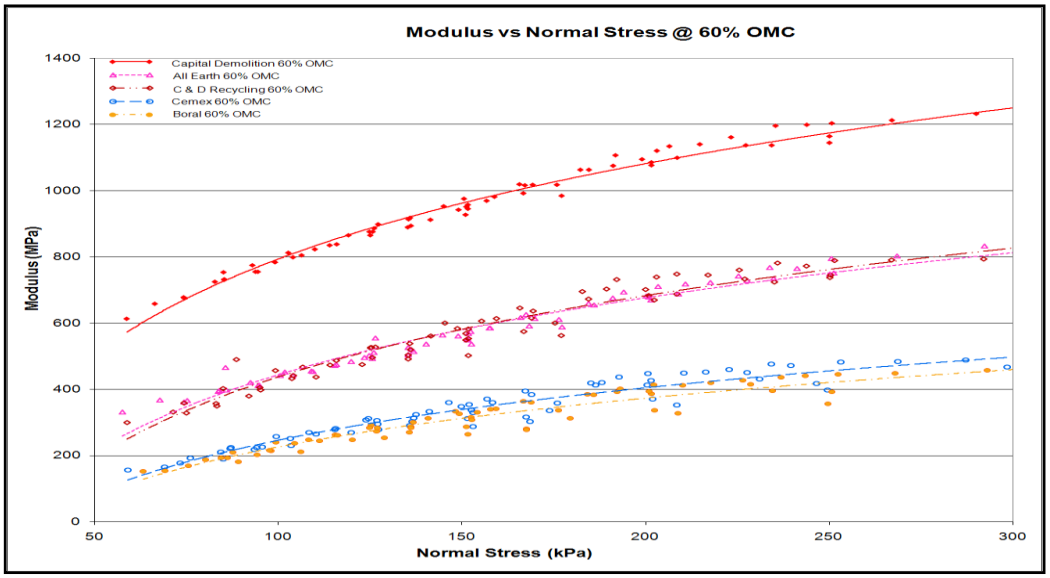
The relationship between modulus and normal stress for the various materials tested at 60% and 80% OMC is shown in Figure 4.26. In this figure, AE represents All Earth, CAP represents Capital Demolition and CD represents C&D Recycling. All the materials are recycled. Capital Demolition, All Earth and C&D Recycling showed very similar values and obtained the highest modulus values.

Material	OMC, %	k_1	k_2	k_3	Resilient Modulus (MPa)							
					σ_1 kPa	**200**	**40**	**200**	**400**	**200**	**400**	**240**
					σ_2 kPa	**50**	**50**	**100**	**100**	**150**	**150**	**94**
All Earth	60	432.5	0.5860	0.0327		440	600	520	670	590	730	540
All Earth	80	351.1	0.2893	0.4113		440	610	450	620	440	620	480
Capital Demolition	60	762.0	0.4192	0.0559		790	1000	880	1070	960	1140	910
Capital Demolition	80	631.9	0.3527	0.1197		670	850	730	900	780	940	760
C&D Rec	60	375.2	0.5311	0.2164		420	610	480	660	520	700	510
C&D Rec	80	356.6	0.3287	0.3344		430	580	440	600	450	610	480

Note: Shaded cells refer to stress states defined in Main Roads WA Road Note 9 (MRWA 2010)

Table 4.13 Material constants K_1 K_2 and K_3 and resilient modulus values under specific vertical and confining stress values

The Capital Demolition road base, which is predominantly structural grade concrete with no brick and tile, clearly showed the highest modulus values. The All Earth and C&D Recycling road base which contained predominantly non-structural concrete with some brick and tile, was estimated to be between 10% and 15% by weight, and showed modulus values significantly higher than the others.



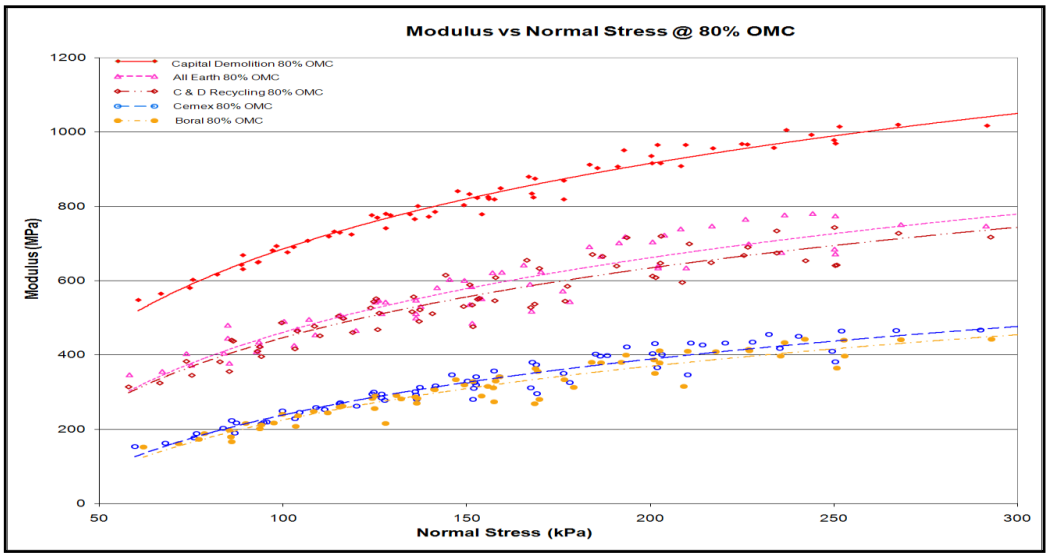


Figure 4.25 Modulus vs normal stress for recycled and quarried road base materials

The above tests were undertaken without curing, and in order to assess the potential changes of modulus with time, one product was selected to undertake resilient modulus testing at 60% OMC over periods of 1, 7 and 28 days curing. All Earth materials were chosen as they represent the middle range of the uncured performance testing.

The results in Figure 4.27 indicate a clear increase in stiffness over time. In practical terms, a higher modulus value will result in lower curvature values and a longer

fatigue life of an asphalt surface. For a spray sealed pavement, permanent deformation is a factor of greater importance.

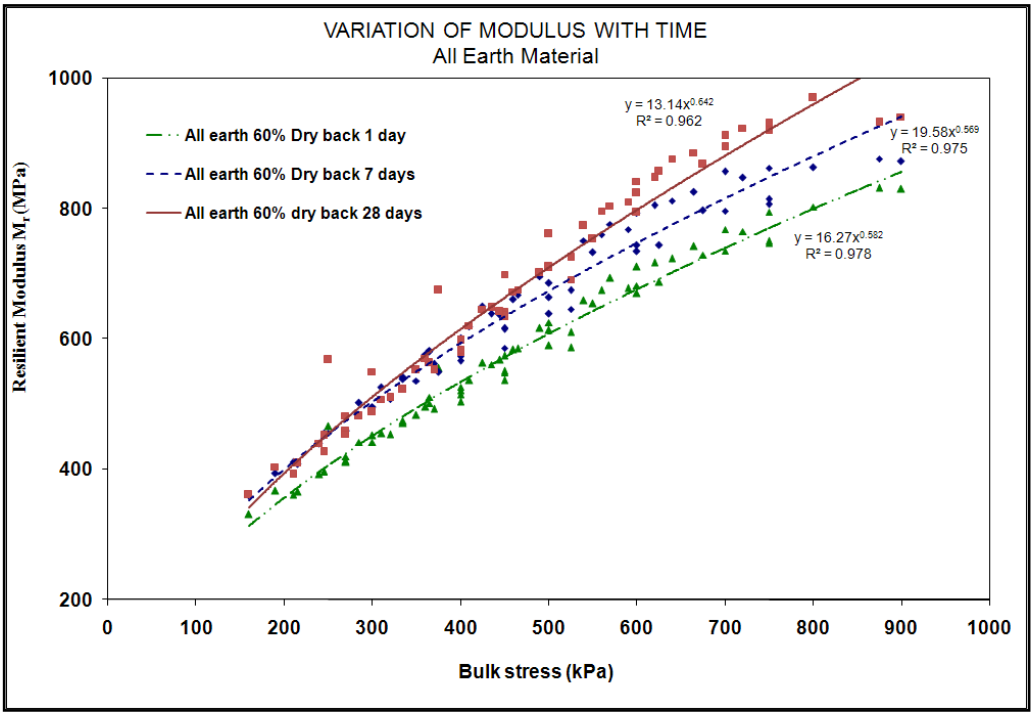


Figure 4.26 All Earth resilient modulus at 1,7 and 28 days

4.5 Analysis of results

The conclusions from this study can be summarised as follows:

4.5.1 Original Washout Crushed Concrete Waste (WCCW)

1. Engineering characteristics of original WCCW are summarised in Table 4.14.

Characteristics	Original WCCW
Liquid Limit (LL),%	22
Plastic Limit (PL),%	20
Plastic Index (PI),%	2
Linear Shrinkage ,%	0
CBR,(Soaked)%	100
MDCS, MPa	1.3
UCS,MPa	0.3
Flakiness Index, %	15
Los Angeles Value, %	29.5

Table 4.14 The engineering characteristics of original WCCW

1. Based on particle size distribution and values of Cu and Cc, the original WCCW is classified in group GP as poorly graded (gap-graded) gravel with sand and little fines. Before and after compaction, particle size distribution shows that there is considerable breakdown of particles during compaction.

2. The material particle shape is triangular with sub-rounded edges. Furthermore, it has a partially porous surface.

3. Quartz and calcite are the main mineral components in WCCW material.

4. Particle density is 2.65t/m^3.

5. The maximum dry density is 1.82t/m^3 while the optimum moisture content is 15.5 %.

6. According to the calculation based on shear test results, the internal friction angle (φ) of 36^0 and an apparent cohesion (c) of 231.1kPa correspond to the Mohr-Coulomb failure envelope of the original WCCW. This indicates original washout crushed concrete waste aggregates attain higher shear strength.

7. Permanent deformation is approximately 2,090 micrometers after 30,000 cycles in stage 3 of the repeat load triaxial (RLT) test method APRG 00/33 developed by the APRB Group. It increases slightly after stage 2. The permanent deformation characteristics of re-graded WCCW can be modelled using Sweere,G.T.H's model from SAMARIS (2004) as $\varepsilon^p=11307N^{0.059}$.

8. Based on the Austroads – APRG 00/33 test standard, resilient modulus characteristics can be modelled by using the K-ϴ model proposed by Hick and Monosmith (1971), as $Mr = 24.48\Theta^{0.47}$.

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4.5.2 Re-graded WCCW

1. Based on the particle size distribution characteristics and values of Cu and Cc, the original WCCW is classified in the group GW, as well-graded gravel with sand and a small amount of fines. After compaction, re-graded WCCW indicates Cu and Cc coefficients as original WCCW.

2. The maximum dry density is 1.89t/m^3 and optimum moisture content is 15 %. Compared with the original WCCW, the maximum dry density increases and the optimum moisture content is slightly reduced.

3. The internal friction angle (φ) of 55.2^0 and an apparent cohesion (c) of 99.4 kPa correspond to the Mohr-Coulomb failure envelope of original WCCW. Compared with the original WCCW, the friction angle increases and cohesion decreases significantly. Shear strength is improved after re-gradation.

4. Permanent deformation is approximately 1,364 micrometers after 30,000 cycles in stage 3 of the repeat load triaxial (RLT) test method APRG 00/33. Deformation increased a little after stage 2. Compared to the original WCCW, permanent deformation was reduced by approximately 35%. The permanent deformation characteristics of re-graded WCCW can be modelled using Sweere,G.T.H's model from SAMARIS (2004) as $\varepsilon^p=799.37N^{0.0496}$.

5. The resilient modulus results of re-graded WCCW were lower than those of the original WCCW. The resilient modulus of the original recycled crushed concrete was higher than that of the re-graded recycle crushed concrete. After re-gradation , the content of the coarse fraction in the material increased while the amount of the sand fraction decreased. This change influenced the elastic behaviour of the material and attempted to reduce the resilient modulus of the re-graded WCCW. Based on the Austroads – APRG 00/33 test standard, resilient modulus characteristics can be modelled by using the K-Θ model proposed by Hick and Monosmith (1971), as $Mr = 8.6047\Theta^{0.6112}$.

6. The almost listed geotechnical and engineering characteristics of WCCW are within the range of the MRWA Specification 501 for base-course material except MDCS and UCS. These values are lower than the specification acceptance limits for crushed rock and crushed recycled concrete base courses.

4.5.3 Construction and Demolition (C&D) Waste

- The mean value of the liquid limit for the construction and demolition material in All Earth, Capital Demolition and C&D Recycing was 35.5 %.

- The mean value of linear shrinkage of the construction and demolition material in All Earth, Capital Demolition and C&D Recycing was 0.27 %.

- Based on the particle size distribution and values of Cu and Cc, C&D Recycling and All Earth were classified in group GP, as poorly graded (gap-graded) gravel with sand and a little fines. The Capital Demolition material was classified as belonging to group GW, as well-graded gravel with sand.

- Regarding C&D Recycling, the maximum dry density and optimum moisture content were 1.96t/m^3 and 11.3% respectively. For All Earth and C&D Recycling material, the maximum dry density and optimum moisture content were 1.86t/m^3 and 10.9%, and for Capital Demolition, 1.91 t/m^3 and 11.3%.

- The unconfined compressive strength of the samples from C&D Recycling were lower than that of Capital Demolition and All Earth, before and after curing. These values gradually increased with time and this strength improvement should be taken as being related to the rehydration of cement residue in wastes.

- The CBR of the Construction and Demolition material lay between 121 % and 171 % compared to a specification minimum of 100%.

- Shear parameters (cohesion and friction angle) of All Earth were 58.4kPa and 56.9^0, respectively. These values are time dependent. After 28 days, both increased dramatically. However, the 7 day results showed a much higher cohesion and a lower friction angle.

- The Capital Demolition waste showed the highest modulus values while All Earth and C&D Recycling waste showed relatively good modulus values.

4.5.4 An evaluation of nominated materials for road construction compared with MRWA Specification 501

To determine the suitable usage of nominated materials in road construction, a comparison with approval standards or specifications of properties is important. In this research, MRWA Specification 501 was chosen. This mainly presents the acceptance limits of characteristics of commonly used materials in base and sub-base courses. Engineering properties of original WCCW and C&D waste materials that have been discovered from experiments were compared with conventional materials such as crushed rock and crushed recycled concrete acceptance limits for a base course in Table 4.15.

Table 4.15 Comparison of original WCCW characteristics with acceptance limits for base courses of MRWA Specification 501

Characterisation	**CRB (Crushed rock base)**	**Crushed Recycled Concrete**	**Original WCCW**	**C&D waste**		
				All Earth	**C&D Recycling**	**Capital Demolition**
Liquid Limit (LL),%	25.0 max	35.0 max	22	34.5		
Plastic Limit (PL),%	n/a	n/a	20			
Plastic Index (PI),%	6.0 max	n/a	2			
Linear Shrinkage ,%	2.0 max 0.4 min	3.0 max	0	0.27		
CBR,(Soaked)%	100 min	100 min	100	121-171		
MDCS, MPa	1.7 MPa min	1.7 MPa min	1.3			
UCS,MPa	n/a	0.6-1.0 MPa	0.3	0.54	0.22	0.67
Flakiness Index, %	30.0 max	n/a	15			
Los Angeles Value, %	35.0 max	40.0 max	29.5			

In this case, in terms of the original WCCW, almost all the listed characteristic values are in a limited range except for MDCS and UCS (marked in red in Table 4.4). MDCS and UCS of the original WCCW is lower than the specification acceptence limit.

Regarding C&D waste, the liquid limit is higher than that for crushed rock base and lower than the rushed recycled concrete acceptance limit.

Table 4.15 illustrates a comparison of engineering properties between original WCCW and C&D Recycling and commonly used materials such as crushed recycled concrete and crushed limestone for sub-base courses.

Table 4.16 Comparison of original WCCW characteristics with acceptance limits for sub-base courses of MRWA Specification 501

Characterisation	**Crushed Recycled Concrete**	**Crushed Limestone**	**Original WCCW**	**C&D waste**		
				All Earth	**C&D Recycling**	**Capital Demolition**
Liquid Limit (LL),%	45.0 max	n/a	22	34.5		
Plastic Limit (PL),%	n/a	n/a	20			
Plastic Index (PI),%	n/a	n/a	2			
Linear Shrinkage ,%	4.0 max	n/a	0	0.27		
CBR,(Soaked)%	50.0 min	30 min	100	121-171		
MDCS, MPa	n/a	n/a	1.3			
UCS,MPa	n/a	n/a	0.3	0.54	0.22	0.67
Flakiness Index, %	n/a	n/a	15			
Los Angeles Value, %	45.0 max	20.0 min 60.0 max	29.5			

According to Table 4.16, all nominated material properties received from experimental processes are within acceptance limits.

The AASHTO soil classification system has been developed, based on Group Index (GI), determined by material particle size distribution and consistency limits for using it as a sub-base material. Due to this classification, all the nominated materials could be silty or clay-like gravel and sand with an excellent to good sub-grade rating (EI-Korchi 2009).

Shear parameters of nominated materials derived from the laboratory results from the study are compared with CBR shear parameters as shown in Table 4.17. The cohesion of the nominated materials is significantly higher than CBR except for All Earth. However, the friction angles of nominated material are close excepting those of the original WCCW.

Table 4.17 Comparison of shear parameters between CBR and nominated materials

Shear parameters	**CBR**	**Original WCCW**	**Re-graded WCCW**	**All Earth**
Cohesion,kPa (c)	32	231.1	99.4	58.4
Friction angle,^{0} (φ)	59	36	55.2	56.9

CHAPTER 5

MECHANICAL-EMPIRICAL ANALYSIS AND DESIGN

5.1 Overview

This chapter shows the responses of pavements modelled on the pavement prototype built by the investigated materials in this study. The resilient modulus values of the four investigated materials were determined from the resilient modulus relationships developed in Chapter 4. The modulus was used as the input parameter for the determination of the appropriate depth of the investigated materials, and was obtained from the CIRCLY 5.0 design program. In the final part of this chapter, the finite element program, ABAQUS, was utilised to determine the horizontal tensile strain and vertical compressive strain at the base course layer and sub-grade level respectively.

5.2 Resilient modulus range of investigated materials

To determine the resilient modulus value of the investigated materials, based on the resilient modulus model developed in Chapter 4, the bulk stress in the designed pavement under Standard Axle (SA) must be identified. The Standard Axle (SA) is a single axle with dual tyres (SADT), applying an axle load of 80 kN to the pavement as shown in Figure 5.1.

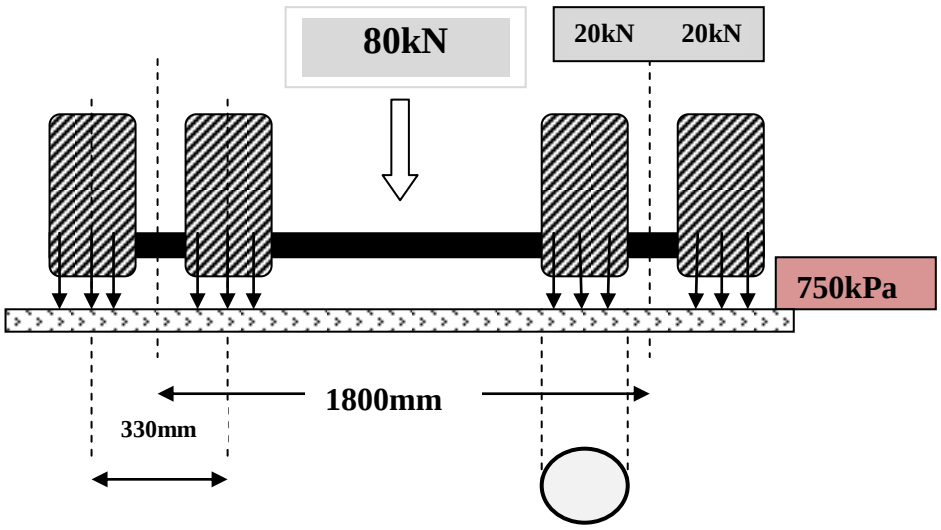


Figure 5.1 Scheme of Standard axle (SA)

As can be seen in Figure 5.1 the load on the tyre is 80kN/4 = 20 kN. The tyre-pavement contact stress is assumed to be uniform and equal to a tyre pressure of 750 kPa. The tyre contact surface is modelled as circular with the radius, R = 92.1mm.

The loading conditions as shown in Figure 5.1, are used to compute the bulk stress in the designed pavement, illustrated in Figure 5.2. Firstly, the vertical stress, assuming a uniformly loaded circular area at the point z = 50mm below the asphalt layer, is calculated by Equation 5-1. This equation was created by Ahlvin and Ulery in 1962 (Das 2010). The vertical stress is the transformed tyre pressure from the standard axle into the top of the base layer.

$$\sigma_{1z} = q\,(A'+B') \qquad (5\text{-}1)$$

where σ_{1z} = vertical stress at z point, kPa

q = uniform load or tyre pressure, kPa

A' = function of z/R

B' = function of r/R

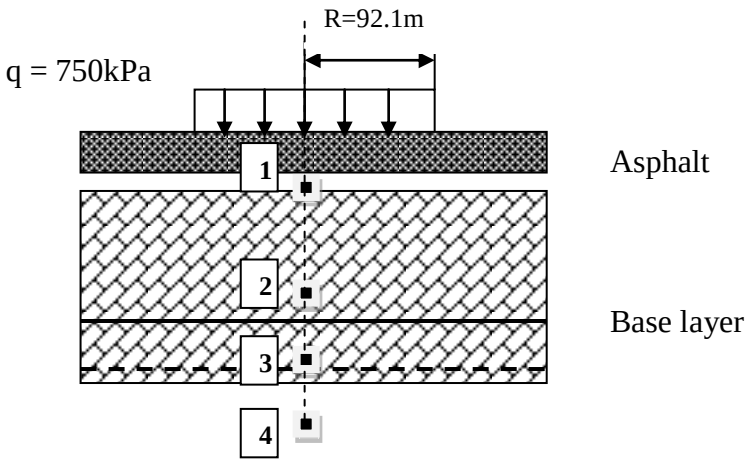


Figure 5.2 Designed pavement configuration for calculation of bulk stress

From equation (1) and Table 10.6 and 10.7 (Das 2010) at the centre of the layer the load is (r=0) and at point 1, which is z = 50 mm (asphalt layer thickness), the vertical stress σ_1= 683.2kPa is found. This vertical stress is used in the calculation of bulk stresses at points 2,3 and 4 in various base course depths of the pavement.

In terms of the base layer, bulk stresses of different depths are calculated from stress equations of the flexible plate along the centre of the plate as shown in Equations 5-2, 5-3 and 5-4.

$$\sigma_1 = q\left[1 - \frac{z^3}{(a^2+z^2)^{1.5}}\right] \quad (5\text{-}2)$$

$$\sigma_3 = \frac{q}{2}\left[1 + 2\nu - \frac{2(1+\nu)z}{(a^2+z^2)^{0.5}} + \frac{z^3}{(a^2+z^2)^{1.5}}\right] \quad (5\text{-}3)$$

$$\theta = \sigma_1 + 2\,\sigma_3 + \gamma z\,(1+2K_0) \quad (5\text{-}4)$$

where σ_1 and σ_3 = principal stresses, kPa

q = the uniform load or tyre pressure, kPa

a = the circular load radius, mm

z = the depth of the point below surface of base layer

ν = the Poisson's ratio

Θ = the bulk stress, kPa

γ = the unit weight of material

K_0 = the coefficient of earth pressure at rest $K_0 = 0.6$

For computing bulk stress, material densities and Poisson's ratio are utilised. See Table 5.1.

Table 5.1 Material properties used for the calculation of bulk stresses

Properties	**Investigated materials**			
	WCCW	**C&D**	**ALL EARTH**	**CAPITAL DEMOLITION**
Density, ton/m^3	1.87	1.96	1.86	1.91
Poisson's ratio	0.35	0.35	0.35	0.35

Table 5.2 demonstrates the results of bulk stress. According to Table 5.2, the bulk stress in an original WCCW base layer is between 1102.4kPa and 266.6kPa at a depth of 0-150mm. These bulk stress measurements are used for computing the resilient modulus of the material using the K-Theta model (section 4.2.12.2), developed from laboratory results. The resilient modulus values with respect to the bulk stress of 1102.4kPa to 266.6kPa are within a range of 658.9MPa to 338.1MPa as can be seen in Figure 5.3.

Table 5.2 Principal and bulk stresses of investigated materials

Point in Figure 5.2	Depth below surface of base layer (mm)	Stresses (kPa)				
		Principal and bulk stresses (kPa)	WCCW	C&D	ALL EARTH	CAPITAL DEMOLITION
1	0	σ_1	668.2	668.2	668.2	668.2
		σ_3	217.1	217.1	217.1	217.1
		θ	1102.4	1102.4	1102.4	1102.4
2	100	σ_1	400.8	400.8	400.8	400.8
		σ_3	43.4	43.4	43.4	43.4
		θ	491.6	491.8	491.6	491.7
3	150	σ_1	253.9	253.9	253.9	253.9
		σ_3	3.3	3.3	3.3	3.3
		θ	266.6	266.8	266.6	266.7
4	225	σ_1	104.3	104.3	104.3	104.3
		σ_3	3.34	3.34	3.34	3.34
		θ	119.9	120.4	119.9	120.1

These values are the suggested values for the resilient modulus of the original WCCW, for the purpose of mechanistic and design analysis. However, a mean value of 500MPa was chosen for the analysis.

For all materials except the original WCCW, the resilient moduli are determined by normal stress, which is presented in Figure 5.4. The figures are plotted from laboratory results. The maximum normal stress is 300kPa. Therefore normal stresses are between 253.9kPa and 104.3kPa (chosen from Table 5.2). The resilient modulus values with respect to the abovementioned normal stress are in the range of 420MPa to 700MPa for C&D Recycling material, 440MPa to 730MPa for All Earth's material and 660MPa to 990MPa for Capital Demolition's material. These discovered values could be the suggested value for the resilient moduli for C&D Recycling, All Earth and Capital Demolition materials (for mechanistic and design analysis). Similarly, with the original WCCW, the mean values of 560MPa, 585MPa and 825MPa

(marked below by a red line) are used in the analysis for C&D Recycling, All Earth and Capital Demolition, respectively. These can be seen in Figure 5.4.

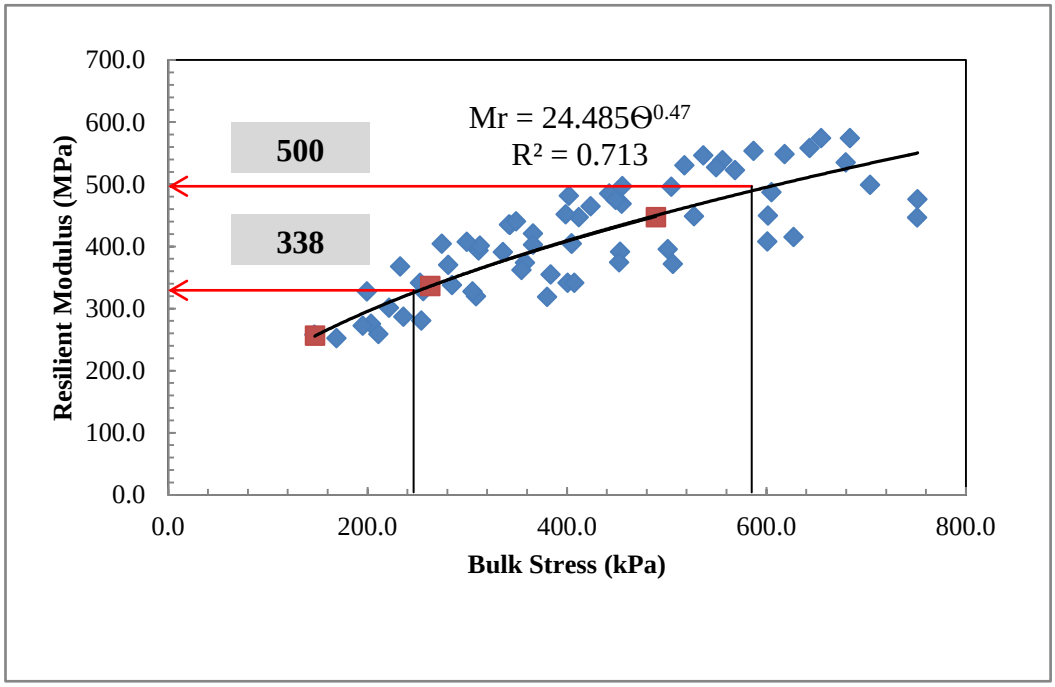


Figure 5.3 Resilient modulus range of original WCCW material

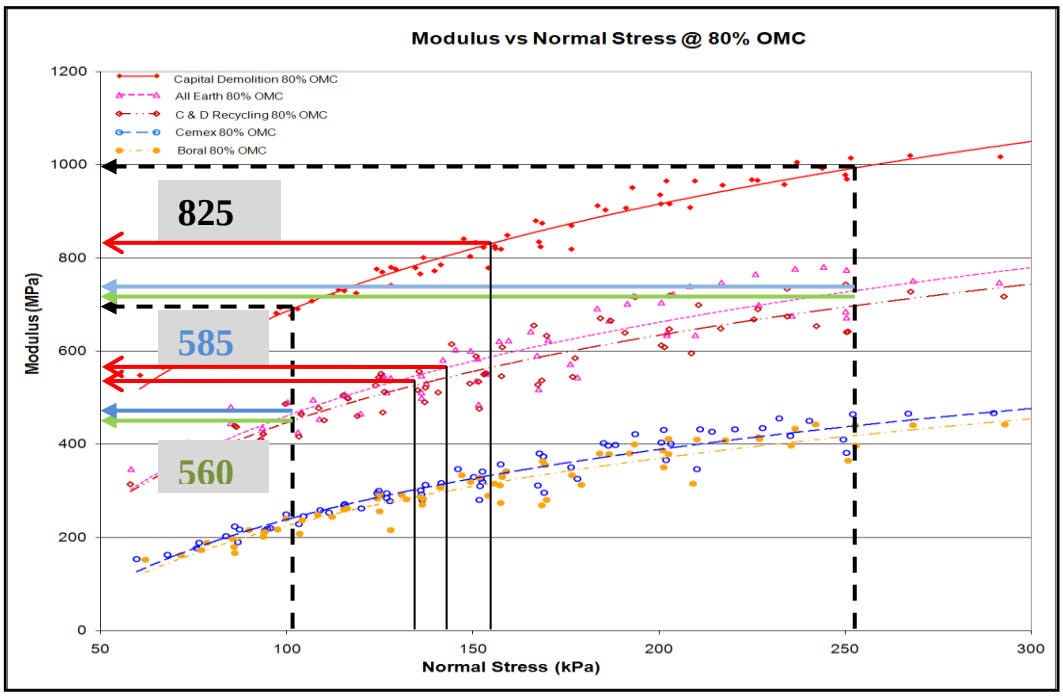


Figure 5.4 Resilient modulus ranges for C&D Recycling, All Earth, and Capital Demolition

5.3 The pavement configuration analysis in CIRCLY 5.0

In this research, the software CIRCLY 5.0 was used for a mechanistic and design analysis of pavements with selected materials.

5.3.1 Analysis load conditions

According to the Austroads "Pavement Design" guidelines, the Standard axle is a single axle with dual tyres with a load of 20kN over a circular area of 92.1mm in diameter. Tyre-pavement contact stress is assumed to be uniform and equal to a tyre pressure of 750kPa. The design analysis conducted on traffic movements in urban and rural residential and industrial areas was between $3x10^5$ESA's to $5x10^6$ESA's (Equivalent Standard Axle) (Pavement Design D2, Western Australia 1998).

5.3.2 Material characteristics

The isotropic materials in the analysis should be consider as homogeneous and elastic – elastic for the asphalt layer and anisotropic-elastic for the granular base and the sub-grade. The following elastic properties were used for input: the vertical elastic modulus (resilient modulus) E_v , the horizontal elastic modulus $E_h = 0.5\ E_v$, Poisson's ratio ν_v and ν_h and the shear modulus $f=E_v/(1+\nu)$, as shown in Table 5.3.

Table 5.3 Material characteristics used in CIRCLY analysis

Pavement layers	Selected materials	Elastic properties	Elastic modulus Ev (MPa)	Elastic modulus Eh (MPa)	Shear modulus, $f=E_v/(1+\nu)$ (MPa)	Poisson's ratio ν
Wearing course	Asphalt	Isotropic	3000	-	-	0.40
Base	**Original WCCW**	Anisotropic	500	250	370	0.35
	C&D	Anisotropic	560	280	415	0.35
	All Earth	Anisotropic	585	292	433	0.35
	Capital Demolition	Anisotropic	825	412	611	0.35
Sub-base	Crushed Limestone	Anisotropic	250	125	185	0.35
Sub grade	Perth sand	Anisotropic	100	50	74	0.35

Table 5.4 and Figure 5.5 show a summary of the pavement design analysed in CIRCLY 5.0. The asphalt and sub-base thicknesses are considered as 50mm and 250 mm constants in the whole analysis. The pavement with crushed rock base (CRB) was chosen as the baseline reference for pavement configuration.

Table 5.4 A summary of pavement configuration, analysed in CIRCLY 5.0

	WCCW Mr=500MPa	**C&D Recycling** Mr=560MPa	**All Earth** Mr=585MPa	**Capital Demolition** Mr=825MPa	**CRB** Mr=350 MPa
Street type-1: Urban and rural residential (Local access street, **3x10^5 ESA's**, 25 year design life)					
Asphalt, mm	50	50	50	50	50
Base course, mm	**105**	**102**	**102**	**102**	**244**
Sub-base, mm	250	250	250	250	250
Sub-grade, mm	-	-	-	-	-
Street type-2: Urban residential (Collector street, **1x10^6 ESA's**, 25 year design life)					
Asphalt, mm	50	50	50	50	50
Base course, mm	**237**	**160**	**151**	**150**	**-**
Sub-base, mm	250	250	250	250	250
Sub-grade, mm	-	-	-	-	-
Street type-3: Urban residential (Distributor road, **2x10^6 ESA's**, 25 year design life)					
Asphalt, mm	50	50	50	50	50
Base course, mm	**-**	**325**	**259**	**175**	**-**
Sub-base, mm	250	250	250	250	250
Sub -grade, mm	-	-	-	-	-
Street type-4: Commercial and Industrial (**5x10^6 ESA's**, 25 year design life)					
Asphalt, mm	50	50	50	50	50
Base course, mm	**-**	-	-	**205**	-
Sub-base, mm	250	250	250	250	250
Sub-grade, mm	-	-	-	-	-

Table 5.4 and Figure 5.5 indicate that all nominated materials have the potential to be effectively utilised in local access streets with 3x10^5 ESA's. In this case, the

minimum base thickness for the original WCCW is 105mm. For C&D Recycling, All Earth and Capital Demolition, the minimum base thickness is 102mm. These thicknesses measure less than half of the crushed rock base (CRB) thickness. For a collector street in an urban residential area with $1x10^6$ ESA's, all the investigated materials are suitable for use as base layers of between 150mm and 237mm with the exception of the CRB material.

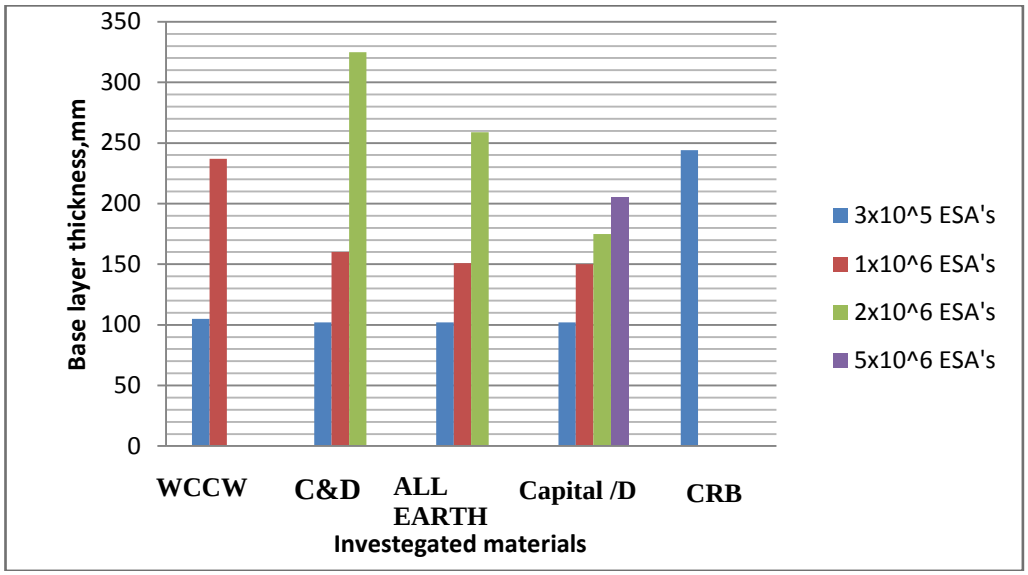


Figure 5.5 Design base layer thicknesses for investigated materials

C&D Recycling, All Earth and Capital Demolition materials work in pavements in distributor streets with $2x10^6$ ESA's. Capital Demolition's materials have the potential for use in pavement base layers but only in roads in commercial and industrial areas. From Figure 5.5, it can be seen that the material with a high resilient modulus demonstrates wide possibilities for use in various street types in urban and residential areas.

5.4 Finite Element analysis in ABAQUS/CAE 6.9

5.4.1 Background

Finite element analysis of pavements was carried out by using the finite element software ABAQUS/CAE 6.9 in street type 1 as shown in Table 5.4 and Figure 5.6. The purpose of this analysis was to assess the critical strains and horizontal tensile and compressive vertical strains on top of the base layer and at the sub-grade level, in the design models. These strains are illustrated in Figure 5.7. Critical strains must be identified in order to evaluate damage such as surface cracking and rutting of the pavement.

ABAQUS, a commercial finite element modelling program, has been widely applied for pavement analysis. Zaghloul and White (1993) simulated the pavement responses under FWD loading for flexible pavement using three-dimensional dynamic analysis in ABAQUS. The main capabilities of ABAQUS in solvinh pavement engineering problem include linear and nonlinear elastic, viscoelastic, and elasto-plastic material modelling, two-dimensional and three dimensional calculation, static, harmonic dynamic, and transient dynamic loading simulation, interface modelling with friction, cracking propagation modelling and thermal gradient analysis. Furthermore, ABAQUS provides many element types that are useful for pavement analysis.

5.4.2 Pavement models considered for the analysis

The designed pavement models selected for this analysis are illustrated in Figure 5.6. They consisted of a 50 mm thick asphalt layer as the surfacing course, a 250mm thick granular layer as the sub-base course, and a sub-grade layer (Perth sand) at the bottom. This was consistent for all models except Model-5. For the base course, four types of investigated materials plus a reference (control) material were selected for each model with a thickness of between 102 mm and 244 mm.

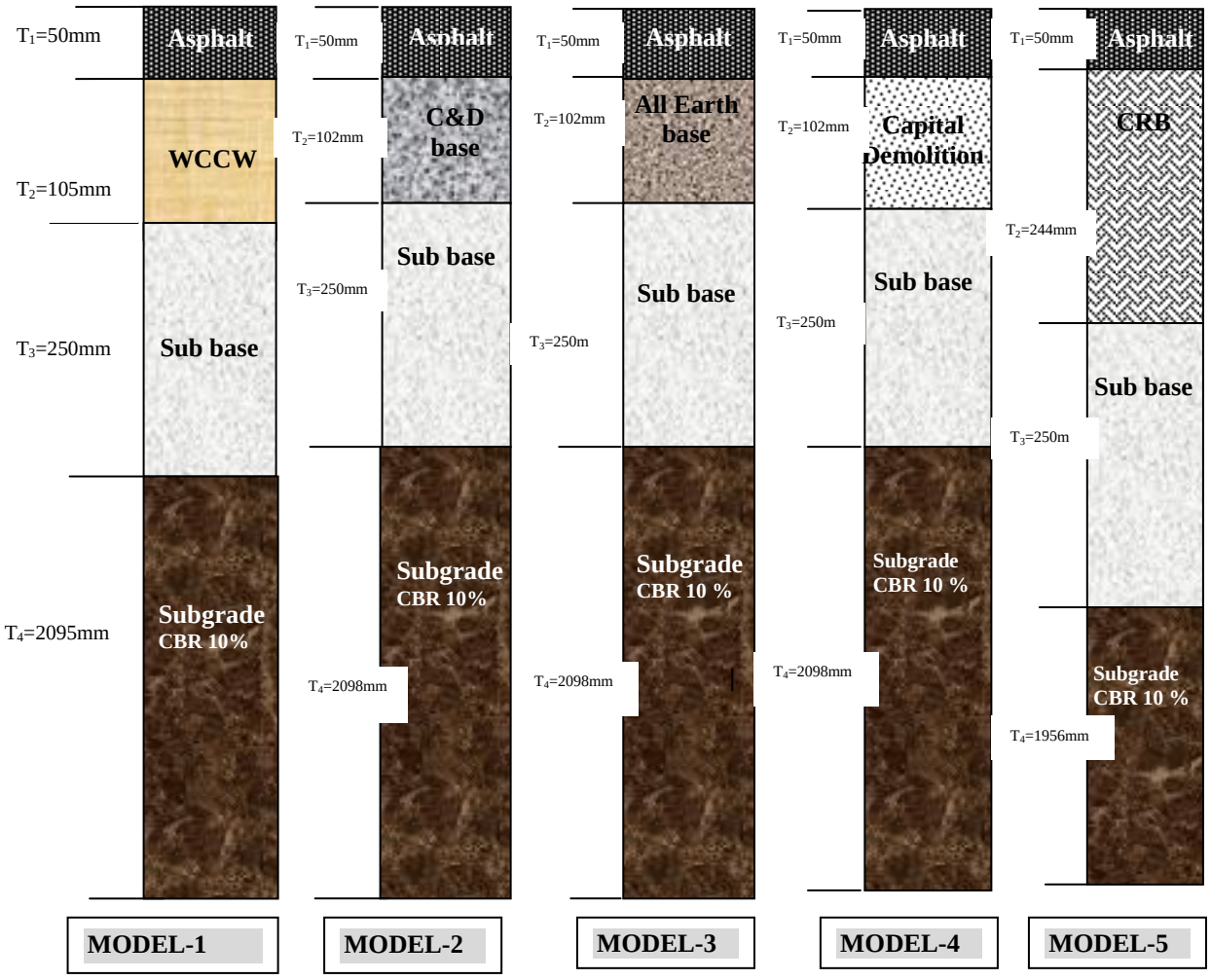
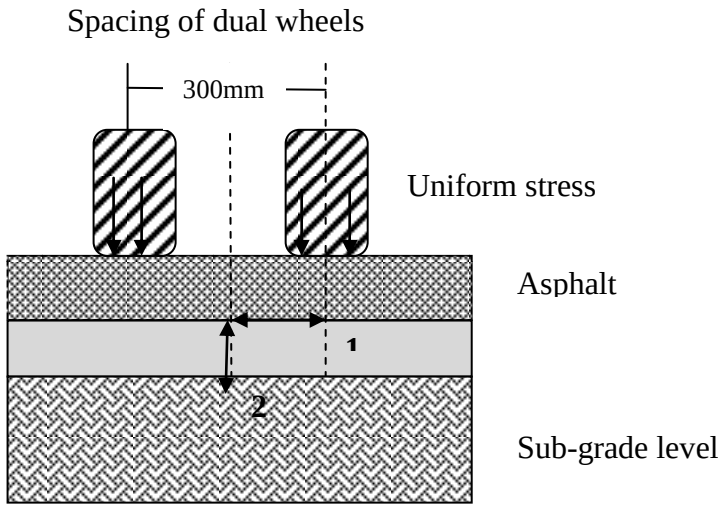


Figure 5.6 Pavement configurations in street type 1 computed using CIRCLY 5.0

The material properties of the pavement layers are taken from Table 5.3.

5.4.3 Analysis condition

Figure 5.8 shows the finite element mesh considered in the analysis. The 20kN wheel load is assumed to be uniformly distributed over the contact area between tyre and pavement. The contact pressure is assumed as being equal to the tyre pressure, which is 750kPa. The pavement block under analysis has a width of 4m and a depth of 2.5m and is subjected to a single wheel load. In ABAQUS, this pavement block is modelled with C2D8R (Continuum 2-Dimensional 8 node elements with reduced integration).



1 – Horizontal tensile strain at bottom of asphalt

2 – Vertical compressive strain at top of sub-grade level

Figure 5.7 Critical strains in pavement layers

The C2D8R element type is quadratic, and the pavement block mesh consists of 100,000 elements. All vertical boundary nodes have roller supports with fixed horizontal boundary nodes at the bottom of the finite element mesh.

5.4.4 Analysis results

The results obtained from ABAQUS /CAE 6.9 analysis are shown in Figure 5.9. This figure mainly shows the comparison of critical strains in each model.

As can be seen from Figure 5.9, the vertical compressive strain and the horizontal tensile strain on top of the sub-grade level and base layer for pavements with WCCW gave measures of (-1338μm) and 260 μm. For pavement with materials from C&D Recycling, the base course measurements were (-1336μm) and 222μm. For pavement with materials from All Earth, the base course measurements were

(-1331μm) and 207μm. For pavement with materials from Capital Demolition, the base course measurements were (-1295μm) and 98μm, and for pavement with CRB materials the base course measurements were (-1032μm) and 356 μm.

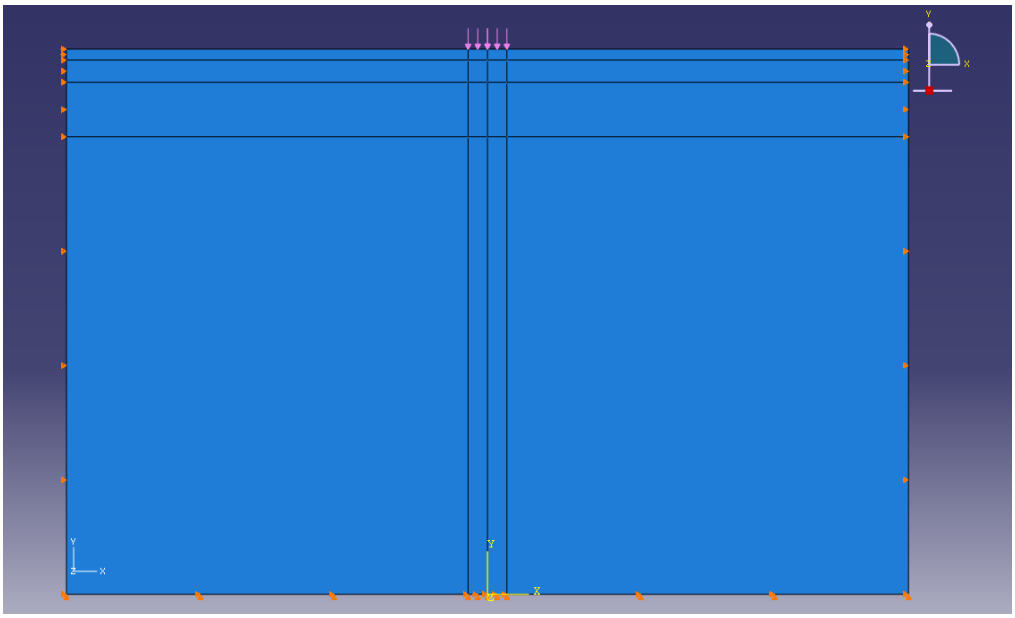


Figure 5.8 The finite element mesh considered in the analysis

With regard to the horizontal tensile strains at the top of the base course in various models, the lowest value result was from Capital Demolition with 98μm and the highest value was CRB with 356μm. For other selected materials, this strain was between 207 and 260μm.

Regarding vertical compressive strain at the top of the sub-grade level in designed pavement models, the values in the models are nearly equal to one another, except those of Capital Demolition and CBR. In terms of WCCW, C&D Recycling and All Earth materials, the strain lies between (-1331) and (-1338)μm.

Comparing the above models with CRB pavement, the strains at the bottom of the asphalt layer are lower in these models, especially in pavement with Capital Demolition materials as the base course. In terms of strain at the top of the sub-grade level in the models, the measures are higher than the strain measurements in the pavement with CBR materials.

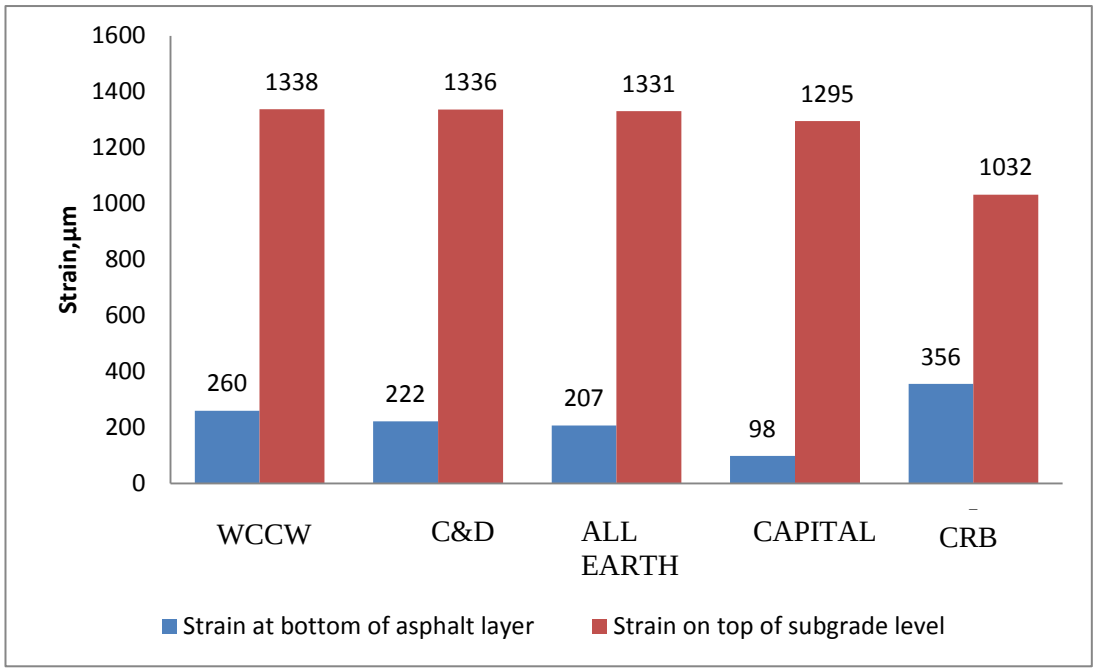


Figure 5.9 Comparison of critical strains in designed models with selected materials

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

This research proposed to determine the potential usage of Western Australian construction waste as a road base material. The research study, undertaken in the Geotechnical Laboratory at Curtin University, investigated the geotechnical and engineering properties of washout crushed concrete waste (WCCW) from Holcim Ltd and the properties of construction and demolition waste materials from the companies: All Earth, Capital Demolition and C&D Recycling. Based on the geotechnical and engineering properties of the investigated materials, their potential use as granular pavement material was evaluated. Using the derived engineering parameters, pavement design configurations were used to gauge pavement responses. The following conclusions are drawn from this study.

6.1 Characteristics of Washout Crushed Concrete Waste (WCCW)

6.1.1 Original WCCW

1 The engineering characteristics of original WCCW are summarised below:

- The liquid limit is 22%.
- The plastic limit is 20%
- The plastic index is 2%
- The linear shrinkage is zero.
- The California bearing ratio (CBR value) is 100% in soaked condition.
- The maximum dry compressive strength is 1.3MPa.
- The unconfined compressive strength is 0.3MPa.
- The flakiness index is 15%
- The Los Angeles value is 29.5%.

2 Based on particle size distribution and values of Cu and Cc, the original WCCW is classified in group GP as poorly-graded (gap-graded) gravel with sand and little fines. Before and after compaction, particle size distribution shows that there is considerable breakdown of particles during compaction.

3 The material's particle shapes are triangular with sub-rounded edges. And they have a partially porous surface.

4 Quartz and calcite are the main mineral components of the WCCW material.

5 Particle density of the WCCW is 2.65t/m^3.

6 The maximum dry density of the WCCW is 1.82t/m^3 while the optimum moisture content is 15.5 %.

7 According to calculations based on shear test results, the internal friction angle (φ) of 36^0 and an apparent cohesion (c) of 231.1kPa correspond to the Mohr-Coulomb failure envelope with regard to the original WCCW. This indicates that original WCCW aggregates attain higher shear strength.

8 Permanent deformation is approximately 2,090 micrometers after 30,000 cycles in stage 3 of the repeat load triaxial (RLT) test method APRG 00/33, (developed by the APRB Group). Deformation increases slightly after stage 2. The permanent deformation characteristics of re-graded WCCW can be modelled using Sweere,G.T.H's model from SAMARIS (2004), as $\varepsilon^p=11307N^{0.059}$.

9 Based on the Austroads – APRG 00/33 test standard, resilient modulus characteristics can be modelled by using the K-ϴ model proposed by Hick and Monosmith (1971), as $Mr = 24.48\Theta^{0.47}$.

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6.1.2 Re-graded WCCW

1. Based on the particle size distribution characteristics and values of Cu and Cc, the original WCCW is classified in the group GW, as well-graded gravel with sand and a small amount of fines. After compaction, re-graded WCCW indicates the same Cu and Cc coefficients as original WCCW.

2. The maximum dry density is 1.89t/m^3 and optimum moisture content is 15 %. Compared with the original WCCW, the maximum dry density of the re-graded material increases and the optimum moisture content is slightly reduced.

3. The internal friction angle (φ) of 55.2^0 and an apparent cohesion (c) of 99.4 kPa correspond to the Mohr-Coulomb failure envelope of the original WCCW. Compared with the original WCCW, the friction angle of the re-graded material increases and cohesion decreases significantly. Shear strength is improved after re-gradation.

4. Permanent deformation is approximately 1,364 micrometers after 30,000 cycles in stage 3 of the repeat load triaxial (RLT) test method APRG 00/33. Deformation increased a little after stage 2. Compared to the original WCCW, permanent deformation was reduced by approximately 35%. The permanent deformation characteristics of re-graded WCCW can be modelled using Sweere, G.T.H's model from SAMARIS (2004) as $\varepsilon^p=799.37N^{0.0496}$.

5. The resilient modulus results of re-graded WCCW were lower than those of the original WCCW. The resilient modulus of the original recycled crushed concrete was higher than that of the re-graded recycle crushed concrete. After re-gradation, the content of the coarse fraction in the material increased while the amount of the sand fraction decreased. This change influenced the elastic behaviour of the material and attempted to reduce the resilient modulus of the re-graded WCCW. Based on the Austroads – APRG 00/33 test standard, resilient modulus characteristics can be modelled by using the K-ϴ model proposed by Hick and Monosmith (1971), as $Mr = 8.6047\Theta^{0.6112}$.

6. The almost listed geotechnical and engineering characteristics of WCCW are within the range of the MRWA Specification 501 for base course materials except MDCS and UCS. These values are lower than the specification acceptance limits for crushed rock and crushed recycled concrete base courses.

6.2 Characteristics of Construction and Demolition (C&D) waste

1. The mean value of the liquid limit for the construction and demolition materials from All Earth, Capital Demolition and C&D Recycing was 35.5 %.

2. The mean value of linear shrinkage of the construction and demolition material from All Earth, Capital Demolition and C&D Recycing was 0.27 %.

3. Based on the particle size distribution and values of Cu and Cc, C&D Recycling and All Earth were classified in group GP, as poorly graded (gap-graded) gravel with sand and little fines. The Capital Demolition material was classified in group GW, as well-graded gravel with sand.

4. Regarding C&D Recycling, the maximum dry density and optimum moisture content were 1.96t/m^3 and 11.3% respectively. For All Earth the maximum dry density and optimum moisture content were 1.86t/m^3 and 10.9%, and for Capital Demolition, 1.91t/m^3 and 11.3%.

5. The unconfined compressive strength of the samples from C&D Recycling was lower than that of Capital Demolition and All Earth, before and after curing. The strength value gradually increased with time and this strength improvement should be taken as being related to the rehydration of cement residue in wastes.

6. The CBR of the Construction and Demolition material lay between 121 % and 171 % compared to the specification minimum of 100%.

7. The shear parameters (cohesion and friction angle) of All Earth were 58.4 kPa and 56.9^0, respectively. These values are time dependent. After 28 days, both increased dramatically. However, the 7 day results showed a much higher cohesion and a lower friction angle.

8. The Capital Demolition waste showed the highest modulus values while All Earth and C&D Recycling waste showed relatively good modulus values.

6.3 Pavement mechanistic and design analysis

1. According to the results from CIRCLY 5.0, these research materials have the potential for use in local access streets with $3x10^5$ ESA's and collector streets with $1x10^6$ ESA's as a granular base course. Furthermore, C&D Recycling, All Earth and Capital Demolition waste materials should perform well as a granular base course in distributor streets with $2x10^6$ ESA's. Moreover, the Capital Demolition waste shows good performance as a granular base course not only in urban residential streets but also in commercial and industrial streets.

2. According to finite element modelling of the horizontal tensile strains at the top of base courses in various models, the lowest value came from Capital Demolition with 98μm and highest value from CRB with 356μm. For other selected materials, this strain was between 207μm and 260μm. The higher the resilient modulus of the granular material the lower the horizontal tensile strain.

3. Regarding vertical compressive strain at the top of the sub-grade level in designed pavement models, the values in the models are almost equal with the exception of Capital Demolition and CBR. In terms of WCCW, C&D

Recycling and All Earth materials, the strain lies between (-1331) and (-1338)μm.

4. Compared to conventional pavement with a CRB base course, the horizontal tensile strain existing in the designed pavement has been found to be lower. In contrast, the vertical compressive strain is higher.

6.4 Final conclusion

Laboratory investigation and pavement and design analysis in this study indicate that the materials selected from the companies: Holcim Ltd, All Earth, Capital Demolition, and C&D Recycling, are suitable to be used as construction materials for the base and sub-base layers of flexible pavement in Western Australia.

6.5 Recommendations for future study

1. Future work could investigate pavement responses on a trial pavement of selected models in-situ, which would verify the results obtained from the experimental and numerical analyses in this research.

2. Materials selected for this research were sourced from concrete material. It is recommended that an investigation of the mechanical characteristics of these materials should be carried out under time-dependent curing conditions of durations such as 60, 90 180 and 360 days, given that the rehydration process in the remaining cement paste influences the unconfined compressive strength (UCS) test results.

REFERENCES

Abu-Lebdeh, Ghassan, Rick Lyles, Gilbert Baladi, and Kamran Ahmed (2003) "Development of alternative pavement distress index models" Department of Civil & Environmental Engineering, Michigan State University

Administration, Federal Highway (2006) " Pavement distress identification manual for the NPS road inventory programm. Cycle 4, 2006-2009, USA: United States of American, Department of Transportation

---

AI-Mansour, Abdullah (1999) "Development of pavement performance models for Riyadh street network." Transportation Research Board No 1655,TRB, National Research Council, Washington,D.C, 25-30.

Alam, Tashina Binte, Magdy Abdelrahman, and Scott A.Schram (2009) "Laboratory characterisation of recycled asphalt pavement as a base layer."Curtin Univesrity Library. 17 Feb 2009. http://dx.doi.org/10.1080/10298430902731362 (accessed May 14, 2010).

Alonso C., and L. Fernandez (2004) "Dehydration and rehydration processes of Cement paste exposed to high temperature environments." Journal of materials Science 39, 2004: 3015-3024.

Asaeda Takashi., and VU Thanh Ca (2000) "Characteristics of permeable pavement during hot summer weather and impact on the thermal environment." Building and Environment, 2000: 363-375.

Austroads. Technical Basis of Austroads Guide to Pavement Technology (2008) Part 2: Pavement Structural Design. Austroads Project No TT1159, Sydney MSW AUSTRALIA: Austroads Incorporated.

Austroads (2008) " Guide to Pavement Technology Part 4A " Granular Base and Subbase Materials"

Berchelot C, Haichert R, Podborochynski D, Wanddzura C, Taylor B, Bews R, Guenther D and Prang C (2008) " Use of Recycled Ashpalt Concrete and Portland Cemenet Concrete in Road Substructure Construction Transportation Research Board Transportation Research Record

Bob, Cechet (2000) "Climate Change Impact on the Pavement Maintenance and Rehabilitation Costs associated with the Australian National Highway Network." http://mssanz.org.au/modsem05/papers/cechet.pdf (accessed July 13, 2010).

Bowman B, 2009 " Recycled concrete roadbase quality investigation- Report for SWIS Grant 4003: Waste Management Authority Perth Western Australia

Centre for Pavement Engineering Education (2005) "Pavement Design."Australian Asphalt Pavement Association

(C-SHRP), Canadian Strategic Highway Research Programm (2006) "Pavement structural design practices across Canada. C-SHRP Technical Brief #23, Ottawa, Ontaria: C-SHRP

David, Hazell (2007) "Optimum Use of Granular Bases: Material Selection for Detailed Performance Evaluation. Austroads Technical Report, Sydney NSW: Austroads.

Das, Braja M (2010) "Principles of Geotechnical Engineering" Cencage Learning

Dimitru I, BakasetasJ, Formosa M, Walter P and Aich B A (1997) " New Recycled Roadbase Developed from Reclaimed Asphalt Pavement (RAP) ,ATERIAL AND Recycled Crushed Concrete Proc. Of the 19th ARRB Conference, Sydney Australia

Drakos, Christos (2005) "Lecture: Flexible Pavement Distress" http://www.ce.ufl.edu/~rroqu/Class Notes TTE4811/Topic 2 - Flexible Pavement Distress.pdf, USA, University of Florida

Ineson.P.R (1990) “Siliceous Components in Aggregates.” Cement & Concrete Composites12 , 1990: 185-190.

EI-Korchi, Mallick Rajib B. and El Korchi Takar (2009) “Pavement Engineering Principles and Practice” CRC Press

Hicks RG, Monismith CL (1971) “Factors influencing the resilient properties of granulr materials” Highway Res Rec 345:15-31

Kim Daehyeon., and Jong Ryeol Kim (2007) “Resilient bahaviour of compacted subgrade soils under the repeated triaxial test.” Construction and Building Materials 21, : 1470-1479.

Kio S, Mahgoub H and A Nazef A (2002) “ Investigation of Recycled Concrete Made with Limestone Aggregate for a Basecourse in Flexible Pavement Transportation Research Report 1787 99 Paper No.02-3098 National Research Council, Washington, DC

Korkiala-Tanttu, Leena (2009) “Calculation method for permanent deformation of unbound pavement materials” PhD Thesis, Espoo, Finland: Helsinki University of Technology

Krishna, Tom V. Mathew and K V (2007) “Introduction to Transportation Engineering”

Leek, Colin (2008) “ Use of recycled crushed demolition materials as base and sub-base in road construction” http://www.cdrecycling.com.au/pdf/ColinLeek.pdf (accessed August 04, 2010).

Lekarp.E ., A.Dawson (1998) “Modelling permanent deformation behaviour of unbound granular materials.” Construction and Building Materials, 1998: 9-18.

MINCAD. CIRCLY 5 (2004) User Manual. User Manual, Vic Australia:MINCAD Systems Pty.Ltd

May RW, Witczak MW (1981) " Effective granular modulus to model pavement responses" Transport Res Rec 810:1-9

Mulungye M.R.,Owende M.M.P., and K.Mellon (2007) "Finite element modelling of Flexible pavement on soft soil subgrade." Material & Design 28, 739-756.

N.S.Hadi, Muhammad, and B.C Bodhinayake (2003) "Non-linear finite element analysis For flexible pavement." Advances in Engineering Software 34: 657-662.

Nikraz, Hamid (2009). Lecture: Transportation Engineering 462. http://engineering.curtin.edu.au/local/docs/unit_outlines/Civil/Semester%202%202009%20PDF/302808%20Transportation%20Engineering%20462.pdf Perth,Western Australia: Curtin University of Technology

O'Flaherty, C.A (1974) " Highways Volume 2 Highway Engineering". Leeds: Edward Arnold.

Perez I., L.Medina and M,G.Romana (2006) "Permanent deformation models for a granular material used in road pavements." Construction and Building Materials 790-800.

Shui Zhonghe, Dongxing, Huiwen Wan and Beibei Cao (2008) "Rehydration reactivity of recycled mortar from concrete waste experienced to thermal treatment." Construction and Building Materials 22, 1723-1729.

Simonsen, Erik. and Ulf Isacsson (1999) "Thaw weakening of pavement structure in Cold regions." Cold Regions Science and Technology 29, 1999: 135-151.

Seed HB, Mitry FG, Monishmith CL,Chan CK (1967) " Prediction of flexible pavement deflections from laboratory repeated load test" NHCRP Report No. 35, National Cooperative Highway Research Program

Standards Australia (1995a) "Methods for sampling and testing aggregates – Los Angeles value" SAIGLOBAL (AS 1141.23 - 1995). *www.saiglobal.com.*

Standards Australia (1995b) " Soil classification tests - Determination of the particle size distribution of a soil - Standard method of analysis by sieving" SAIGLOBAL (AS 1289.3.6.1 - 1995). *www.saiglobal.com*.

Standards Australia (1995c) "Soil strength and consolidation tests – Determination of the resilent modulus and permanent deformation of granular unbound pavement materials" SAIGLOBAL (AS 1289.6.8.1 – 1995). *www. saiglobal.com.*

Standards Australia (1998) " Soil strength and consolidation tests – Determination of the California Bearing Ratio of a soil - Standard laboratory method for a remoulded specimen" SAIGLOBAL (AS 1289.6.1.1 - 1998). *www.saiglobal.com*.

Standards Australia (2003) "Soil compaction and density tests – Determination of the dry density/moisture content relation of a soil using modified compactive effort" SAIGLOBAL (AS 1289.5.2.1- 2003). *www.saiglobal.com*.

Standards Australia (2006a) "Determination of the cone liquid limit of soil – One point method" SAIGLOBAL (AS 1289.3.9.2 - 2006). *www.saiglobal.com.*

Standards Australia (2006b) "Soil classification tests - Determination of the soil particle density of a soil - Standard method" SAIGLOBAL (AS 1289.3.5.1 – 2006). *www.saiglobal. com.*

Standards Australia (2008a) " Soil classification tests - Determination of the Linear shrinkage of a soil - Standard method" SAIGLOBAL (AS 1289.3.4.1 - 2008). *www.saiglobal.com.*

Standards Australia (2008b) "Unconfined compressive strength of compacted materials" SAIGLOBAL (AS 5101.4 - 2008). *www.saiglobal.com.*

Standards Australia (2009a) " Soil classification tests - Determination of the plastic limit of a soil - Standard Method" SAIGLOBAL (AS 1289.3.2.1 - 2009). *www.saiglobal.com.*

Standards Australia (2009b) "Soil classification tests - Calculation of the plasticity index of a soil" SAIGLOBAL (AS 1289.3.3.1 - 2009). *www.saiglobal.com.*

Theyse L.T., Legge, F.T.H., Pretorius,P.C., and Wolff,H (2007) "A Yield Strength Model for Partially Saturated Unbound Granular Material." Road and Pavement Materials, Vol.8.No.3, 2007: 423-448.

Transportation, Washington State Department of. WSDOT Pavement Guide (2003) http://training.ce.washington.edu/wsdot/ (accessed May 10, 2010).

Uzan J (1985) "Characterization of granular material. Transport Res Rec 1022:52-59

Voung B and Brimble R (2008) "Austroads Repeated Load Triaxial Test Method-Determination of permanent deformation and resilent modulus characteristics of unbound granular materials under drained conditions . APRG 00/33 (MA) June. APPB TR Vermont South

Wang Huajun., Linbo Liu., Zhihao Chen (2010) "Experimental investigation of hydronic show melting process on the included pavement."Cold Regions Science and Technology 63, 2010: 44-49.

Wardle, Leigh.J., Bruce Roadway. Mincad Systems. 7-11 12 1998. http://www.mincad.com.au/Arrb98Ppaper/Arrb98Paper.htm (accessed 06 24, 2010).

Yoder E, J. and M,.W. Witczak (1975) "Principles of pavement design" United States of America: John Woley & Sons.Inc, 1975.

Zaghloul,S.M., and T.D.,White (1993) “ Use of Three-Dimensional, Dynamic Finite Elelemt Program for Analysis of Flexible Pavement” In Transportation Research Record 1388,TRB,National Research Council, Washington, DC, 60-69p

APPENDIX A

WASHOUT CRUSHED CONCRETE WASTE (WCCW)

CHARACTERISATION

Appendix A.1 Modified Compaction Test

SOIL MECHANIC LABORATORY CURTIN UNIVERSITY

Project	WCCW in Holcim LTD	**Source of Soil**	Perth, Holcim LTD	**Compaction Method**	Modified	**Mould Dimension**	Diameter 105mm	Depth 115.5mm
Location	Building 204	**Date Tested**	22/12/2009	**Hammer Weight**	4.9kg	**Drop Height**	450mm	
Soil Description	Original WCCW	**Tested by**	Nara	**No Layers**	5	**No. Blows**	25 per layer	

COMPACTION

Assumed water content,%	**12**			**16**			**18**			**20**		
Test No	1	2	3	1	2	3	1	2	3	1	2	3
Weight of air dried soil used, %	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500
Water content of dried soil, g	0	0	0	0	0	0	0	0	0	0	0	0
Amount of water added, g	300	300	300	400	400	400	450	450	450	500	500	500
Weight of wet soil + mould, g	6444	6551	6540	6619	6612	6622	6662	6632	6640	6539	6550	6549
Weight of mould, g	4541	4553	4553	4553	4553	4553	4553	4553	4553	4553	4553	4553
Weight of wet soil, g (W)	1903	1998	1987	2066	2059	2069	2109	2074	2087	1986	1997	1996
Wet density, g/cm ^{3} ρ (total) = W/V	1.990	1.990	1.990	2.070	2.060	2.070	2.110	2.070	2.090	1.990	2.000	2.000
Dry soil density, g/cm^3 ρ (dry) = 100 ρ (total)/ (100+w)	**1.760**	**1.760**	**1.760**	**1.780**	**1.770**	**1.780**	**1.800**	**1.780**	**1.800**	**1.590**	**1.610**	**1.610**

WATER CONTENT

Container No	1	2	3	7	8	9	10	11	12	13	14	15
Weight of wet soil + container, g	119.7	91.2	123.2	327.4	349.3	314.5	332.5	340.3	371.9	338.3	354.9	400.6
Weight of dry soil + container, g	108.9	82.5	112.9	288.1	308	278.6	292.9	300.3	324.2	276.5	296.2	343.8
Weight of water , g	10.8	8.7	10.3	39.3	41.3	35.9	39.6	40.0	47.7	61.8	58.7	56.8
Weight of container, g	23.9	22.9	23.3	52.5	56.0	56.5	57.9	52.8	58.4	55.8	51.4	58.7
Weight of dry soil, g	85.0	59.6	89.6	235.6	251.3	222.1	235.0	247.5	265.8	220.7	244.8	285.1
Moisture content, % (w)	13.0	14.0	12.0	17.0	16.0	16.0	17.0	16.0	18.0	28.0	24.0	20.0
OPTIMUM MOISTURE CONTENT (OMC)	**15.5%**											
MAXIMUM DRY DENSITY (MDD)	**1.82g/cm^3**											

SOIL MECHANIC LABORATORY CURTIN UNIVERSITY

Project	Re-graded WCCW in Holcim LTD	**Source of Soil**	Perth, Holcim LTD	**Compaction Method**	Modified	**Mould Dimension**	Diameter 105mm	Depth 115.5mm
Location	Building 204	**Date Tested**	2/03/2010	**Hammer Weight**	4.9kg	**Drop Height**	450mm	
Soil Description	Original WCCW	**Tested by**	Nara	**No Layers**	5	**No. Blows**	25 per layer	

COMPACTION

Assumed water content,%	**12**			**16**			**18**		
Test No	1	2	3	1	2	3	1	2	3
Weight of air dried soil used, %	2500	2500	2500	2500	2500	2500	2500	2500	2500
Water content of dried soil, g	0	0	0	0	0	0	0	0	0
Amount of water added, g	305	305	305	375	375	375	425	425	425
Weight of wet soil + mould, g	6580	6566	6586	6652	6670	6669	6622	6637	6630
Weight of mould, g	4534	4534	4534	4534	4534	4534	4534	4534	4534
Weight of wet soil, g (W)	2046	2032	2052	2118	2136	2135	2088	2103	2096
Wet density, g/cm ^{3} ρ (total) = W/V	2.05	2.04	2.06	2.13	2.15	2.14	2.09	2.11	2.10
Dry soil density, g/cm^3 ρ (dry) = 100 ρ (total)/ (100+w)	**1.810**	**1.810**	**1.820**	**1.870**	**1.900**	**1.890**	**1.810**	**1.840**	**1.810**

WATER CONTENT

Container No	1	2	3	7	8	9	10	11	12
Weight of wet soil + container, g	387.0	397.0	370.0	450.0	375.0	406.0	422.0	368.0	453.0
Weight of dry soil + container, g	348.4	352.7	329.9	396.3	333.7	359.6	366.3	322.1	397.8
Weight of water , g	57.0	56.0	52.0	58.0	58.0	53.0	58.0	51.0	51.0
Weight of container, g	38.6	44.3	40.4	53.7	41.3	46.4	55.7	45.9	55.2
Weight of dry soil, g	291.4	34.1	318	392	317	35.3	364	317	346.8
Moisture content, % (w)	0.132	0.129	0.127	0.137	0.13	0.131	0.153	0.145	0.159
OPTIMUM MOISTURE CONTENT (OMC)	**15.0%**								
MAXIMUM DRY DENSITY (MDD)	**1.89g/cm^3**								

Appendix A.2 Sieve Analysis

Sample location:	**Holcim LTD, Perth WA**
Sample Description:	**Before compaction**
Sample Number:	**WCCW-1**
Total weight of sample, g	2500.0
Dry mass of sample pre-washing, g	279.0
Dry mass of sample after washing, g	262.9
Loss of mass through washing, g	16.0
Total % passing 0.075mm sieve	3.0

Sieve Analysis

Sieve Opening, mm	Wt Soil Retained ,g	Percent Retained, %	Cumulative Percent Passing, %	Cumulative Percent Retained, %
19.00	75.00	3.00	97.00	3.00
13.20	284.00	11.36	85.64	14.36
9.500	321.00	12.84	72.80	27.20
6.700	292.00	11.68	61.10	38.88
4.750	171.00	6.84	54.28	45.72
2.360	224.00	8.96	45.32	54.68
1.180	113.76	4.55	40.17	59.23
0.600	223.04	8.92	31.20	68.15
0.425	206.16	8.24	23.00	76.39
0.300	186.52	7.46	15.50	83.85
0.150	247.80	9.91	5.60	93.76
0.075	47.70	1.90	3.70	95.66
0	17.10	0.68	3.00	96.34

Sample location:	**Holcim LTD, Perth WA**
Sample Description:	**Before compaction**
Sample Number:	**WCCW-2**
Total weight of sample, g	2000.0
Dry mass of sample pre-washing, g	334.0
Dry mass of sample after washing, g	303.0
Loss of mass through washing, g	31.0
Total % passing 0.075mm sieve	5.3

Sieve Analysis

Sieve Opening, mm	Wt Soil Retained ,g	Percent Retained, %	Cumulative Percent Passing, %	Cumulative Percent Retained, %
19.00	16.00	0.80	99.20	0.85
13.20	134.00	6.70	92.50	7.50
9.500	197.00	9.85	82.60	17.35
6.700	180.00	9.00	73.60	26.35
4.750	137.00	6.85	66.80	33.20
2.360	188.00	9.40	57.40	42.60
1.180	51.24	8.86	47.50	51.28
0.600	81.97	13.89	33.60	65.17
0.425	57.26	9.70	23.90	74.87
0.300	57.26	9.70	14.20	84.57
0.150	40.42	6.85	7.30	91.42
0.075	5.21	0.88	6.45	92.30
0	6.71	1.14	5.31	93.44

Sample location:	**Holcim LTD, Perth WA**
Sample Description:	**Before compaction**
Sample Number:	**WCCW-3**
Total weight of sample, g	2000.0
Dry mass of sample pre-washing, g	275.0
Dry mass of sample after washing, g	251.0
Loss of mass through washing, g	24.0
Total % passing 0.075mm sieve	2.8

Sieve Analysis

Sieve Opening, mm	Wt Soil Retained ,g	Percent Retained, %	Cumulative Percent Passing, %	Cumulative Percent Retained, %
19.00	34.00	1.70	98.30	0.85
13.20	131.00	6.55	91.75	8.25
9.500	235.00	11.75	80.00	20.00
6.700	179.00	8.95	71.25	28.95
4.750	124.00	6.20	65.05	35.15
2.360	229.00	11.45	53.60	46.60
1.180	36.45	7.07	44.30	53.67
0.600	69.38	13.50	30.80	67.17
0.425	54.49	10.60	20.20	77.77
0.300	43.11	8.36	11.90	86.13
0.150	38.07	7.38	4.50	93.51
0.075	5.90	1.14	3.30	94.65
0	2.82	0.55	2.79	95.20

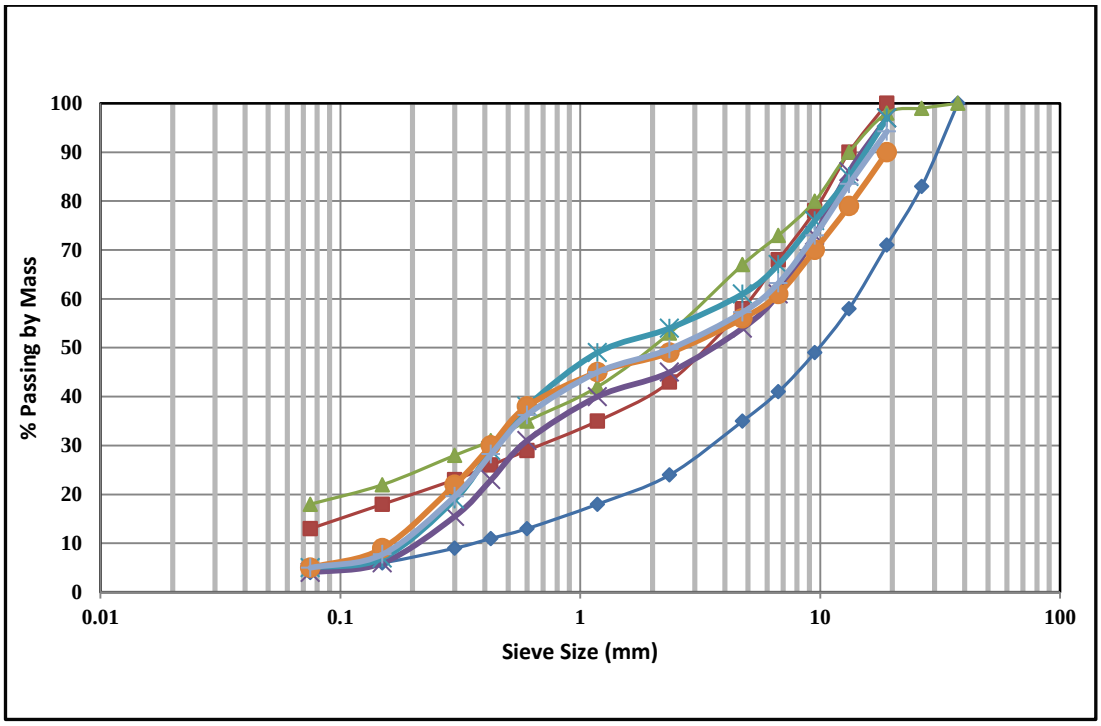

Figure A-2-1: Material Grading Curves of WCCW Before Compaction

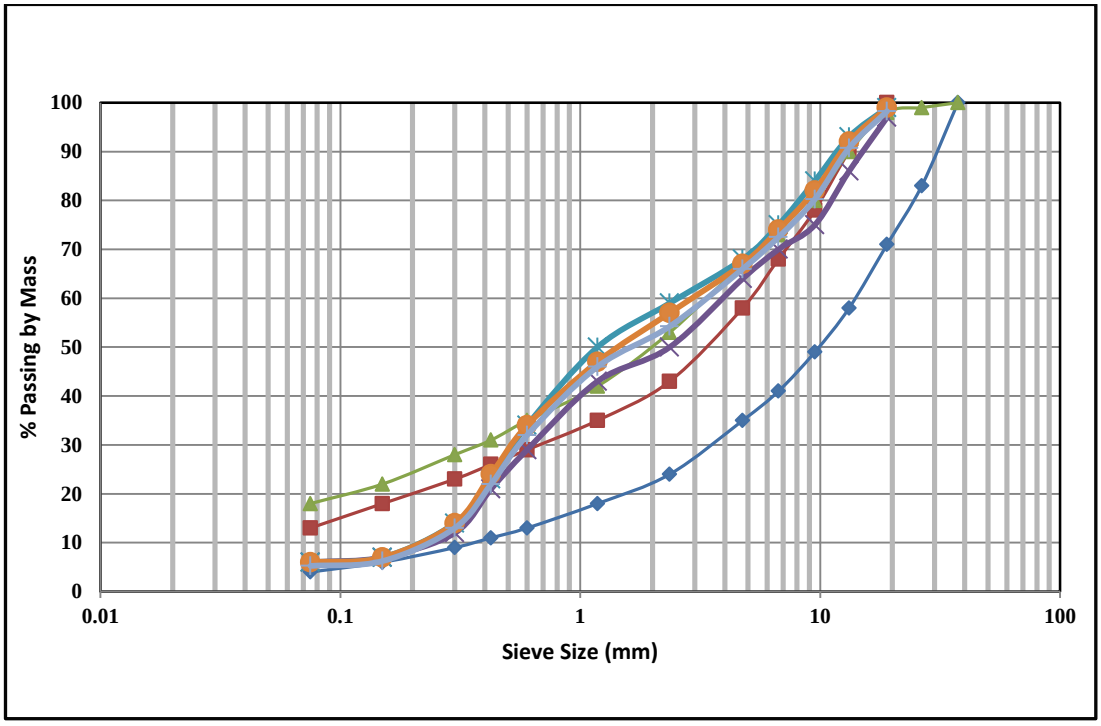

Figure A-2-2: Material Grading Curves of WCCW After Compaction

Appendix A.3 California Bearing Ration test (Unsoaked ,Modified Compaction)

Soil Description:	WCCW		**Sourse of soil:**	Holcim LTD,Perth,WA
Compaction Method:	Modified		**Tested date:**	24/09/2009
Hammer weight	4.9	kg	**Mould Dimension:**	d=152x178 mm
No. of layer	5		**Dropped Height :**	450 mm
			No.of Blow:	53 blow per layer

COMPACTION MOISTURE CONTENTS			
WATER CONTENT	container number	S-1	S-2
Weight of wet soil+ container	g	411.9	382.8
Weight of dry soil+ container	g	364.6	341.2
Weight of water	g	47.3	41.6
Weight of container	g	77.2	77.4
Weight of dry soil	g	287.4	263.8
Water content, w	%	14.1	13.6
Average water content,w	%	13.8	

AFTER COMPACTION DENSITY		
Weight of wet soil+ mould+ base plate	g	11751.0
Weight of mould+ base plate	g	7525.0
Weight of wet soil, W	g	4226.0
Wet density, r(total) = W/V	g/cm3	2.0
Dry soil density	g/cm3	1.76
r (dry) = 100r(total)/(100+w)		

Penetration data	
Penetration (mm)	**Force gauge reading (kN)**
0.00	0.00
0.50	2.05
1.00	3.75
1.50	6.00
2.00	7.90
2.50	10.00
3.00	11.60
4.00	14.80
5.00	17.50
7.50	23.10
10.00	27.80

Corrected load at:
2.5 mm Penetration = 10.00 kN
5.0 mm Penetration = 17.50 kN

Appendix A.4 California Bearing Ration test (Soaked ,Modified Compaction)

Soil Description:	WCCW		**Sourse of soil:**	Holcim LTD,Perth,WA
Compaction Method:	Modified		**Tested date:**	24/09/2009
Hammer weight	4.9	kg	**Mould Dimension:**	d=152x178 mm
No. of layer	5		**Dropped Height :**	450 mm
			No.of Blow:	53 blow per layer

COMPACTION MOISTURE CONTENTS			
WATER CONTENT	container number	S-1	S-2
Weight of wet soil+ container	g	499.4	493.4
Weight of dry soil+ container	g	443.3	426.4
Weight of water	g	80.8	78.3
Weight of container	g	56.1	60.2
Weight of dry soil	g	418.6	415.8
Water content, w	%	13.4	13.9
Average water content,w	%	13.6	

AFTER COMPACTION DENSITY		
Weight of wet soil+ mould+ base plate	g	11688
Weight of mould+ base plate	g	7525
Weight of wet soil, W	g	4163
Wet density, r(total) = W/V	g/cm3	3629.5
Dry soil density	g/cm3	1.97
r (dry) = 100r(total)/(100+w)		1.70

Penetration data	
Penetration (mm)	**Force gauge reading (kN)**
0.00	0.00
0.50	3.55
1.00	5.75
1.50	8.2
2.00	10.5
2.50	12.8
3.00	14.6
4.00	18.0
5.00	20.7
7.50	25.9
10.00	30.8

Corrected load at:
2.5 mm Penetration = 12.8 kN
5.0 mm Penetration = 20.7kN

Appendix A.5 Flakiness Index Test

Material	**WCCW**
Source	**Holcim Ltd,Perth**
Location	**Geotechnical Laboratory**
Sample date	**02/06/09**

Samples	**Sieve size (mm)**	**Passing (%)**	**Mass of fraction (g)**	**Mass passing slot/gauge (g)**	**Flaky particles (%)**
			M1	**M2**	$\frac{M2}{M1}x100$
Sample-1	26.5	197	197	21	10.7
	19.0	230	230	42	18.3
	13.2	183	183	25	13.7
	9.5	164	164	33	20.1
		Totals	774	121	
		Flakiness Index (%)	**15.6**		
Sample-2	26.5	145	145	19	13.1
	19.0	166	166	30	18.1
	13.2	238	238	27	11.3
	9.5	174	174	28	16.1
		Totals	723	104	
		Flakiness Index (%)	**14.4**		

Appendix A.6 Repeated Loading Triaxial Test (Original and Re-graded WCCW)

SAMPLE	Sample-1				Sample-2				Sample-3			
Sequences	**Axial**	**Deviator**	**Confining**	**Bulk**	**Axial**	**Deviator**	**Confining**	**Bulk**	**Axial**	**Deviator**	**Confining**	**Bulk**
	Modulus,Mr	**Stress,**	**Stress,**	**Stress,**	**Modulus,Mr**	**Stress,**	**Stress,**	**Stress,**	**Modulus,Mr**	**Stress,**	**Stress,**	**Stress,**
	Mpa	kPa	kPa	kPa	Mpa	kPa	kPa	kPa	Mpa	kPa	kPa	kPa
0	284.96	100.44	52.10	204.64	253.05	100.43	51.44	203.30	287.84	100.88	51.41	203.70
1	331.35	150.30	77.46	305.22	285.11	150.34	76.75	303.84	341.72	163.67	77.40	318.48
2	358.57	200.43	100.16	400.75	304.87	201.01	100.00	401.00	360.22	201.43	100.00	401.43
3	393.80	250.17	126.47	503.11	325.62	250.90	125.75	502.41	396.12	261.00	126.33	513.66
4	431.91	301.10	150.01	601.12	356.04	300.87	150.00	600.87	435.38	301.36	150.00	601.36
5	358.53	201.06	101.97	405.00	299.38	200.54	101.64	403.82	366.20	210.51	101.97	414.44
6	294.44	150.24	51.89	254.01	255.26	150.68	51.49	253.65	291.21	151.10	51.75	254.61
7	359.38	225.57	77.62	380.82	322.51	225.45	77.40	380.25	382.63	235.90	77.34	390.58
8	403.78	301.24	100.03	501.30	361.96	301.04	100.03	501.10	420.95	301.12	100.21	501.53
9	426.46	375.88	126.29	628.47	379.33	375.98	125.94	627.86	438.99	374.35	125.87	626.09
10	467.37	451.24	150.00	751.25	403.48	450.89	150.00	750.89	468.90	452.59	150.00	752.59
11	334.65	225.12	77.84	380.79	293.73	225.76	77.18	380.13	327.99	226.12	77.05	380.23
12	279.18	125.16	42.66	210.49	243.05	125.89	42.45	210.78	254.18	126.91	42.58	212.07
13	273.11	100.37	34.46	169.29	238.18	100.75	33.54	167.84	245.65	103.49	33.30	170.10
14	303.93	150.10	42.74	235.57	276.49	150.57	42.66	235.88	279.84	151.38	42.78	236.94
15	339.69	200.19	53.01	306.20	314.76	200.23	52.59	305.40	328.27	201.08	51.97	305.02
16	397.72	300.77	76.49	453.76	375.30	301.06	76.30	453.67	400.53	300.67	76.52	453.70

17	455.02	400.99	100.86	602.71	428.32	400.51	100.66	601.83	465.73	401.45	100.03	601.52
18	485.95	500.50	125.28	751.07	453.97	501.07	125.16	751.40	487.17	501.95	125.33	752.62
19	384.10	300.65	76.05	452.75	362.50	301.26	76.04	453.33	375.96	301.09	75.48	452.05
20	285.52	125.24	33.97	193.19	269.08	125.48	33.69	192.86	261.44	132.52	33.88	200.29
21	275.63	100.43	23.31	147.05	258.37	100.81	23.00	146.80	239.85	101.34	22.92	147.18
22	311.80	150.15	34.25	218.64	301.56	150.33	33.88	218.08	290.23	160.72	33.99	228.70
23	345.77	200.95	42.10	285.14	340.33	201.05	41.73	284.51	326.51	201.67	41.69	285.05
24	380.51	250.54	53.55	357.64	376.36	250.90	52.98	356.86	364.97	254.05	52.99	360.02
25	448.67	376.22	75.94	528.10	445.39	376.21	75.45	527.11	450.77	377.57	75.31	528.18
26	507.47	500.86	101.93	704.72	493.25	501.20	101.58	704.36	496.12	501.06	101.50	704.06
27	368.97	250.38	52.24	354.86	368.63	251.33	51.70	354.73	347.32	251.40	51.48	354.36
28	340.85	188.38	34.24	256.86	332.61	180.34	34.52	249.38	310.51	193.43	34.52	262.46
29	406.35	300.73	52.38	405.49	414.46	300.95	51.65	404.26	393.21	301.81	51.49	404.79
30	490.49	451.01	76.76	604.54	491.87	450.40	77.46	605.31	478.40	451.07	77.51	606.09
31	406.04	300.55	52.53	405.62	419.50	301.08	51.81	404.70	387.45	301.50	51.74	404.99
32	344.90	180.27	33.14	246.56	358.09	180.33	34.44	249.22	321.01	194.18	34.49	263.16
33	393.63	250.37	43.20	336.76	410.32	251.25	42.28	335.81	367.95	251.62	42.23	336.08
34	371.91	210.79	32.36	275.52	389.16	210.40	33.97	278.34	348.81	220.81	34.31	289.42
35	422.58	280.41	43.53	367.47	441.90	281.01	42.37	365.76	397.91	280.89	42.29	365.46
36	469.56	351.13	51.50	454.13	488.87	350.87	52.48	455.82	446.80	349.60	52.94	455.47
37	533.19	525.76	77.34	680.45	549.76	526.00	76.15	678.29	521.85	528.54	76.00	680.54
38	406.70	280.63	42.13	364.89	427.98	281.00	42.73	366.47	373.53	280.63	43.35	367.33
39	339.37	150.54	25.56	201.66	356.83	150.31	24.18	198.67	286.27	150.40	23.93	198.26
40	396.75	245.99	32.86	311.71	423.29	246.10	32.61	311.32	359.95	244.57	33.63	311.83
41	448.80	325.87	43.68	413.22	474.24	325.92	43.03	411.98	418.37	326.07	42.55	411.16
42	493.28	401.27	51.95	505.18	523.75	401.26	51.26	503.79	470.06	400.61	52.44	505.49

43	405.69	245.43	33.99	313.41	432.84	245.54	33.82	313.19	364.14	245.93	33.34	312.61
44	372.84	185.23	24.10	233.43	401.74	185.75	23.09	231.92	327.43	185.69	24.18	234.05
45	435.89	275.82	33.56	342.94	468.74	275.85	33.96	343.77	398.35	276.24	33.36	342.97
46	492.64	370.95	42.89	456.73	530.17	371.23	41.65	454.52	467.22	371.08	42.45	455.97
47	538.12	450.49	52.06	554.61	569.15	450.76	52.98	556.71	509.39	452.55	52.41	557.37
48	436.09	275.95	33.71	343.37	473.06	276.19	32.49	341.17	395.31	276.31	32.88	342.07
49	407.61	226.18	23.23	272.63	443.83	225.27	25.20	275.67	360.27	227.25	24.48	276.21
50	477.58	335.83	33.83	403.49	520.43	335.80	32.55	400.90	446.26	337.28	32.56	402.40
51	545.76	451.67	41.62	534.91	581.06	450.50	43.75	538.00	512.59	452.03	43.04	538.12
52	560.17	550.85	52.92	656.70	612.01	549.07	51.47	652.01	550.74	553.97	51.30	656.56
53	409.58	251.09	23.29	297.66	452.71	250.58	25.25	301.07	359.45	251.07	24.56	300.19
54	478.15	376.03	34.38	444.79	529.69	375.86	32.67	441.20	447.39	377.68	32.11	441.90
55	547.87	501.56	41.98	585.53	595.58	501.10	43.59	588.27	517.60	502.50	43.19	588.88
56	434.57	300.42	25.44	351.30	488.94	301.05	23.72	348.49	396.91	302.46	22.90	348.26
57	522.47	450.63	32.75	516.14	578.66	450.69	33.98	518.64	490.06	451.58	33.86	519.30
58	557.32	600.54	43.55	687.64	613.87	599.12	42.25	683.63	552.14	597.89	41.36	680.61
59	510.69	501.61	32.95	567.50	571.65	501.13	34.04	569.22	485.75	502.42	33.82	570.06
60	443.05	349.87	24.74	399.35	502.57	350.68	23.83	398.34	408.79	353.29	22.88	399.06
61	534.31	551.15	33.05	617.25	600.89	550.61	33.70	618.00	510.00	552.62	33.84	620.30
62	456.07	375.41	24.37	424.16	517.98	375.75	23.85	423.44	418.80	378.41	22.90	424.21
63	541.47	575.39	33.19	641.77	615.17	576.38	33.48	643.34	517.86	578.11	33.88	645.86
64	464.33	401.13	24.10	449.32	530.75	400.78	23.90	448.58	429.47	403.87	22.90	449.66
65	508.89	500.81	24.14	549.09	588.88	500.64	24.23	549.10	483.69	501.67	24.83	551.32

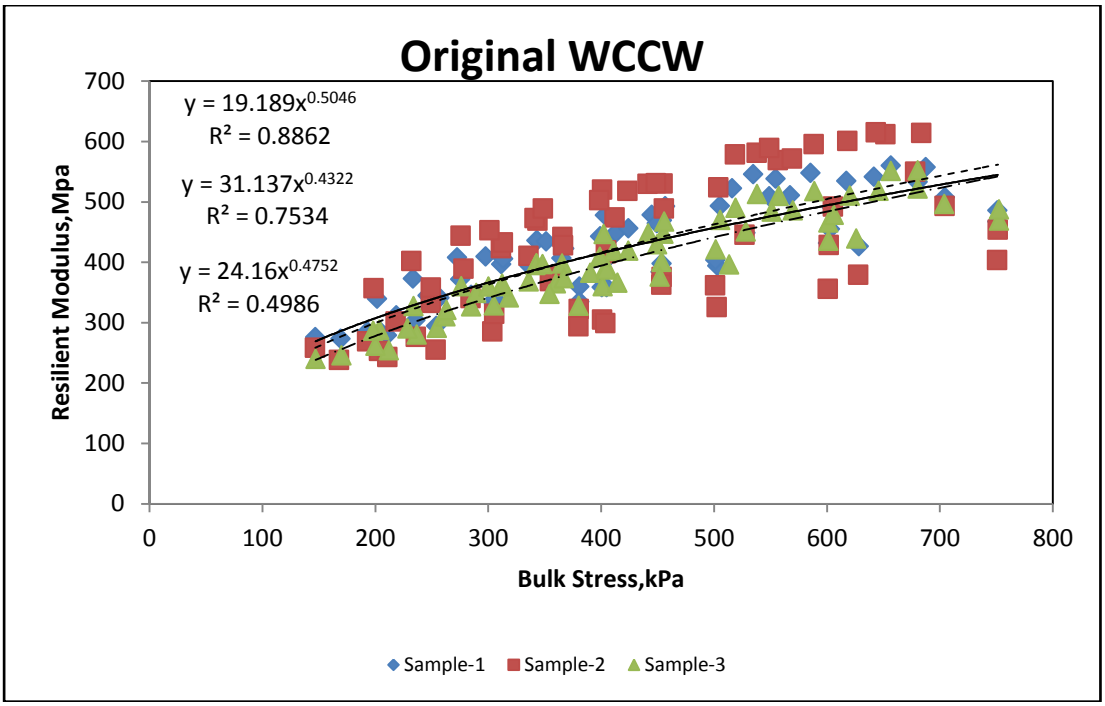

Figure A-6-1: Resilient Modulus of Original WCCW

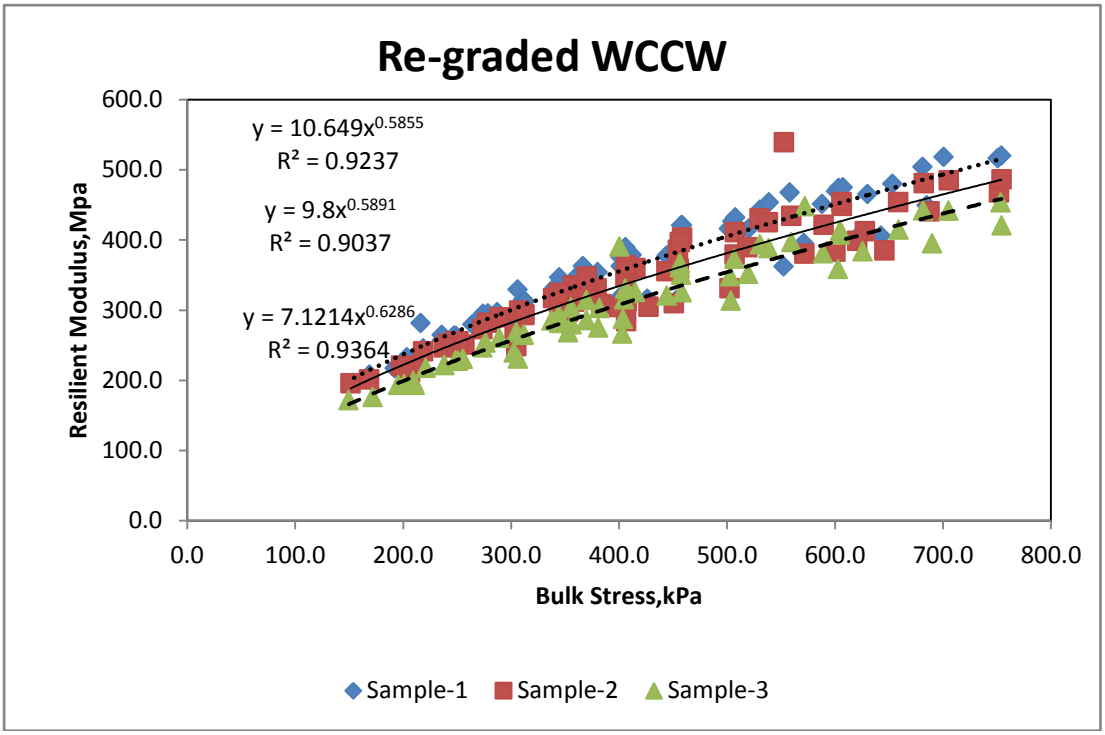

Figure A-6-2: Resilient Modulus of Re-graded WCCW

SAMPLE	Sample-1				Sample-2				Sample-3			
Sequences	**Axial**	**Deviator**	**Confining**	**Bulk**	**Axial**	**Deviator**	**Confining**	**Bulk**	**Axial**	**Deviator**	**Confining**	**Bulk**
	Modulus,Mr	**Stress,**	**Stress,**	**Stress,**	**Modulus,Mr**	**Stress,**	**Stress,**	**Stress,**	**Modulus,Mr**	**Stress,**	**Stress,**	**Stress,**
	Mpa	kPa	kPa	kPa	Mpa	kPa	kPa	kPa	Mpa	kPa	kPa	kPa
0	281.22	107.38	54.45	216.28	211.13	99.59	53.39	206.37	198.80	101.14	54.21	209.55
1	329.38	150.64	77.74	306.12	248.43	151.33	76.84	305.01	230.46	150.68	77.89	306.46
2	375.18	199.39	101.09	401.56	284.23	200.56	103.05	406.66	266.41	200.15	101.44	403.02
3	426.11	250.62	127.25	505.11	330.97	249.42	126.49	502.39	313.42	250.67	126.50	503.67
4	469.05	299.75	150.74	601.22	382.87	300.58	150.00	600.58	358.31	300.60	151.24	603.07
5	362.41	199.44	101.10	401.64	312.21	201.03	103.13	407.30	287.08	200.29	101.65	403.58
6	279.46	155.12	54.54	264.21	250.77	149.67	53.62	256.91	230.03	149.64	52.85	255.33
7	353.65	224.91	77.66	380.23	331.12	225.29	77.05	379.39	302.93	225.21	78.24	381.70
8	415.65	299.97	100.99	501.94	378.70	300.42	103.33	507.09	347.72	299.71	101.67	503.06
9	465.16	375.29	127.44	630.17	412.30	374.68	126.60	627.87	383.52	375.67	125.00	625.66
10	516.02	450.38	150.19	750.75	467.55	452.15	150.00	752.15	420.22	451.20	151.55	754.30
11	326.27	224.65	76.72	378.10	308.32	225.82	79.00	383.81	275.03	225.55	77.56	380.67
12	235.45	128.62	45.04	218.71	220.82	124.80	44.31	213.43	193.13	124.63	43.16	210.95
13	207.97	99.66	34.59	168.84	200.93	100.14	34.11	168.36	175.89	100.71	35.56	171.82
14	256.75	149.67	43.24	236.15	251.69	150.52	45.39	241.30	221.78	150.41	43.88	238.18
15	308.75	201.87	54.62	311.11	298.89	199.61	53.92	307.45	268.37	199.48	52.73	304.93
16	395.22	299.57	77.58	454.74	385.76	300.10	77.26	454.62	350.08	300.16	78.78	457.72
17	473.73	401.93	100.76	603.44	448.44	400.01	103.30	606.61	407.24	400.30	102.00	604.30
18	520.02	499.53	127.27	754.06	485.99	500.88	126.78	754.44	453.07	503.19	125.15	753.50
19	371.14	299.46	77.59	454.65	358.69	300.64	77.44	455.52	325.29	300.28	78.95	458.19

20	217.22	124.54	33.91	192.36	220.62	125.99	36.08	198.16	193.22	126.07	34.74	195.55
21	195.83	101.34	26.52	154.38	195.62	100.15	25.58	151.32	171.37	100.18	24.71	149.60
22	245.43	149.30	34.63	218.56	241.33	149.99	34.28	218.54	217.27	150.94	35.01	220.96
23	296.60	200.34	43.37	287.07	289.49	200.10	44.73	289.55	260.16	200.45	44.33	289.10
24	346.17	250.61	54.63	359.87	334.58	249.45	53.94	357.32	303.73	249.48	53.07	355.62
25	442.87	375.36	77.68	530.72	430.23	375.72	77.25	530.22	393.40	374.80	77.84	530.48
26	517.85	498.81	100.95	700.71	484.49	499.73	102.94	705.61	441.42	500.53	102.41	705.36
27	325.95	250.47	54.95	360.37	311.73	250.50	54.00	358.49	279.65	249.77	53.23	356.23
28	262.47	179.30	34.98	249.26	255.20	180.25	34.19	248.63	228.62	179.89	34.32	248.53
29	372.53	301.84	53.01	407.85	358.23	300.22	54.32	408.87	324.04	300.55	54.02	408.58
30	474.79	449.47	78.89	607.25	453.76	450.31	78.00	606.32	413.29	450.37	77.27	604.91
31	361.44	299.63	53.66	406.95	347.41	299.75	53.13	406.01	315.02	299.46	52.67	404.81
32	263.34	179.45	33.97	247.38	255.39	180.11	35.58	251.26	227.62	180.24	35.30	250.83
33	332.14	250.56	45.03	340.62	316.79	250.58	44.29	339.15	284.83	249.93	43.73	337.39
34	295.02	209.47	34.55	278.58	281.88	209.87	34.09	278.05	253.47	209.46	33.53	276.52
35	362.61	280.47	43.11	366.70	347.64	280.13	45.03	370.19	314.03	280.14	44.86	369.86
36	420.95	349.74	54.31	458.37	403.13	350.80	53.85	458.49	366.37	349.71	53.39	456.49
37	503.71	526.54	77.31	681.15	480.42	528.17	77.04	682.25	441.70	528.60	76.63	681.86
38	333.65	280.10	43.27	366.65	316.88	280.48	45.28	371.04	285.57	280.05	44.91	369.87
39	232.56	151.09	26.16	203.41	219.78	150.89	25.47	201.83	194.86	150.23	25.26	200.76
40	314.59	242.34	34.37	311.07	293.40	244.61	33.78	312.18	265.49	244.40	33.61	311.63
41	378.62	325.13	43.49	412.10	359.67	325.14	45.01	415.16	325.44	325.04	45.02	415.07
42	431.90	399.45	54.10	507.65	410.91	400.42	53.51	507.43	373.14	400.13	53.33	506.79
43	312.19	244.25	34.29	312.82	292.49	244.62	33.79	312.21	264.26	244.48	33.64	311.75
44	264.65	184.94	25.43	235.80	246.50	185.07	26.42	237.91	221.73	185.32	26.50	238.33
45	346.60	274.51	35.07	344.66	324.40	275.42	34.52	344.46	292.99	275.26	34.48	344.22

46	420.34	370.42	43.59	457.61	396.77	370.13	43.16	456.44	360.56	370.08	43.15	456.39
47	467.18	449.66	54.18	558.01	434.24	450.74	54.48	559.69	396.78	450.20	54.65	559.50
48	336.43	274.46	35.03	344.51	310.59	275.59	34.56	344.70	281.11	275.45	34.64	344.74
49	294.75	224.33	24.93	274.18	272.76	224.61	24.46	273.52	246.80	224.50	24.56	273.62
50	389.49	334.95	35.59	406.13	363.38	335.20	35.70	406.60	330.17	335.34	35.15	405.64
51	453.13	450.65	44.19	539.02	425.09	450.20	43.94	538.08	388.19	450.54	44.03	538.59
52	479.73	547.73	52.82	653.37	453.54	553.59	52.59	658.77	414.45	553.53	52.66	658.84
53	287.89	250.51	26.64	303.78	266.10	250.42	26.46	303.34	239.34	250.22	26.19	302.60
54	377.35	375.22	34.59	444.39	355.15	375.07	34.47	444.01	320.47	375.14	34.60	444.33
55	451.00	502.07	43.02	588.12	421.46	503.52	43.02	589.56	380.63	502.64	43.14	588.93
56	317.53	299.63	26.16	351.95	297.53	300.22	26.35	352.92	267.95	300.47	26.27	353.00
57	415.94	451.74	34.28	520.31	389.45	450.36	34.37	519.11	351.53	450.41	34.54	519.48
58	449.00	597.57	43.73	685.02	440.42	602.01	42.82	687.65	394.71	603.94	43.03	690.00
59	395.10	501.06	35.03	571.13	380.36	501.21	35.23	571.66	447.93	500.80	35.59	571.97
60	317.61	351.09	24.83	400.75	303.92	350.12	25.01	400.14	390.38	349.69	25.34	400.37
61	404.02	550.39	35.23	620.85	398.46	554.23	33.30	620.84	0.00	552.61	34.25	621.11
62	315.96	375.15	25.53	426.21	304.71	375.52	25.99	427.50	0.00	375.10	24.87	424.83
63	405.94	575.09	33.76	642.61	384.75	577.66	34.10	645.87	0.00	578.92	33.79	646.49
64	313.52	399.92	26.54	453.00	309.69	402.48	24.21	450.90	0.00	401.56	24.44	450.43
65	362.14	501.96	25.23	552.42	538.81	501.29	25.82	552.93	0.00	504.88	24.14	553.15

Appendix A.7 Permanent Deformation (Original and Re-graded WCCW)

Sequences	Cycles	Permanent deformation,micrometer				Permanent Strain,%			
		Sample -1	Sample -2	Sample -3	**Mean**	Sample - 1	Sample -2	Sample -3	**Mean**
0	0	1460	1554	1824	**1613**	0.730	0.777	0.912	**0.806**
1	500	1533	1657	1927	**1706**	0.767	0.828	0.964	**0.853**
2	1000	1573	1711	1983	**1756**	0.786	0.855	0.992	**0.878**
3	1500	1597	1746	2021	**1788**	0.798	0.873	1.011	**0.894**
4	2000	1616	1774	2046	**1812**	0.808	0.887	1.023	**0.906**
5	2500	1632	1794	2062	**1829**	0.816	0.897	1.031	**0.915**
6	3000	1644	1809	2075	**1843**	0.822	0.904	1.038	**0.921**
7	3500	1654	1821	2087	**1854**	0.827	0.911	1.043	**0.927**
8	4000	1662	1833	2096	**1864**	0.831	0.916	1.048	**0.932**
9	4500	1671	1843	2105	**1873**	0.835	0.921	1.052	**0.936**
10	5000	1677	1851	2111	**1880**	0.839	0.926	1.055	**0.940**
11	5500	1683	1859	2115	**1886**	0.842	0.930	1.058	**0.943**
12	6000	1687	1866	2120	**1891**	0.844	0.933	1.060	**0.946**
13	6500	1691	1871	2125	**1896**	0.846	0.936	1.063	**0.948**
14	7000	1696	1876	2130	**1901**	0.848	0.938	1.065	**0.950**
15	7500	1699	1881	2133	**1904**	0.850	0.940	1.067	**0.952**
16	8000	1703	1885	2136	**1908**	0.851	0.943	1.068	**0.954**
17	8500	1704	1890	2139	**1911**	0.852	0.945	1.069	**0.955**
18	9000	1706	1894	2142	**1914**	0.853	0.947	1.071	**0.957**
19	9500	1708	1898	2146	**1917**	0.854	0.949	1.073	**0.959**
20	10000	1728	1930	2170	**1943**	0.864	0.965	1.085	**0.971**
21	10500	1735	1941	2177	**1951**	0.868	0.970	1.089	**0.976**
22	11000	1741	1950	2184	**1958**	0.871	0.975	1.092	**0.979**
23	11500	1745	1959	2190	**1965**	0.873	0.979	1.095	**0.982**
24	12000	1749	1966	2195	**1970**	0.874	0.983	1.097	**0.985**
25	12500	1752	1973	2197	**1974**	0.876	0.987	1.099	**0.987**
26	13000	1756	1979	2200	**1978**	0.878	0.990	1.100	**0.989**
27	13500	1759	1984	2204	**1982**	0.879	0.992	1.102	**0.991**
28	14000	1761	1988	2207	**1985**	0.881	0.994	1.104	**0.993**
29	14500	1764	1992	2210	**1989**	0.882	0.996	1.105	**0.994**
30	15000	1765	1996	2211	**1991**	0.883	0.998	1.105	**0.995**
31	15500	1767	2000	2213	**1993**	0.883	1.000	1.106	**0.996**
32	16000	1768	2004	2215	**1996**	0.884	1.002	1.108	**0.998**
33	16500	1770	2008	2217	**1998**	0.885	1.004	1.109	**0.999**
34	17000	1771	2010	2219	**2000**	0.886	1.005	1.109	**1.000**
35	17500	1773	2012	2219	**2001**	0.886	1.006	1.110	**1.001**
36	18000	1774	2014	2221	**2003**	0.887	1.007	1.111	**1.002**
37	18500	1774	2017	2222	**2004**	0.887	1.009	1.111	**1.002**
38	19000	1775	2020	2224	**2006**	0.887	1.010	1.112	**1.003**

39	19500	1775	2022	2225	**2007**	0.888	1.011	1.112	**1.004**
40	20000	1789	2044	2240	**2024**	0.894	1.022	1.120	**1.012**
41	20500	1794	2052	2245	**2030**	0.897	1.026	1.123	**1.015**
42	21000	1797	2061	2250	**2036**	0.899	1.030	1.125	**1.018**
43	21500	1800	2069	2254	**2041**	0.900	1.034	1.127	**1.020**
44	22000	1803	2076	2257	**2045**	0.901	1.038	1.129	**1.023**
45	22500	1805	2083	2261	**2050**	0.903	1.041	1.131	**1.025**
46	23000	1808	2088	2265	**2054**	0.904	1.044	1.133	**1.027**
47	23500	1811	2093	2269	**2058**	0.905	1.046	1.134	**1.028**
48	24000	1813	2099	2271	**2061**	0.906	1.049	1.136	**1.030**
49	24500	1814	2104	2274	**2064**	0.907	1.052	1.137	**1.032**
50	25000	1816	2110	2278	**2068**	0.908	1.055	1.139	**1.034**
51	25500	1818	2116	2281	**2072**	0.909	1.058	1.141	**1.036**
52	26000	1820	2119	2283	**2074**	0.910	1.059	1.142	**1.037**
53	26500	1823	2122	2286	**2077**	0.911	1.061	1.143	**1.038**
54	27000	1825	2126	2289	**2080**	0.913	1.063	1.144	**1.040**
55	27500	1827	2131	2292	**2083**	0.913	1.065	1.146	**1.041**
56	28000	1828	2135	2295	**2086**	0.914	1.067	1.147	**1.043**
57	28500	1830	2138	2296	**2088**	0.915	1.069	1.148	**1.044**
58	29000	1832	2141	2298	**2090**	0.916	1.070	1.149	**1.045**
59	30000	1834	2140	2301	**2092**	0.917	1.070	1.151	**1.046**

Appendix A. 8 Shear Test (Original WCCW)

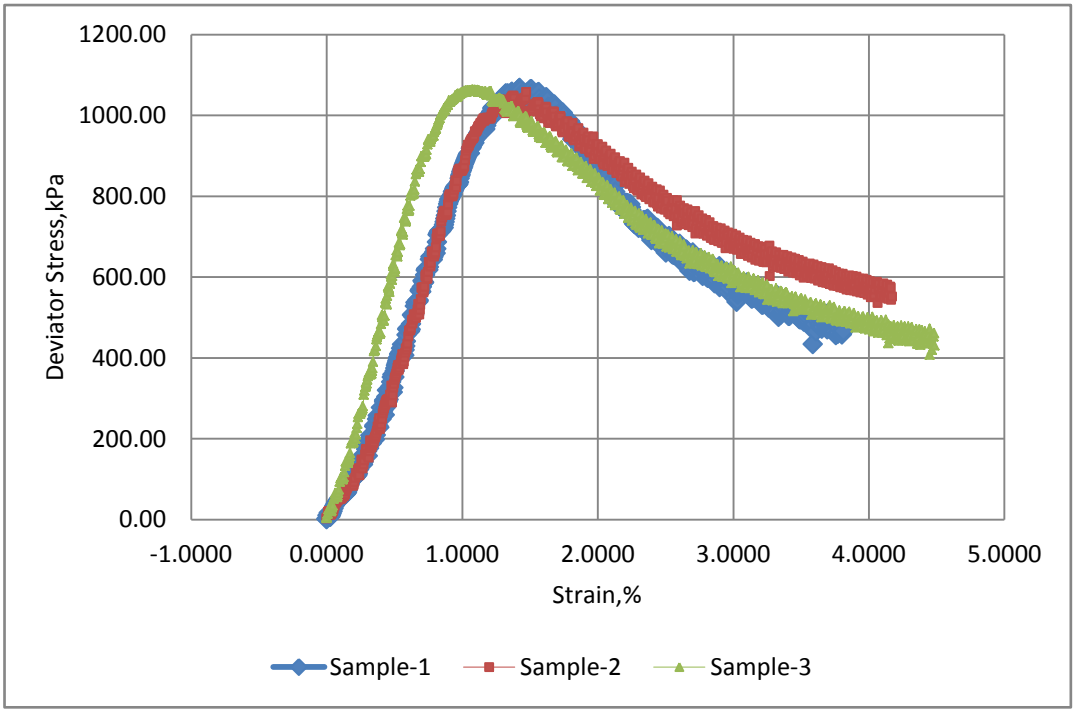

Figure A-8-1: Deviator stress vs strain at confining pressure 40kPa

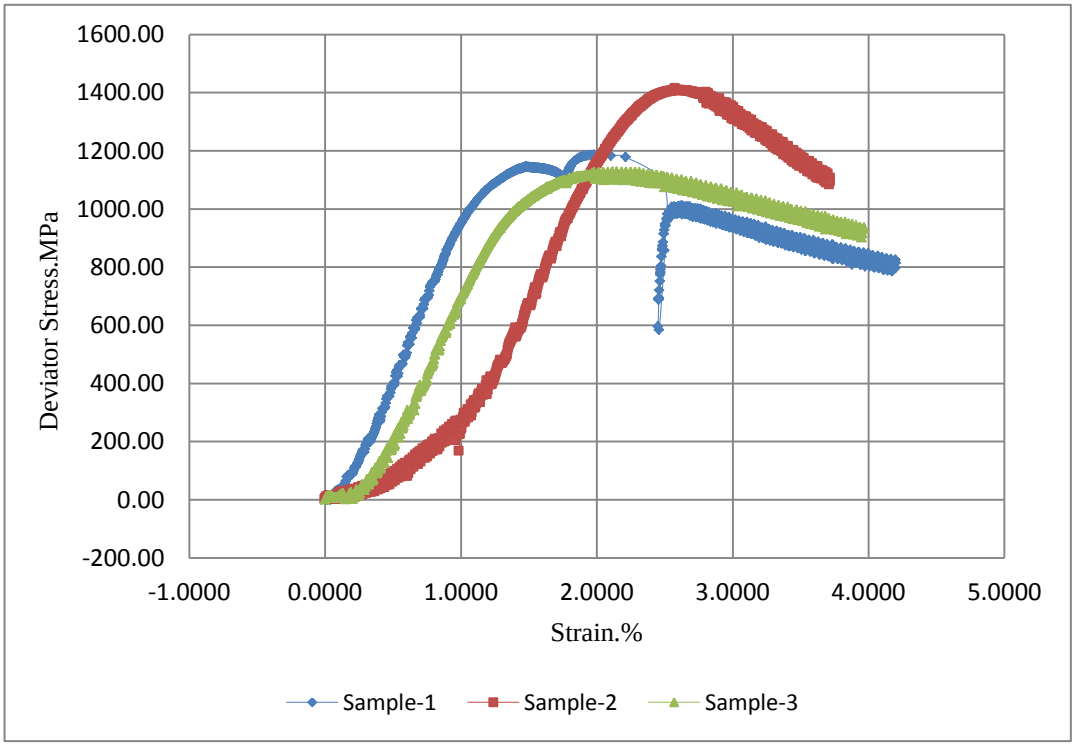

Figure A-8-2: Deviator stress vs strain at confining pressure 80kPa

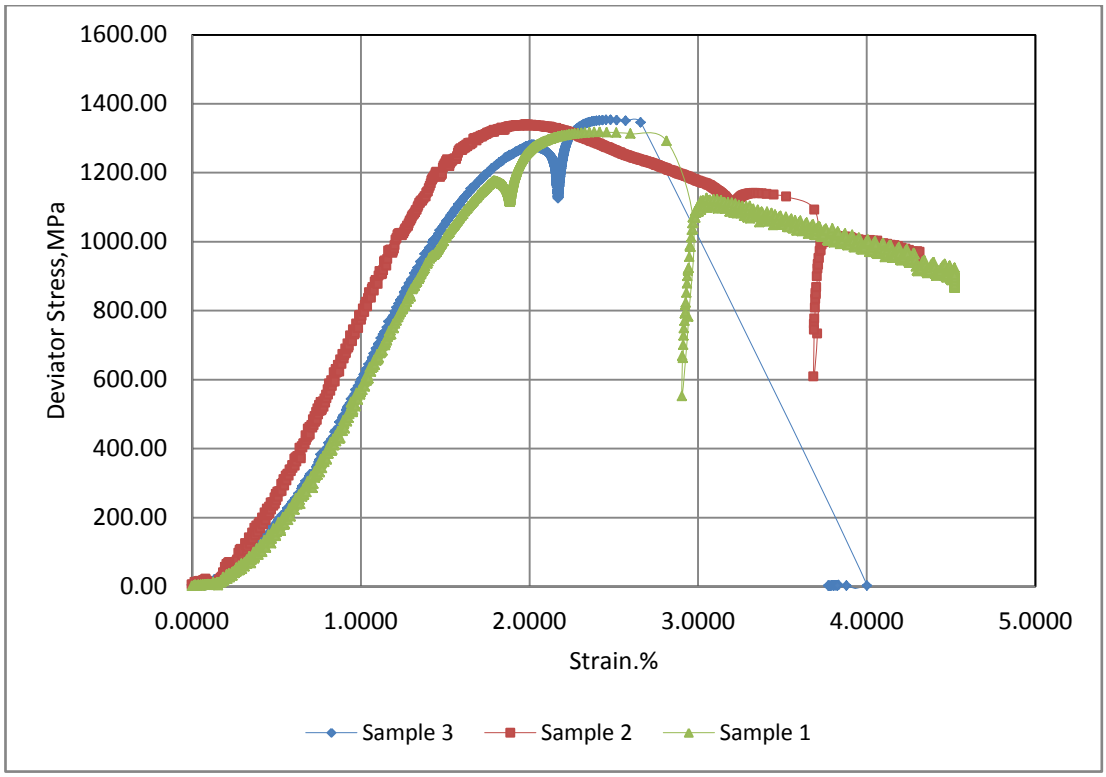

Figure A-8-3: Deviator stress vs strain at confining pressure 120kPa

Samples	**Confining pressure, kPa**		
	40	**80**	**120**
Sample-1	1064.4	1115.3	1178.7
Sample-2	1031.9	1401.5	1335.7
Sample-3	986.1	1126.5	1280.9

Table A-8-1 Maximum deviator stress in various confining pressure

APPENDIX B

C&D WASTE CHARACTERISATION

Appendix B.1 Modified Compaction Test

SOIL MECHANIC LABORATORY CURTIN UNIVERSITY

Project	All Earth	**Source of Soil**	Perth, Holcim LTD	**Compaction Method**	Modified	**Mould Dimension**	Diameter 105mm	Depth 115.5mm
Location	Building 204	**Date Tested**	22/12/2009	**Hammer Weight**	4.9kg	**Drop Height**	450mm	
Soil Description	Original WCCW	**Tested by**	Nara	**No Layers**	5	**No. Blows**	25 per layer	

COMPACTION

Assumed water content,%	**8**	**9**	**10**	**11**	**12**	**13**
Test No	1	2	3	1	2	3
Weight of air dried soil used, %	2035	2252	2227	2116	2158	2081
Water content of dried soil, g	8	9	10	11	12	13
Amount of water added, g	162.8	202.68	222.7	232.76	258.96	270.53
Weight of wet soil + mould, g	5812	6012	6526	6601	6639	6053
Weight of mould, g	4006	4006	4545	4545	4545	4010
Weight of wet soil, g (W)	1806	2006	1981	2056	2094	2043
Wet density, g/cm ^{3} ρ (total) = W/V	1.81	2.01	1.98	2.06	2.09	2.04
Dry soil density, g/cm^3 ρ (dry) = 100 ρ (total)/ (100+w)	**1.672**	**1.840**	**1.98**	**1.852**	**1.869**	**1.808**

OPTIMUM MOISTURE CONTENT (OMC)	**10.9%**
MAXIMUM DRY DENSITY (MDD)	**1.86g/cm^3**

SOIL MECHANIC LABORATORY CURTIN UNIVERSITY

Project	C&D Recycling	**Source of Soil**	Perth, Holcim LTD	**Compaction Method**	Modified	**Mould Dimension**	Diameter 105mm	Depth 115.5mm
Location	Building 204	**Date Tested**	13/5/2009	**Hammer Weight**	4.9kg	**Drop Height**	450mm	
Soil Description	Original WCCW	**Tested by**	Nara	**No Layers**	5	**No. Blows**	25 per layer	

COMPACTION

Assumed water content,%	**9**	**10**	**11**	**12**	**13**
Test No	1	2	3	4	5
Weight of air dried soil used, %	2005	2006	2001	2005	2004
Water content of dried soil, g	9	10	11	12	13
Amount of water added, g	180.45	200.6	220.11	240.6	260.52
Weight of wet soil + mould, g	6550	6672	6718	6733	6664
Weight of mould, g	4553	4553	4553	4553	4553
Weight of wet soil, g (W)	1997	2119	2165	2180	2111
Wet density, g/cm ^{3} ρ (total) = W/V	2.00	2.12	2.16	2.18	2.11
Dry soil density, g/cm^3 ρ (dry) = 100 ρ (total)/ (100+w)	**1.832**	**1.926**	**1.950**	**1.946**	**1.868**

OPTIMUM MOISTURE CONTENT (OMC)	**11.3%**
MAXIMUM DRY DENSITY (MDD)	**1.96g/cm^3**

SOIL MECHANIC LABORATORY CURTIN UNIVERSITY

Project	Capital Demolition	**Source of Soil**	Perth, Holcim LTD	**Compaction Method**	Modified	**Mould Dimension**	Diameter 105mm	Depth 115.5mm
Location	Building 204	**Date Tested**	15/5/2009	**Hammer Weight**	4.9kg	**Drop Height**	450mm	
Soil Description	Original WCCW	**Tested by**	Nara	**No Layers**	5	**No. Blows**	25 per layer	

COMPACTION

Assumed water content,%	**8**	**10**	**11**	**14**	**20**
Test No	1	2	3	4	5
Weight of air dried soil used, %	2038	2468	2399	2208	2265
Water content of dried soil, g	8	10	11	14	20
Amount of water added, g	163.04	246.8	263.89	309.12	453
Weight of wet soil + mould, g	6532	6647	666.3	6682	6713
Weight of mould, g	4553	4548	4548	4548	4548
Weight of wet soil, g (W)	1979	2099	2115	2134	2165
Wet density, g/cm ^{3} ρ (total) = W/V	1.98	2.10	2.11	2.13	2.16
Dry soil density, g/cm^3 ρ (dry) = 100 ρ (total)/ (100+w)	**1.832**	**1.908**	**1.905**	**1.872**	**1.804**

OPTIMUM MOISTURE CONTENT (OMC)	**11.3%**
MAXIMUM DRY DENSITY (MDD)	**1.91g/cm^3**

Appendix B.2 Shear Test

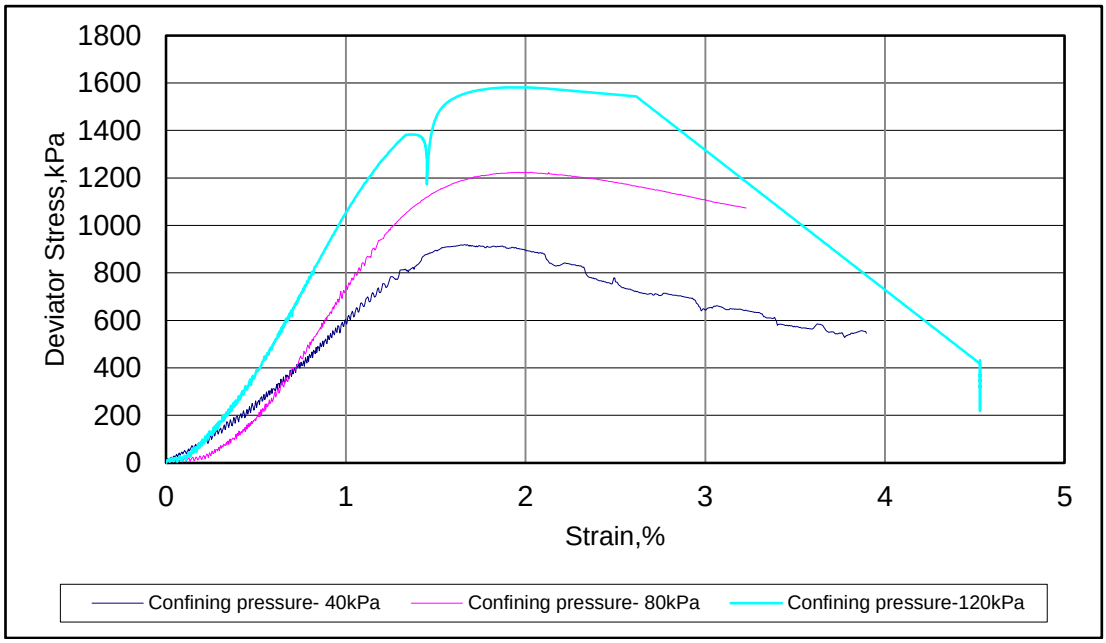

Figure B-2-1: Deviator stress vs strain at various confining pressure after 1 day (All Earth)

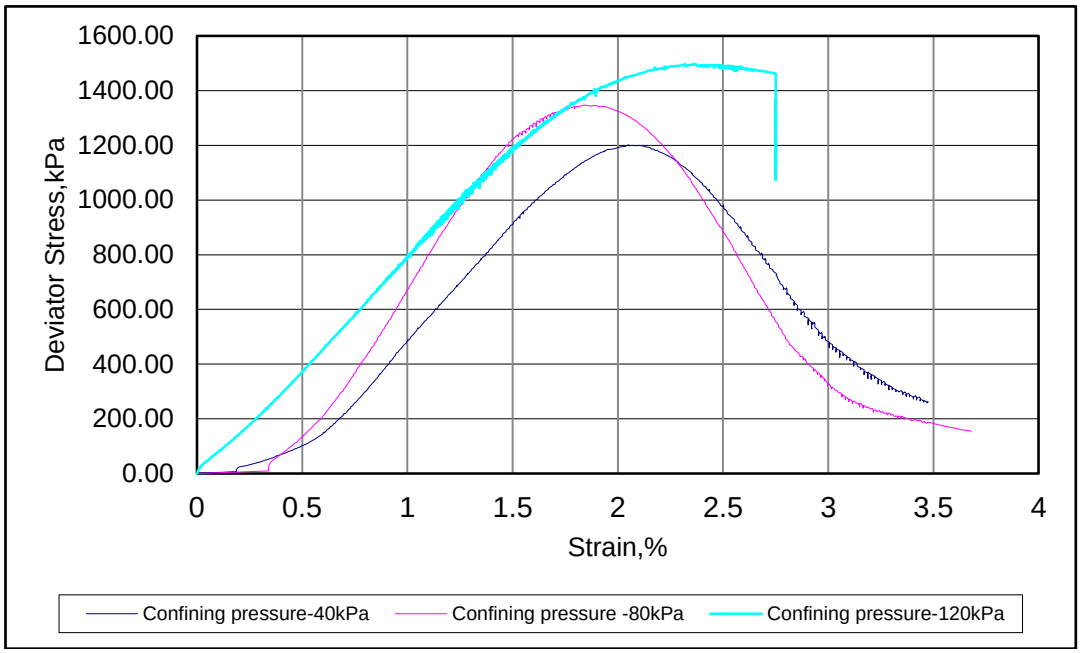

Figure B-2-2: Deviator stress vs strain at various confining pressure after 7 day (All Earth)

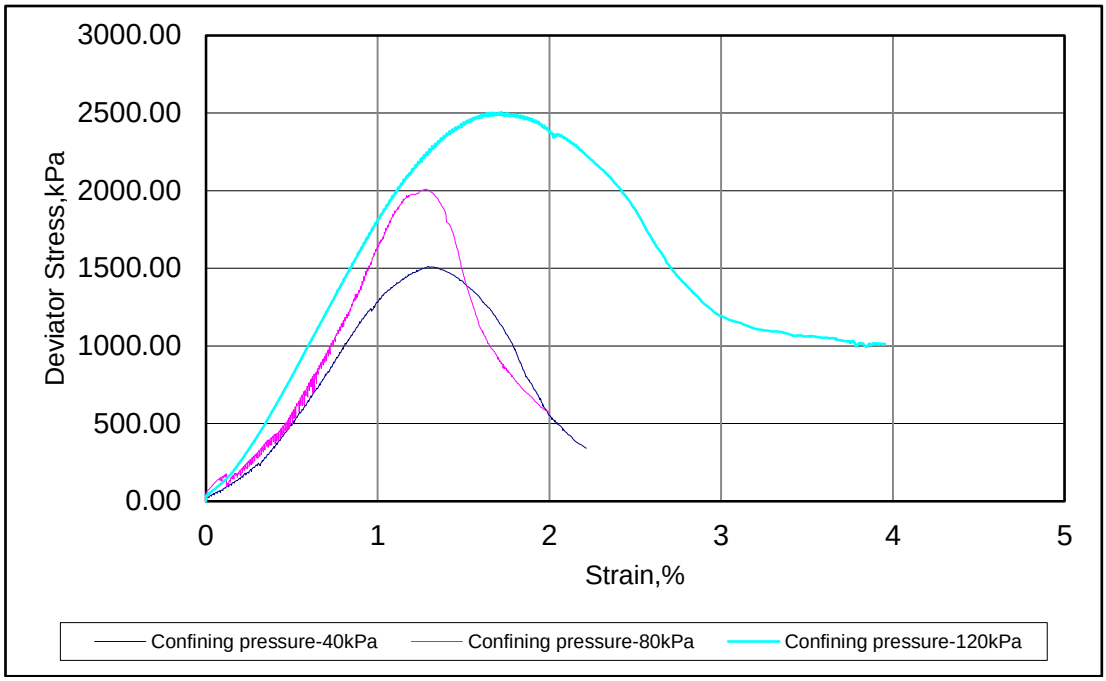

Figure B-2-3: Deviator stress vs strain at various confining pressure after 28 days (All Earth)

Curing days	σ3,	σ1,	q=σd	q=σd/2	p=(σ1+σ3)/2	p=(σ1+2σ3)/3
1	40.00	959.00	919.00	459.50	499.5	346.33
	80.00	1300.00	1220.00	610.00	690	486.67
	120.00	1702.00	1582.00	791.00	911	647.33
7	40.00	1239.00	1199.00	599.50	639.5	439.67
	80.00	1429.00	1349.00	674.50	754.5	529.67
	120.00	1618.00	1498.00	749.00	869	619.33
28	40.00	1557.00	1517.00	758.50	798.5	545.67
	80.00	2091.00	2011.00	1005.50	1085.5	750.33
	120.00	2626.00	2506.00	1253.00	1373	955.33

Table B-2-1: q and p values at various curing days in All Earth material

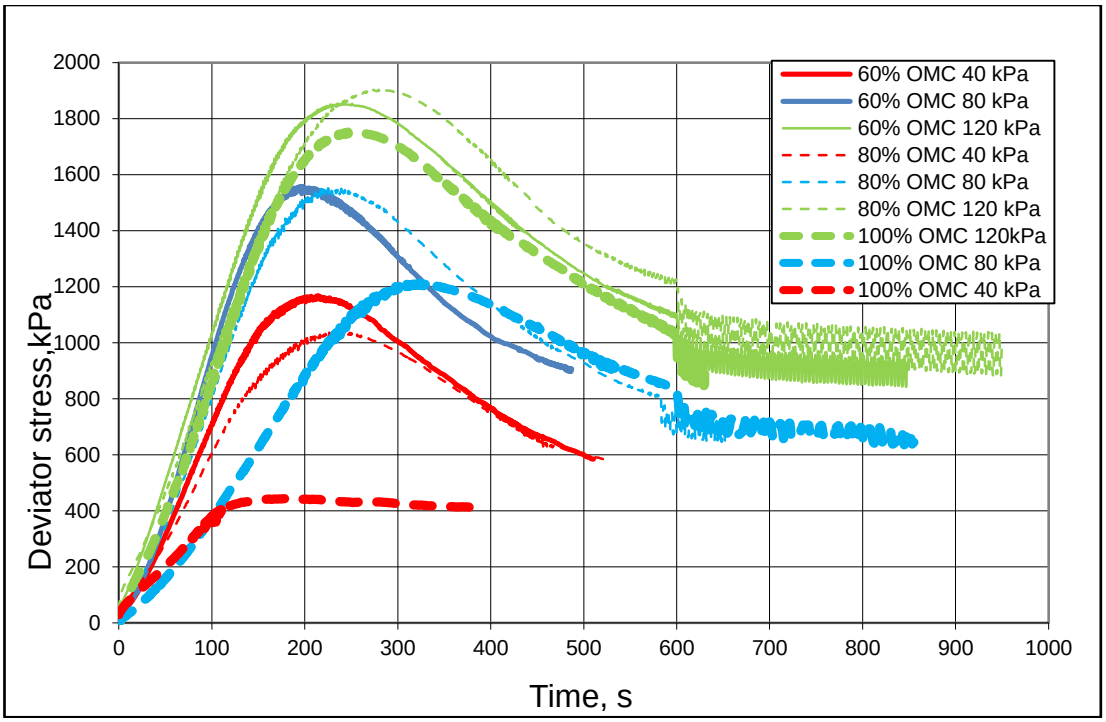

Figure B-2-4: Deviator stress vs time in C&D Recycling

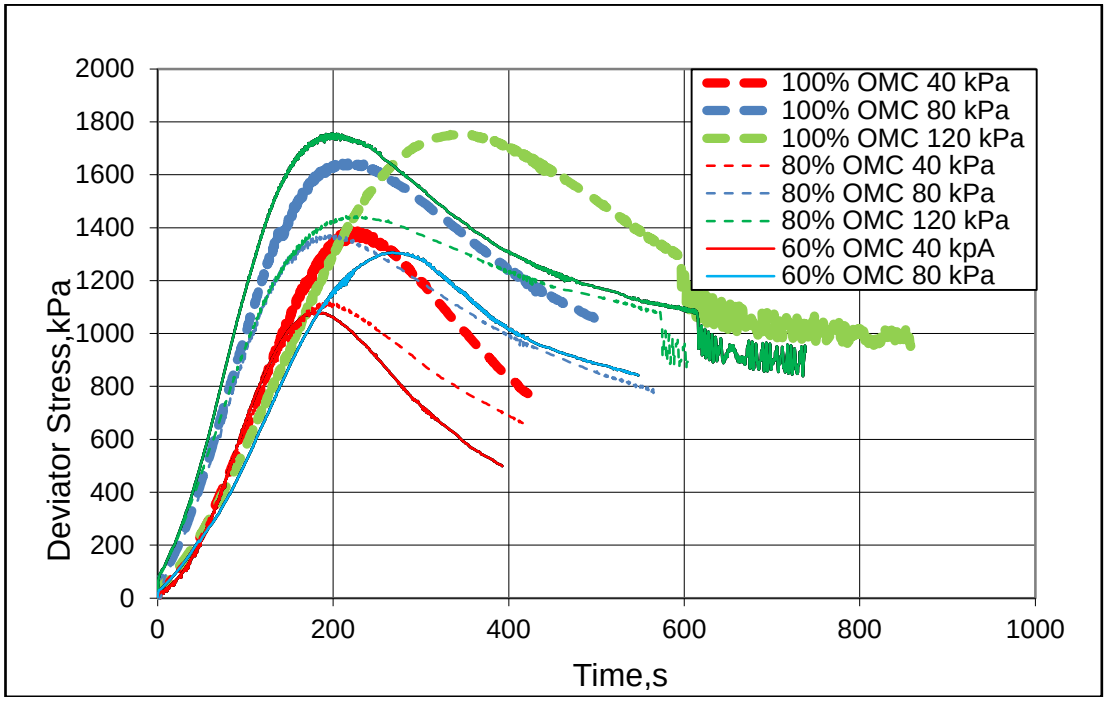

Figure B-2-5: Deviator stress vs time in Capital Demolition

APPENDIX C

RESULTS FROM CIRCLY 5.0

Street type-1 (Local access street,3x10^5 ESA's, 25 years design life)

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CIRCLY Version 5.0r (1 July 2010)

Layer no.  1 is INCLUDED in max. CDF calculation
Layer no.  4 is INCLUDED in max. CDF calculation

Job Title: Nara-1 WCCW 500MPa

Damage Factor Calculation

Assumed number of damage pulses per movement:
   One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

   ID: 2004-1 Title: Austroads 2004 - Example 1 - Unbound Granular Pavement

   Load   Load         Movements
    No.   ID
    1     ESA75-Full   3.00E+05

Details of Load Groups:

   Load   Load        Load        Load            Radius    Pressure/
Exponent
    No.   ID          Category    Type                      Ref. stress
    1     ESA75-Full  SA750-Full  Vertical Force     92.1    0.75
0.00

   Load Locations:
   Location   Load        Gear          X          Y      Scaling     Theta
    No.       ID          No.                             Factor
    1         ESA75-Full   1          -165.0        0.0   1.00E+00      0.00
    2         ESA75-Full   1           165.0        0.0   1.00E+00      0.00
    3         ESA75-Full   1          1635.0        0.0   1.00E+00      0.00
    4         ESA75-Full   1          1965.0        0.0   1.00E+00      0.00


Layout of result points on horizontal plane:

 Xmin: -165   Xmax:  165   Xdel:  165
   Y:     0

Details of Layered System:

   ID: wccw road Title: ROAD WITH WCCW BASE

   Layer  Lower    Material    Isotropy   Modulus    P.Ratio
    No.   i/face   ID                      (or Ev)    (or vvh)  F
Eh         vh

    1     rough    Asph3000    Iso.       3.00E+03   0.40
    2     rough    WCCW        Aniso.     5.00E+02   0.35      3.70E+02
2.50E+02   0.35
    3     rough    Gran_250    Aniso.     2.50E+02   0.35      1.90E+02
1.25E+02   0.35
    4     rough    Sub_CBR10   Aniso.     1.00E+02   0.45      6.90E+01
5.00E+01   0.45


   Performance Relationships:

  Layer  Location Performance  Component  Perform.   Perform.  Traffic
    No.           ID                     Constant   Exponent  Multiplier
    1     bottom   Asph3000     ETH        0.004067    5.000     1.000
```

```
    4     top      Sub_2004     EZZ          0.009300    7.000     1.600

   Reliability Factors: Not Used.

   Details of Layers to be sublayered:
   Layer no.  2:  Austroads (2004) sublayering
   Layer no.  3:  Austroads (2004) sublayering

Automatic layer thickness design:

 Layer number to be designed:  2
   Minimum thickness:  0
   Maximum thickness:  5000

Results:

   Layer  Thickness  Material     Load          Critical       CDF
    No.              ID           ID            Strain
    1       50.00    Asph3000     ESA75-Full    -3.26E-04      9.90E-01
    2      102.09    wccw                        n/a           n/a
    3      250.00    Gran_250                    n/a           n/a
    4        0.00    Sub_CBR10    ESA75-Full     5.63E-04      1.43E-03
```

CIRCLY Version 5.0r (1 July 2010)

Layer no. 1 is INCLUDED in max. CDF calculation
Layer no. 4 is INCLUDED in max. CDF calculation

Job Title: Nara-1 C&D Recycling 560MPa

Damage Factor Calculation

Assumed number of damage pulses per movement:
 One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

   ID: 2004-1 Title: Austroads 2004 - Example 1 - Unbound Granular Pavement

Load No.	Load ID	Movements
1	ESA75-Full	3.00E+05

Details of Load Groups:

Load No.	Load ID	Load Category	Load Type	Radius	Pressure/ Ref. stress	Exponent
1	ESA75-Full	SA750-Full	Vertical Force	92.1	0.75	0.00

Load Locations:

Location No.	Load ID	Gear No.	X	Y	Scaling Factor	Theta
1	ESA75-Full	1	-165.0	0.0	1.00E+00	0.00
2	ESA75-Full	1	165.0	0.0	1.00E+00	0.00
3	ESA75-Full	1	1635.0	0.0	1.00E+00	0.00
4	ESA75-Full	1	1965.0	0.0	1.00E+00	0.00

Layout of result points on horizontal plane:

  Xmin: -165   Xmax: 165   Xdel: 165
   Y: 0

Details of Layered System:

   ID: wccw road Title: ROAD WITH WCCW BASE

Layer No.	Lower i/face	Material ID	Isotropy	Modulus (or Ev)	P.Ratio (or vvh)	F	Eh	vh
1	rough	Asph3000	Iso.	3.00E+03	0.40			
2	rough	C&D	Aniso.	5.60E+02	0.35	4.15E+02	2.80E+02	0.35
3	rough	Gran_250	Aniso.	2.50E+02	0.35	1.90E+02	1.25E+02	0.35
4	rough	Sub_CBR10	Aniso.	1.00E+02	0.45	6.90E+01	5.00E+01	0.45

Performance Relationships:

Layer No.	Location	Performance ID	Component	Perform. Constant	Perform. Exponent	Traffic Multiplier

1	bottom	Asph3000	ETH	0.004067	5.000	1.000
4	top	Sub_2004	EZZ	0.009300	7.000	1.600

Reliability Factors: Not Used.

Details of Layers to be sublayered:

Layer no. 2: Austroads (2004) sublayering
Layer no. 3: Austroads (2004) sublayering

Automatic layer thickness design:

Layer number to be designed: 2
Minimum thickness: 0
Maximum thickness: 5000

Results:

Layer No.	Thickness	Material ID	Load ID	Critical Strain	CDF
1	50.00	Asph3000	ESA75-Full	-3.26E-04	9.99E-01
2	101.55	C&D Recycling		n/a	n/a
3	250.00	Gran_250		n/a	n/a
4	0.00	Sub_CBR10	ESA75-Full	5.64E-04	1.45E-03

CIRCLY Version 5.0r (1 July 2010)

Layer no. 1 is INCLUDED in max. CDF calculation
Layer no. 4 is INCLUDED in max. CDF calculation

Job Title: Nara-1 All EARTH 585MPa

Damage Factor Calculation

Assumed number of damage pulses per movement:
One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

ID: 2004-1 Title: Austroads 2004 - Example 1 - Unbound Granular Pavement

Load No.	Load ID	Movements
1	ESA75-Full	3.00E+05

Details of Load Groups:

Load No.	Load ID	Load Category	Load Type	Radius	Pressure/ Ref. stress	Exponent
1	ESA75-Full	SA750-Full	Vertical Force	92.1	0.75	0.00

Load Locations:

Location No.	Load ID	Gear No.	X	Y	Scaling Factor	Theta
1	ESA75-Full	1	-165.0	0.0	1.00E+00	0.00
2	ESA75-Full	1	165.0	0.0	1.00E+00	0.00
3	ESA75-Full	1	1635.0	0.0	1.00E+00	0.00
4	ESA75-Full	1	1965.0	0.0	1.00E+00	0.00

Layout of result points on horizontal plane:

Xmin: -165 Xmax: 165 Xdel: 165
Y: 0

Details of Layered System:

ID: wccw road Title: ROAD WITH WCCW BASE

Layer No.	Lower i/face	Material ID	Isotropy	Modulus (or Ev)	P.Ratio (or vvh)	F	Eh	vh
1	rough	Asph3000	Iso.	3.00E+03	0.40			
2	rough	ALL EART	Aniso.	5.85E+02	0.35	4.33E+02	2.92E+02	0.35
3	rough	Gran_250	Aniso.	2.50E+02	0.35	1.90E+02	1.25E+02	0.35
4	rough	Sub_CBR10	Aniso.	1.00E+02	0.45	6.90E+01	5.00E+01	0.45

Performance Relationships:

Layer No.	Location	Performance ID	Component	Perform. Constant	Perform. Exponent	Traffic Multiplier
1	bottom	Asph3000	ETH	0.004067	5.000	1.000
4	top	Sub_2004	EZZ	0.009300	7.000	1.600

Reliability Factors: Not Used.

Details of Layers to be sublayered:

Layer no. 2: Austroads (2004) sublayering
Layer no. 3: Austroads (2004) sublayering

Automatic layer thickness design:

Layer number to be designed: 2
Minimum thickness: 0
Maximum thickness: 5000

Results:

Layer No.	Thickness	Material ID	Load ID	Critical Strain	CDF
1	50.00	Asph3000	ESA75-Full	-3.26E-04	9.91E-01
2	102.03	ALL EART		n/a	n/a
3	250.00	Gran_250		n/a	n/a
4	0.00	Sub_CBR10	ESA75-Full	5.63E-04	1.44E-03

CIRCLY Version 5.0r (1 July 2010)

Layer no. 1 is INCLUDED in max. CDF calculation
Layer no. 4 is INCLUDED in max. CDF calculation

Job Title: Nara-1 Capital Demolition 825MPa

Damage Factor Calculation

Assumed number of damage pulses per movement:
One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

ID: 2004-1 Title: Austroads 2004 - Example 1 - Unbound Granular Pavement

Load No.	Load ID	Movements
1	ESA75-Full	3.00E+05

Details of Load Groups:

Load No.	Load ID	Load Category	Load Type	Radius	Pressure/ Ref. stress	Exponent
1	ESA75-Full	SA750-Full	Vertical Force	92.1	0.75	0.00

Load Locations:

Location No.	Load ID	Gear No.	X	Y	Scaling Factor	Theta
1	ESA75-Full	1	-165.0	0.0	1.00E+00	0.00
2	ESA75-Full	1	165.0	0.0	1.00E+00	0.00
3	ESA75-Full	1	1635.0	0.0	1.00E+00	0.00
4	ESA75-Full	1	1965.0	0.0	1.00E+00	0.00

Layout of result points on horizontal plane:
Xmin: -165 Xmax: 165 Xdel: 165
Y: 0

Details of Layered System:

ID: wccw road Title: ROAD WITH WCCW BASE

Layer No.	Lower i/face	Material ID	Isotropy	Modulus (or Ev)	P.Ratio (or vvh)	F	Eh	vh
1	rough	Asph3000	Iso.	3.00E+03	0.40			
2	rough	CAPITALnew	Aniso.	8.25E+02	0.35	6.11E+02	4.12E+02	0.35
3	rough	Gran_250	Aniso.	2.50E+02	0.35	1.90E+02	1.25E+02	0.35
4	rough	Sub_CBR10	Aniso.	1.00E+02	0.45	6.90E+01	5.00E+01	0.45

Performance Relationships:

Layer No.	Location	Performance ID	Component	Perform. Constant	Perform. Exponent	Traffic Multiplier
1	bottom	Asph3000	ETH	0.004067	5.000	1.000
4	top	Sub_2004	EZZ	0.009300	7.000	1.600

Reliability Factors: Not Used.

Details of Layers to be sublayered:

Layer no. 2: Austroads (2004) sublayering
Layer no. 3: Austroads (2004) sublayering

Automatic layer thickness design:

Layer number to be designed: 2
Minimum thickness: 0
Maximum thickness: 5000

Results:

Layer No.	Thickness	Material ID	Load ID	Critical Strain	CDF
1	50.00	Asph3000	ESA75-Full	-3.26E-04	9.90E-01
2	102.05	CAPITALnew		n/a	n/a
3	250.00	Gran_250		n/a	n/a
4	0.00	Sub_CBR10	ESA75-Full	5.63E-04	1.43E-03

CIRCLY Version 5.0r (1 July 2010)

Layer no. 1 is INCLUDED in max. CDF calculation
Layer no. 4 is INCLUDED in max. CDF calculation

Job Title: Nara-1 CRB 350MPa

Damage Factor Calculation

Assumed number of damage pulses per movement:
One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

ID: 2004-1 Title: Austroads 2004 - Example 1 - Unbound Granular Pavement

Load No.	Load ID	Movements
1	ESA75-Full	3.00E+05

Details of Load Groups:

Load No.	Load ID	Load Category	Load Type	Radius	Pressure/ Ref. stress	Exponent
1	ESA75-Full	SA750-Full	Vertical Force	92.1	0.75	0.00

Load Locations:

Location No.	Load ID	Gear No.	X	Y	Scaling Factor	Theta
1	ESA75-Full	1	-165.0	0.0	1.00E+00	0.00
2	ESA75-Full	1	165.0	0.0	1.00E+00	0.00
3	ESA75-Full	1	1635.0	0.0	1.00E+00	0.00
4	ESA75-Full	1	1965.0	0.0	1.00E+00	0.00

Layout of result points on horizontal plane:
Xmin: -165 Xmax: 165 Xdel: 165
Y: 0

Details of Layered System:

ID: wccw road Title: ROAD WITH WCCW BASE

Layer No.	Lower i/face	Material ID	Isotropy	Modulus (or Ev)	P.Ratio (or vvh)	F	Eh	vh
1	rough	Asph3000	Iso.	3.00E+03	0.40			
2	rough	Gran_350	Aniso.	3.50E+02	0.35	2.60E+02	1.75E+02	0.35
3	rough	Gran_250	Aniso.	2.50E+02	0.35	1.90E+02	1.25E+02	0.35
4	rough	Sub_CBR10	Aniso.	1.00E+02	0.45	6.90E+01	5.00E+01	0.45

Performance Relationships:

Layer No.	Location	Performance ID	Component	Perform. Constant	Perform. Exponent	Traffic Multiplier
1	bottom	Asph3000	ETH	0.004067	5.000	1.000
4	top	Sub_2004	EZZ	0.009300	7.000	1.600

Reliability Factors: Not Used.

Details of Layers to be sublayered:
Layer no. 2: Austroads (2004) sublayering
Layer no. 3: Austroads (2004) sublayering

Automatic layer thickness design:

Layer number to be designed: 2
Minimum thickness: 0
Maximum thickness: 5000

Results:

Layer No.	Thickness	Material ID	Load ID	Critical Strain	CDF
1	50.00	Asph3000	ESA75-Full	-3.26E-04	1.00E+00
2	243.46	Gran_350		n/a	n/a
3	250.00	Gran_250		n/a	n/a
4	0.00	Sub_CBR10	ESA75-Full	3.62E-04	6.50E-05

Street type-2 (Collector street,1x10^6 ESA's, 25 year design life)

```
CIRCLY Version 5.0r (1 July 2010)

   Layer no.  1 is INCLUDED in max. CDF calculation
   Layer no.  4 is INCLUDED in max. CDF calculation

Job Title: Nara-1 WCCW 500MPa

Damage Factor Calculation

Assumed number of damage pulses per movement:
   One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

   ID: 2004-1 Title: Austroads 2004 - Example 1 - Unbound Granular Pavement

   Load   Load         Movements
    No.   ID
    1     ESA75-Full   1.00E+06

Details of Load Groups:

   Load   Load        Load        Load            Radius    Pressure/
Exponent
    No.   ID          Category    Type                      Ref. stress
    1     ESA75-Full  SA750-Full  Vertical Force     92.1    0.75
0.00

   Load Locations:
   Location   Load        Gear          X          Y      Scaling     Theta
    No.       ID          No.                              Factor
    1         ESA75-Full   1          -165.0        0.0   1.00E+00      0.00
    2         ESA75-Full   1           165.0        0.0   1.00E+00      0.00
    3         ESA75-Full   1          1635.0        0.0   1.00E+00      0.00
    4         ESA75-Full   1          1965.0        0.0   1.00E+00      0.00

Layout of result points on horizontal plane:
   Xmin: -165   Xmax:  165   Xdel:  165
   Y:     0

Details of Layered System:

   ID: wccw road Title: ROAD WITH WCCW BASE

   Layer  Lower    Material   Isotropy   Modulus    P.Ratio
    No.   i/face   ID                      (or Ev)    (or vvh)  F
Eh         vh
    1     rough    Asph3000   Iso.       3.00E+03   0.40
    2     rough    washcon    Aniso.     5.00E+02   0.35      3.70E+02
2.50E+02   0.35
    3     rough    Gran_250   Aniso.     2.50E+02   0.35      1.90E+02
1.25E+02   0.35
    4     rough    Sub_CBR10  Aniso.     1.00E+02   0.45      6.90E+01
5.00E+01   0.45

   Performance Relationships:

   Layer  Location Performance  Component  Perform.   Perform.  Traffic
    No.            ID                     Constant   Exponent  Multiplier
    1     bottom   Asph3000     ETH         0.004067    5.000     1.000
    4     top      Sub_2004     EZZ         0.009300    7.000     1.600

   Reliability Factors: Not Used.
```

Details of Layers to be sublayered:

Layer no. 2: Austroads (2004) sublayering
Layer no. 3: Austroads (2004) sublayering

Automatic layer thickness design:

Layer number to be designed: 2
Minimum thickness: 0
Maximum thickness: 5000

Results:

Layer No.	Thickness	Material ID	Load ID	Critical Strain	CDF
1	50.00	Asph3000	ESA75-Full	-2.57E-04	1.00E+00
2	236.60	washcon		n/a	n/a
3	250.00	Gran_250		n/a	n/a
4	0.00	Sub_CBR10	ESA75-Full	3.53E-04	1.82E-04

CIRCLY Version 5.0r (1 July 2010)

Layer no. 1 is INCLUDED in max. CDF calculation
Layer no. 4 is INCLUDED in max. CDF calculation

Job Title: Nara-1 C&D Recycling 560MPa

Damage Factor Calculation

Assumed number of damage pulses per movement:
One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

ID: 2004-1 Title: Austroads 2004 - Example 1 - Unbound Granular Pavement

Load No.	Load ID	Movements
1	ESA75-Full	1.00E+06

Details of Load Groups:

Load No.	Load ID	Load Category	Load Type	Radius	Pressure/ Ref. stress	Exponent
1	ESA75-Full	SA750-Full	Vertical Force	92.1	0.75	0.00

Load Locations:

Location No.	Load ID	Gear No.	X	Y	Scaling Factor	Theta
1	ESA75-Full	1	-165.0	0.0	1.00E+00	0.00
2	ESA75-Full	1	165.0	0.0	1.00E+00	0.00
3	ESA75-Full	1	1635.0	0.0	1.00E+00	0.00
4	ESA75-Full	1	1965.0	0.0	1.00E+00	0.00

Layout of result points on horizontal plane:
Xmin: -165 Xmax: 165 Xdel: 165
Y: 0

Details of Layered System:

ID: wccw road Title: ROAD WITH WCCW BASE

Layer No.	Lower i/face	Material ID	Isotropy	Modulus (or Ev)	P.Ratio (or vvh)	F	Eh	vh
1	rough	Asph3000	Iso.	3.00E+03	0.40			
2	rough	C&D	Aniso.	5.60E+02	0.35	4.15E+02	2.80E+02	0.35
3	rough	Gran_250	Aniso.	2.50E+02	0.35	1.90E+02	1.25E+02	0.35
4	rough	Sub_CBR10	Aniso.	1.00E+02	0.45	6.90E+01	5.00E+01	0.45

Performance Relationships:

Layer No.	Location	Performance ID	Component	Perform. Constant	Perform. Exponent	Traffic Multiplier
1	bottom	Asph3000	ETH	0.004067	5.000	1.000
4	top	Sub_2004	EZZ	0.009300	7.000	1.600

Reliability Factors: Not Used.

Details of Layers to be sublayered:

Layer no. 2: Austroads (2004) sublayering
Layer no. 3: Austroads (2004) sublayering

Automatic layer thickness design:

Layer number to be designed: 2
Minimum thickness: 0
Maximum thickness: 5000

Results:

Layer No.	Thickness	Material ID	Load ID	Critical Strain	CDF
1	50.00	Asph3000	ESA75-Full	-2.57E-04	1.00E+00
2	160.12	C&D		n/a	n/a
3	250.00	Gran_250		n/a	n/a
4	0.00	Sub_CBR10	ESA75-Full	4.48E-04	9.70E-04

CIRCLY Version 5.0r (1 July 2010)

Layer no. 1 is INCLUDED in max. CDF calculation
Layer no. 4 is INCLUDED in max. CDF calculation

Job Title: Nara-1 All Earth 585MPa

Damage Factor Calculation

Assumed number of damage pulses per movement:
One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

ID: 2004-1 Title: Austroads 2004 - Example 1 - Unbound Granular Pavement

Load No.	Load ID	Movements
1	ESA75-Full	1.00E+06

Details of Load Groups:

Load No.	Load ID	Load Category	Load Type	Radius	Pressure/ Ref. stress	Exponent
1	ESA75-Full	SA750-Full	Vertical Force	92.1	0.75	0.00

Load Locations:

Location No.	Load ID	Gear No.	X	Y	Scaling Factor	Theta
1	ESA75-Full	1	-165.0	0.0	1.00E+00	0.00
2	ESA75-Full	1	165.0	0.0	1.00E+00	0.00
3	ESA75-Full	1	1635.0	0.0	1.00E+00	0.00
4	ESA75-Full	1	1965.0	0.0	1.00E+00	0.00

Layout of result points on horizontal plane:
Xmin: -165 Xmax: 165 Xdel: 165
Y: 0

Details of Layered System:

ID: wccw road Title: ROAD WITH WCCW BASE

Layer No.	Lower i/face	Material ID	Isotropy	Modulus (or Ev)	P.Ratio (or vvh)	F	Eh	vh
1	rough	Asph3000	Iso.	3.00E+03	0.40			
2	rough	ALL EART	Aniso.	5.85E+02	0.35	4.33E+02	2.92E+02	0.35
3	rough	Gran_250	Aniso.	2.50E+02	0.35	1.90E+02	1.25E+02	0.35
4	rough	Sub_CBR10	Aniso.	1.00E+02	0.45	6.90E+01	5.00E+01	0.45

Performance Relationships:

Layer No.	Location	Performance ID	Component	Perform. Constant	Perform. Exponent	Traffic Multiplier
1	bottom	Asph3000	ETH	0.004067	5.000	1.000
4	top	Sub_2004	EZZ	0.009300	7.000	1.600

Reliability Factors: Not Used.

Details of Layers to be sublayered:

Layer no. 2: Austroads (2004) sublayering
Layer no. 3: Austroads (2004) sublayering

Automatic layer thickness design:

Layer number to be designed: 2
Minimum thickness: 0
Maximum thickness: 5000

Results:

Layer No.	Thickness	Material ID	Load ID	Critical Strain	CDF
1	50.00	Asph3000	ESA75-Full	-2.56E-04	9.87E-01
2	150.79	ALL EART		n/a	n/a
3	250.00	Gran_250		n/a	n/a
4	0.00	Sub_CBR10	ESA75-Full	4.62E-04	1.20E-03

CIRCLY Version 5.0r (1 July 2010)

Layer no. 1 is INCLUDED in max. CDF calculation
Layer no. 4 is INCLUDED in max. CDF calculation

Job Title: Nara-1 Capital Demolition 825MPa

Damage Factor Calculation

Assumed number of damage pulses per movement:
One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

ID: 2004-1 Title: Austroads 2004 - Example 1 - Unbound Granular Pavement

Load No.	Load ID	Movements
1	ESA75-Full	1.00E+06

Details of Load Groups:

Load No.	Load ID	Load Category	Load Type	Radius	Pressure/ Ref. stress	Exponent
1	ESA75-Full	SA750-Full	Vertical Force	92.1	0.75	0.00

Load Locations:

Location No.	Load ID	Gear No.	X	Y	Scaling Factor	Theta
1	ESA75-Full	1	-165.0	0.0	1.00E+00	0.00
2	ESA75-Full	1	165.0	0.0	1.00E+00	0.00
3	ESA75-Full	1	1635.0	0.0	1.00E+00	0.00
4	ESA75-Full	1	1965.0	0.0	1.00E+00	0.00

Layout of result points on horizontal plane:

Xmin: -165 Xmax: 165 Xdel: 165
Y: 0

Details of Layered System:

ID: wccw road Title: ROAD WITH WCCW BASE

Layer No.	Lower i/face	Material ID	Isotropy	Modulus (or Ev)	P.Ratio (or vvh)	F	Eh	vh
1	rough	Asph3000	Iso.	3.00E+03	0.40			
2	rough	CAPITALnew	Aniso.	8.25E+02	0.35	6.11E+02	4.12E+02	0.35
3	rough	Gran_250	Aniso.	2.50E+02	0.35	1.90E+02	1.25E+02	0.35
4	rough	Sub_CBR10	Aniso.	1.00E+02	0.45	6.90E+01	5.00E+01	0.45

Performance Relationships:

Layer No.	Location	Performance ID	Component	Perform. Constant	Perform. Exponent	Traffic Multiplier
1	bottom	Asph3000	ETH	0.004067	5.000	1.000
4	top	Sub_2004	EZZ	0.009300	7.000	1.600

Reliability Factors: Not Used.

Details of Layers to be sublayered:

Layer no. 2: Austroads (2004) sublayering
Layer no. 3: Austroads (2004) sublayering

Automatic layer thickness design:

Layer number to be designed: 2
Minimum thickness: 0
Maximum thickness: 5000

Results:

Layer No.	Thickness	Material ID	Load ID	Critical Strain	CDF
1	50.00	Asph3000	ESA75-Full	-2.57E-04	1.00E+00
2	150.26	CAPITALnew		n/a	n/a
3	250.00	Gran_250		n/a	n/a
4	0.00	Sub_CBR10	ESA75-Full	4.63E-04	1.22E-03

Street type-3 (Distributor road, 2x10^{6}ESA's, 25 year design life)

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CIRCLY Version 5.0r (1 July 2010)

   Layer no.  1 is INCLUDED in max. CDF calculation
   Layer no.  4 is INCLUDED in max. CDF calculation

Job Title: Nara-1 C&D Recycling 560MPa

Damage Factor Calculation

Assumed number of damage pulses per movement:
   One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

   ID: 2004-1 Title: Austroads 2004 - Example 1 - Unbound Granular Pavement

   Load   Load         Movements
    No.   ID
    1     ESA75-Full   2.00E+06

Details of Load Groups:

   Load   Load        Load        Load            Radius    Pressure/
Exponent
    No.   ID          Category    Type                      Ref. stress
    1     ESA75-Full  SA750-Full  Vertical Force     92.1    0.75
0.00

   Load Locations:

   Location   Load        Gear          X          Y      Scaling     Theta
    No.       ID          No.                             Factor
    1         ESA75-Full   1          -165.0        0.0   1.00E+00      0.00
    2         ESA75-Full   1           165.0        0.0   1.00E+00      0.00
    3         ESA75-Full   1          1635.0        0.0   1.00E+00      0.00
    4         ESA75-Full   1          1965.0        0.0   1.00E+00      0.00

Layout of result points on horizontal plane:
   Xmin: -165   Xmax:  165   Xdel:  165
   Y:     0

Details of Layered System:

   ID: wccw road Title: ROAD WITH WCCW BASE

   Layer  Lower    Material     Isotropy   Modulus    P.Ratio
    No.   i/face   ID                      (or Ev)    (or vvh)  F
Eh         vh

    1     rough    Asph3000   Iso.       3.00E+03   0.40
    2     rough    C&D        Aniso.     5.60E+02   0.35      4.15E+02
2.80E+02   0.35
    3     rough    Gran_250   Aniso.     2.50E+02   0.35      1.90E+02
1.25E+02   0.35
    4     rough    Sub_CBR10  Aniso.     1.00E+02   0.45      6.90E+01
5.00E+01   0.45

   Performance Relationships:

   Layer  Location Performance  Component  Perform.   Perform.  Traffic
    No.            ID                     Constant   Exponent  Multiplier
    1     bottom   Asph3000     ETH         0.004067    5.000     1.000
    4     top      Sub_2004     EZZ         0.009300    7.000     1.600

   Reliability Factors: Not Used.
```

Details of Layers to be sublayered:

Layer no. 2: Austroads (2004) sublayering
Layer no. 3: Austroads (2004) sublayering

Automatic layer thickness design:

Layer number to be designed: 2
Minimum thickness: 0
Maximum thickness: 5000

Results:

Layer No.	Thickness	Material ID	Load ID	Critical Strain	CDF
1	50.00	Asph3000	ESA75-Full	-2.23E-04	9.99E-01
2	325.50	C&D		n/a	n/a
3	250.00	Gran_250		n/a	n/a
4	0.00	Sub_CBR10	ESA75-Full	2.68E-04	5.27E-05

CIRCLY Version 5.0r (1 July 2010)

Layer no. 1 is INCLUDED in max. CDF calculation
Layer no. 4 is INCLUDED in max. CDF calculation

Job Title: Nara-1 All Earth 585MPa

Damage Factor Calculation

Assumed number of damage pulses per movement:
One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

ID: 2004-1 Title: Austroads 2004 - Example 1 - Unbound Granular Pavement

Load No.	Load ID	Movements
1	ESA75-Full	2.00E+06

Details of Load Groups:

Load No.	Load ID	Load Category	Load Type	Radius	Pressure/ Ref. stress	Exponent
1	ESA75-Full	SA750-Full	Vertical Force	92.1	0.75	0.00

Load Locations:

Location No.	Load ID	Gear No.	X	Y	Scaling Factor	Theta
1	ESA75-Full	1	-165.0	0.0	1.00E+00	0.00
2	ESA75-Full	1	165.0	0.0	1.00E+00	0.00
3	ESA75-Full	1	1635.0	0.0	1.00E+00	0.00
4	ESA75-Full	1	1965.0	0.0	1.00E+00	0.00

Layout of result points on horizontal plane:
Xmin: -165 Xmax: 165 Xdel: 165
Y: 0

Details of Layered System:

ID: wccw road Title: ROAD WITH WCCW BASE

Layer No.	Lower i/face	Material ID	Isotropy	Modulus (or Ev)	P.Ratio (or vvh)	F	Eh	vh
1	rough	Asph3000	Iso.	3.00E+03	0.40			
2	rough	ALL EART	Aniso.	5.85E+02	0.35	4.33E+02	2.92E+02	0.35
3	rough	Gran_250	Aniso.	2.50E+02	0.35	1.90E+02	1.25E+02	0.35
4	rough	Sub_CBR10	Aniso.	1.00E+02	0.45	6.90E+01	5.00E+01	0.45

Performance Relationships:

Layer No.	Location	Performance ID	Component	Perform. Constant	Perform. Exponent	Traffic Multiplier
1	bottom	Asph3000	ETH	0.004067	5.000	1.000
4	top	Sub_2004	EZZ	0.009300	7.000	1.600

Reliability Factors: Not Used.

Details of Layers to be sublayered:

Layer no. 2: Austroads (2004) sublayering
Layer no. 3: Austroads (2004) sublayering

Automatic layer thickness design:

Layer number to be designed: 2
Minimum thickness: 0
Maximum thickness: 5000

Results:

Layer No.	Thickness	Material ID	Load ID	Critical Strain	CDF
1	50.00	Asph3000	ESA75-Full	-2.23E-04	1.00E+00
2	258.88	ALL EART		n/a	n/a
3	250.00	Gran_250		n/a	n/a
4	0.00	Sub_CBR10	ESA75-Full	3.23E-04	1.95E-04

CIRCLY Version 5.0r (1 July 2010)

Layer no. 1 is INCLUDED in max. CDF calculation
Layer no. 4 is INCLUDED in max. CDF calculation

Job Title: Nara-1 Capital Demolition 825MPa

Damage Factor Calculation

Assumed number of damage pulses per movement:
One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

ID: 2004-1 Title: Austroads 2004 - Example 1 - Unbound Granular Pavement

Load No.	Load ID	Movements
1	ESA75-Full	2.00E+06

Details of Load Groups:

Load No.	Load ID	Load Category	Load Type	Radius	Pressure/ Ref. stress	Exponent
1	ESA75-Full	SA750-Full	Vertical Force	92.1	0.75	0.00

Load Locations:

Location No.	Load ID	Gear No.	X	Y	Scaling Factor	Theta
1	ESA75-Full	1	-165.0	0.0	1.00E+00	0.00
2	ESA75-Full	1	165.0	0.0	1.00E+00	0.00
3	ESA75-Full	1	1635.0	0.0	1.00E+00	0.00
4	ESA75-Full	1	1965.0	0.0	1.00E+00	0.00

Layout of result points on horizontal plane:

Xmin: -165 Xmax: 165 Xdel: 165
Y: 0

Details of Layered System:

ID: wccw road Title: ROAD WITH WCCW BASE

Layer No.	Lower i/face	Material ID	Isotropy	Modulus (or Ev)	P.Ratio (or vvh)	F	Eh	vh
1	rough	Asph3000	Iso.	3.00E+03	0.40			
2	rough	CAPITALnew	Aniso.	8.25E+02	0.35	6.11E+02	4.12E+02	0.35
3	rough	Gran_250	Aniso.	2.50E+02	0.35	1.90E+02	1.25E+02	0.35
4	rough	Sub_CBR10	Aniso.	1.00E+02	0.45	6.90E+01	5.00E+01	0.45

Performance Relationships:

Layer No.	Location	Performance ID	Component	Perform. Constant	Perform. Exponent	Traffic Multiplier
1	bottom	Asph3000	ETH	0.004067	5.000	1.000
4	top	Sub_2004	EZZ	0.009300	7.000	1.600

Reliability Factors: Not Used.

Details of Layers to be sublayered:

Layer no. 2: Austroads (2004) sublayering
Layer no. 3: Austroads (2004) sublayering

Automatic layer thickness design:

Layer number to be designed: 2
Minimum thickness: 0
Maximum thickness: 5000

Results:

Layer No.	Thickness	Material ID	Load ID	Critical Strain	CDF
1	50.00	Asph3000	ESA75-Full	-2.23E-04	9.87E-01
2	175.20	CAPITALnew		n/a	n/a
3	250.00	Gran_250		n/a	n/a
4	0.00	Sub_CBR10	ESA75-Full	4.18E-04	1.19E-03

Street type-4 (Commercial and Industral, 5x10^6 ESA's, 25 year desing life

```
CIRCLY Version 5.0r (1 July 2010)

   Layer no.  1 is INCLUDED in max. CDF calculation
   Layer no.  4 is INCLUDED in max. CDF calculation

Job Title: Nara-1 Capital 825MPa

Damage Factor Calculation

Assumed number of damage pulses per movement:
   One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

   ID: 2004-1 Title: Austroads 2004 - Example 1 - Unbound Granular Pavement

   Load   Load         Movements
    No.   ID
    1     ESA75-Full   5.00E+06

Details of Load Groups:

   Load   Load        Load        Load            Radius    Pressure/
Exponent
    No.   ID          Category    Type                      Ref. stress

    1     ESA75-Full  SA750-Full  Vertical Force     92.1    0.75
0.00

   Load Locations:
   Location   Load        Gear          X          Y      Scaling     Theta
    No.       ID          No.                              Factor

    1         ESA75-Full   1          -165.0        0.0   1.00E+00      0.00
    2         ESA75-Full   1           165.0        0.0   1.00E+00      0.00
    3         ESA75-Full   1          1635.0        0.0   1.00E+00      0.00
    4         ESA75-Full   1          1965.0        0.0   1.00E+00      0.00

Layout of result points on horizontal plane:

   Xmin: -165   Xmax:  165   Xdel:  165
   Y:     0

Details of Layered System:

   ID: wccw road Title: ROAD WITH WCCW BASE

   Layer  Lower    Material     Isotropy   Modulus    P.Ratio
    No.   i/face   ID                      (or Ev)    (or vvh)  F
Eh         vh
    1     rough    Asph3000     Iso.       3.00E+03   0.40
    2     rough    CAPITALnew   Aniso.     8.25E+02   0.35      6.11E+02
4.12E+02   0.35
    3     rough    Gran_250     Aniso.     2.50E+02   0.35      1.90E+02
1.25E+02   0.35
    4     rough    Sub_CBR10    Aniso.     1.00E+02   0.45      6.90E+01
5.00E+01   0.45

   Performance Relationships:

   Layer  Location Performance  Component  Perform.   Perform.  Traffic
    No.            ID                     Constant   Exponent  Multiplier
    1     bottom   Asph3000     ETH         0.004067    5.000     1.000
    4     top      Sub_2004     EZZ         0.009300    7.000     1.600
```

Reliability Factors: Not Used.

Details of Layers to be sublayered:

Layer no. 2: Austroads (2004) sublayering
Layer no. 3: Austroads (2004) sublayering

Automatic layer thickness design:

Layer number to be designed: 2
Minimum thickness: 0
Maximum thickness: 5000

Results:

Layer No.	Thickness	Material ID	Load ID	Critical Strain	CDF
1	50.00	Asph3000	ESA75-Full	-1.85E-04	9.85E-01
2	204.83	CAPITALnew		n/a	n/a
3	250.00	Gran_250		n/a	n/a
4	0.00	Sub_CBR10	ESA75-Full	3.71E-04	1.29E-03

APPENDIX D

RESULTS FROM FINITE ELEMENT ANALYSIS (ABAQUS/CAE 6.9)

WCCW					C&D				
Pavement depth,m	E11	µm	E22	µm	Pavement depth,m	E11	µm	E22	µm
0.0000	-0.000799	-799.4	0.0002	156.6	0.0000	-0.000785	-784.8	0.0002	150.3
-0.0100	-0.000574	-573.7	0.0001	62.0	0.0100	-0.000569	-569.3	0.0001	60.0
-0.0200	-0.000359	-358.7	0.0000	-24.4	0.0200	-0.000364	-364.2	0.0000	-22.4
-0.0300	-0.000151	-150.9	-0.0001	-105.4	0.0300	-0.000166	-166.2	-0.0001	-99.5
-0.0400	0.000054	53.6	-0.0002	-184.3	0.0400	0.000028	28.1	-0.0002	-174.2
-0.0500	**0.000259**	**258.8**	**-0.0003**	**-264.0**	**0.0500**	**0.000222**	**222.3**	**-0.0002**	**-249.1**
-0.0500	**0.000260**	**259.9**	**-0.0009**	**-911.1**	**0.0500**	**0.000223**	**223.3**	**-0.0008**	**-811.7**
-0.0595	0.000322	321.6	-0.0009	-908.2	0.0602	0.000290	290.0	-0.0008	-811.5
-0.0691	0.000374	373.8	-0.0009	-899.7	0.0704	0.000347	347.0	-0.0008	-805.7
-0.0786	0.000419	419.0	-0.0009	-887.6	0.0806	0.000398	397.6	-0.0008	-796.7
0.0882	0.000460	459.7	-0.0009	-874.0	0.0908	0.000444	444.3	-0.0008	-786.7
-0.0977	0.000498	498.0	-0.0009	-860.3	0.1010	0.000490	489.8	-0.0008	-777.5
-0.1073	0.000536	535.6	-0.0008	-847.9	0.1112	0.000536	536.0	-0.0008	-770.8
-0.1168	0.000574	574.2	-0.0008	-838.0	0.1214	0.000585	585.2	-0.0008	-768.1
-0.1264	0.000615	615.5	-0.0008	-831.6	0.1316	0.000639	639.2	-0.0008	-770.7
-0.1359	0.000661	660.8	-0.0008	-830.0	0.1418	0.000700	700.2	-0.0008	-780.3
0.1455	0.000712	711.8	-0.0008	-834.3	**0.1520**	**0.000770**	**770.4**	**-0.0008**	**-798.5**
-0.1550	**0.000770**	**770.3**	**-0.0008**	**-845.7**	**0.1520**	**0.000771**	**771.2**	**-0.0013**	**-1275.2**
-0.1550	**0.000771**	**770.9**	**-0.0013**	**-1277.3**	0.1620	0.000754	753.6	-0.0012	-1228.4
-0.1650	0.000754	753.8	-0.0012	-1230.7	0.1720	0.000737	737.3	-0.0012	-1184.6
-0.1750	0.000738	737.9	-0.0012	-1187.1	0.1820	0.000722	722.4	-0.0011	-1143.7
-0.1850	0.000723	723.4	-0.0011	-1146.3	0.1920	0.000709	709.0	-0.0011	-1105.5
-0.1950	0.000710	710.2	-0.0011	-1108.2	0.2020	0.000697	697.0	-0.0011	-1069.9
-0.2050	0.000698	698.4	-0.0011	-1072.6	0.2120	0.000686	686.4	-0.0010	-1036.7
0.2150	0.000688	688.0	-0.0010	-1039.5	0.2220	0.000677	677.3	-0.0010	-1005.8
0.2250	0.000679	679.0	-0.0010	-1008.6	0.2320	0.000670	669.6	-0.0010	-977.2
0.2350	0.000671	671.4	-0.0010	-979.9	0.2420	0.000663	663.4	-0.0010	-950.7
0.2450	0.000665	665.2	-0.0010	-953.4	0.2520	0.000659	658.6	-0.0009	-926.3
0.2550	0.000660	660.5	-0.0009	-928.8	0.2620	0.000655	655.2	-0.0009	-903.8
0.2650	0.000657	657.1	-0.0009	-906.2	0.2720	0.000653	653.3	-0.0009	-883.2
0.2750	0.000655	655.3	-0.0009	-885.5	0.2820	0.000653	653.0	-0.0009	-864.5
0.2850	0.000655	654.9	-0.0009	-866.7	0.2920	0.000654	654.1	-0.0008	-847.6
0.2950	0.000656	656.0	-0.0008	-849.7	0.3020	0.000657	656.9	-0.0008	-832.5
0.3050	0.000659	658.8	-0.0008	-834.6	0.3120	0.000661	661.3	-0.0008	-819.3
0.3150	0.000663	663.2	-0.0008	-821.2	0.3220	0.000667	667.4	-0.0008	-807.9
0.3250	0.000669	669.3	-0.0008	-809.7	0.3320	0.000675	675.3	-0.0008	-798.3
0.3350	0.000677	677.2	-0.0008	-800.1	0.3420	0.000685	685.2	-0.0008	-790.7
0.3450	0.000687	687.0	-0.0008	-792.4	0.3520	0.000697	697.0	-0.0008	-785.1
0.3550	0.000699	698.9	-0.0008	-786.7	0.3620	0.000711	711.0	-0.0008	-781.5
0.3650	0.000713	712.9	-0.0008	-783.1	0.3720	0.000727	727.3	-0.0008	-780.1

0.3750	0.000729	729.2	-0.0008	-781.6	0.3820	0.000746	746.1	-0.0008	-780.9
0.3850	0.000748	748.1	-0.0008	-782.5	0.3920	0.000768	767.7	-0.0008	-784.2
0.3950	0.000770	769.7	-0.0008	-785.8	**0.4020**	**0.000792**	**792.1**	**-0.0008**	**-790.2**
0.4050	**0.000794**	**794.3**	**-0.0008**	**-791.7**	**0.4020**	**0.000792**	**792.3**	**-0.0013**	**-1335.9**
0.4050	**0.000794**	**794.5**	**-0.0013**	**-1338.0**	0.4120	0.000775	775.1	-0.0013	-1310.2
0.4150	0.000777	777.1	-0.0013	-1312.1	0.4220	0.000759	758.7	-0.0013	-1285.6
0.4250	0.000760	760.5	-0.0013	-1287.2	0.4320	0.000743	742.9	-0.0013	-1262.0
0.4351	0.000745	744.6	-0.0013	-1263.3	0.4420	0.000728	727.7	-0.0012	-1239.2
0.4451	0.000729	729.2	-0.0012	-1240.4	0.4520	0.000713	713.2	-0.0012	-1217.4
0.4551	0.000715	714.5	-0.0012	-1218.4	0.4619	0.000699	699.2	-0.0012	-1196.3
0.4651	0.000700	700.4	-0.0012	-1197.1	0.4719	0.000686	685.7	-0.0012	-1176.0
0.4752	0.000687	686.8	-0.0012	-1176.7	0.4819	0.000673	672.7	-0.0012	-1156.5
0.4852	0.000674	673.7	-0.0012	-1157.0	0.4919	0.000660	660.2	-0.0011	-1137.6
0.4952	0.000661	661.0	-0.0011	-1137.9	0.5019	0.000648	648.1	-0.0011	-1119.4
0.5052	0.000649	648.8	-0.0011	-1119.6	0.5119	0.000636	636.4	-0.0011	-1101.8
0.5153	0.000637	637.0	-0.0011	-1101.8	0.5219	0.000625	625.1	-0.0011	-1084.7
0.5253	0.000626	625.6	-0.0011	-1084.7	0.5319	0.000614	614.2	-0.0011	-1068.2
0.5353	0.000615	614.6	-0.0011	-1068.1	0.5419	0.000604	603.6	-0.0011	-1052.3
0.5453	0.000604	604.0	-0.0011	-1052.0	0.5519	0.000593	593.4	-0.0010	-1036.8
0.5554	0.000594	593.6	-0.0010	-1036.5	0.5618	0.000583	583.4	-0.0010	-1021.8
0.5654	0.000584	583.6	-0.0010	-1021.4	0.5718	0.000574	573.8	-0.0010	-1007.3
0.5754	0.000574	573.9	-0.0010	-1006.8	0.5818	0.000564	564.5	-0.0010	-993.2
0.5854	0.000565	564.5	-0.0010	-992.6	0.5918	0.000555	555.4	-0.0010	-979.5
0.5955	0.000555	555.4	-0.0010	-978.8	0.6018	0.000547	546.6	-0.0010	-966.2
0.6055	0.000546	546.5	-0.0010	-965.5	0.6118	0.000538	538.0	-0.0010	-953.3
0.6155	0.000538	537.9	-0.0010	-952.5	0.6218	0.000530	529.7	-0.0009	-940.7
0.6255	0.000529	529.5	-0.0009	-939.8	0.6318	0.000522	521.6	-0.0009	-928.5
0.6356	0.000521	521.3	-0.0009	-927.6	0.6418	0.000514	513.7	-0.0009	-916.6
0.6456	0.000513	513.3	-0.0009	-915.6	0.6518	0.000506	506.0	-0.0009	-905.1
0.6556	0.000506	505.6	-0.0009	-904.0	0.6618	0.000498	498.5	-0.0009	-893.8
0.6656	0.000498	498.1	-0.0009	-892.7	0.6717	0.000491	491.2	-0.0009	-882.8
0.6756	0.000491	490.7	-0.0009	-881.6	0.6817	0.000484	484.0	-0.0009	-872.1
0.6857	0.000484	483.5	-0.0009	-870.9	0.6917	0.000477	477.1	-0.0009	-861.7
0.6957	0.000477	476.5	-0.0009	-860.4	0.7017	0.000470	470.3	-0.0009	-851.5
0.7057	0.000470	469.7	-0.0009	-850.2	0.7117	0.000464	463.6	-0.0008	-841.5
0.7157	0.000463	463.0	-0.0008	-840.2	0.7217	0.000457	457.1	-0.0008	-831.8
0.7258	0.000456	456.5	-0.0008	-830.5	0.7317	0.000451	450.8	-0.0008	-822.4
0.7358	0.000450	450.1	-0.0008	-821.0	0.7417	0.000445	444.6	-0.0008	-813.1
0.7458	0.000444	443.9	-0.0008	-811.7	0.7517	0.000439	438.5	-0.0008	-804.1
0.7558	0.000438	437.8	-0.0008	-802.7	0.7617	0.000433	432.6	-0.0008	-795.3
0.7659	0.000432	431.8	-0.0008	-793.8	0.7716	0.000427	426.8	-0.0008	-786.7
0.7759	0.000426	426.0	-0.0008	-785.2	0.7816	0.000421	421.1	-0.0008	-778.2
0.7859	0.000420	420.3	-0.0008	-776.7	0.7916	0.000416	415.5	-0.0008	-770.0
0.7959	0.000415	414.7	-0.0008	-768.4	0.8016	0.000410	410.1	-0.0008	-761.9
0.8060	0.000409	409.2	-0.0008	-760.3	0.8116	0.000405	404.7	-0.0008	-754.0

0.8160	0.000404	403.9	-0.0008	-752.4	0.8216	0.000400	399.5	-0.0007	-746.3
0.8260	0.000399	398.6	-0.0007	-744.7	0.8316	0.000394	394.4	-0.0007	-738.7
0.8360	0.000393	393.4	-0.0007	-737.1	0.8416	0.000389	389.3	-0.0007	-731.3
0.8461	0.000388	388.4	-0.0007	-729.7	0.8516	0.000384	384.4	-0.0007	-724.0
0.8561	0.000383	383.4	-0.0007	-722.4	0.8616	0.000380	379.5	-0.0007	-716.9
0.8661	0.000379	378.6	-0.0007	-715.3	0.8716	0.000375	374.8	-0.0007	-710.0
0.8761	0.000374	373.8	-0.0007	-708.3	0.8815	0.000370	370.1	-0.0007	-703.1
0.8861	0.000369	369.1	-0.0007	-701.5	0.8915	0.000365	365.5	-0.0007	-696.4
0.8962	0.000364	364.5	-0.0007	-694.8	0.9015	0.000361	361.0	-0.0007	-689.9
0.9062	0.000360	360.0	-0.0007	-688.2	0.9115	0.000357	356.6	-0.0007	-683.4
0.9162	0.000356	355.5	-0.0007	-681.8	0.9215	0.000352	352.2	-0.0007	-677.1
0.9262	0.000351	351.2	-0.0007	-675.4	0.9315	0.000348	347.9	-0.0007	-670.9
0.9363	0.000347	346.9	-0.0007	-669.2	0.9415	0.000344	343.7	-0.0007	-664.8
0.9463	0.000343	342.6	-0.0007	-663.2	0.9515	0.000340	339.6	-0.0007	-658.9
0.9563	0.000339	338.5	-0.0007	-657.2	0.9615	0.000336	335.5	-0.0007	-653.0
0.9663	0.000334	334.4	-0.0007	-651.3	0.9715	0.000332	331.5	-0.0006	-647.3
0.9764	0.000330	330.4	-0.0006	-645.6	0.9814	0.000328	327.6	-0.0006	-641.6
0.9864	0.000326	326.5	-0.0006	-640.0	0.9914	0.000324	323.7	-0.0006	-636.1
0.9964	0.000323	322.6	-0.0006	-634.4	1.0014	0.000320	319.9	-0.0006	-630.7
1.0064	0.000319	318.8	-0.0006	-629.0	1.0114	0.000316	316.2	-0.0006	-625.3
1.0165	0.000315	315.0	-0.0006	-623.6	1.0214	0.000312	312.5	-0.0006	-620.1
1.0265	0.000311	311.3	-0.0006	-618.4	1.0314	0.000309	308.8	-0.0006	-614.9
1.0365	0.000308	307.7	-0.0006	-613.2	1.0414	0.000305	305.2	-0.0006	-609.9
1.0465	0.000304	304.1	-0.0006	-608.2	1.0514	0.000302	301.7	-0.0006	-604.9
1.0566	0.000301	300.6	-0.0006	-603.2	1.0614	0.000298	298.3	-0.0006	-600.0
1.0666	0.000297	297.1	-0.0006	-598.3	1.0714	0.000295	294.8	-0.0006	-595.2
1.0766	0.000294	293.7	-0.0006	-593.5	1.0814	0.000291	291.5	-0.0006	-590.4
1.0866	0.000290	290.3	-0.0006	-588.8	1.0913	0.000288	288.1	-0.0006	-585.8
1.0967	0.000287	287.0	-0.0006	-584.1	1.1013	0.000285	284.9	-0.0006	-581.2
1.1067	0.000284	283.7	-0.0006	-579.5	1.1113	0.000282	281.6	-0.0006	-576.7
1.1167	0.000280	280.5	-0.0006	-575.1	1.1213	0.000278	278.5	-0.0006	-572.3
1.1267	0.000277	277.3	-0.0006	-570.6	1.1313	0.000275	275.3	-0.0006	-567.9
1.1368	0.000274	274.2	-0.0006	-566.3	1.1413	0.000272	272.2	-0.0006	-563.7
1.1468	0.000271	271.1	-0.0006	-562.0	1.1513	0.000269	269.2	-0.0006	-559.5
1.1568	0.000268	268.0	-0.0006	-557.8	1.1613	0.000266	266.2	-0.0006	-555.3
1.1668	0.000265	265.0	-0.0006	-553.7	1.1713	0.000263	263.2	-0.0006	-551.2
1.1768	0.000262	262.1	-0.0005	-549.6	1.1813	0.000260	260.3	-0.0005	-547.2
1.1869	0.000259	259.1	-0.0005	-545.6	1.1913	0.000257	257.4	-0.0005	-543.3
1.1969	0.000256	256.2	-0.0005	-541.6	1.2012	0.000255	254.6	-0.0005	-539.4
1.2069	0.000253	253.4	-0.0005	-537.8	1.2112	0.000252	251.7	-0.0005	-535.6
1.2169	0.000251	250.6	-0.0005	-533.9	1.2212	0.000249	249.0	-0.0005	-531.8
1.2270	0.000248	247.8	-0.0005	-530.2	1.2312	0.000246	246.2	-0.0005	-528.1
1.2370	0.000245	245.1	-0.0005	-526.5	1.2412	0.000244	243.5	-0.0005	-524.4
1.2470	0.000242	242.4	-0.0005	-522.8	1.2512	0.000241	240.9	-0.0005	-520.8
1.2570	0.000240	239.7	-0.0005	-519.2	1.2612	0.000238	238.2	-0.0005	-517.3

1.2671	0.000237	237.1	-0.0005	-515.7	1.2712	0.000236	235.6	-0.0005	-513.8
1.2771	0.000234	234.5	-0.0005	-512.2	1.2812	0.000233	233.0	-0.0005	-510.4
1.2871	0.000232	231.9	-0.0005	-508.8	1.2912	0.000231	230.5	-0.0005	-507.0
1.2971	0.000229	229.3	-0.0005	-505.4	1.3011	0.000228	228.0	-0.0005	-503.6
1.3072	0.000227	226.8	-0.0005	-502.1	1.3111	0.000226	225.5	-0.0005	-500.4
1.3172	0.000224	224.4	-0.0005	-498.8	1.3211	0.000223	223.1	-0.0005	-497.1
1.3272	0.000222	221.9	-0.0005	-495.6	1.3311	0.000221	220.6	-0.0005	-493.9
1.3372	0.000219	219.5	-0.0005	-492.4	1.3411	0.000218	218.3	-0.0005	-490.8
1.3473	0.000217	217.1	-0.0005	-489.3	1.3511	0.000216	215.9	-0.0005	-487.7
1.3573	0.000215	214.7	-0.0005	-486.2	1.3611	0.000214	213.6	-0.0005	-484.6
1.3673	0.000212	212.4	-0.0005	-483.1	1.3711	0.000211	211.2	-0.0005	-481.6
1.3773	0.000210	210.1	-0.0005	-480.1	1.3811	0.000209	209.0	-0.0005	-478.7
1.3873	0.000208	207.8	-0.0005	-477.2	1.3911	0.000207	206.7	-0.0005	-475.7
1.3974	0.000206	205.6	-0.0005	-474.3	1.4011	0.000204	204.5	-0.0005	-472.9
1.4074	0.000203	203.3	-0.0005	-471.4	1.4110	0.000202	202.3	-0.0005	-470.0
1.4174	0.000201	201.1	-0.0005	-468.6	1.4210	0.000200	200.1	-0.0005	-467.2
1.4274	0.000199	198.9	-0.0005	-465.8	1.4310	0.000198	197.9	-0.0005	-464.4
1.4375	0.000197	196.8	-0.0005	-463.0	1.4410	0.000196	195.8	-0.0005	-461.7
1.4475	0.000195	194.6	-0.0005	-460.3	1.4510	0.000194	193.7	-0.0005	-459.0
1.4575	0.000193	192.5	-0.0005	-457.6	1.4610	0.000192	191.6	-0.0005	-456.4
1.4675	0.000190	190.4	-0.0005	-455.0	1.4710	0.000189	189.5	-0.0005	-453.8
1.4776	0.000188	188.4	-0.0005	-452.4	1.4810	0.000187	187.4	-0.0005	-451.2
1.4876	0.000186	186.3	-0.0004	-449.8	1.4910	0.000185	185.4	-0.0004	-448.6
1.4976	0.000184	184.3	-0.0004	-447.2	1.5010	0.000183	183.4	-0.0004	-446.1
1.5076	0.000182	182.3	-0.0004	-444.7	1.5109	0.000181	181.4	-0.0004	-443.6
1.5177	0.000180	180.3	-0.0004	-442.3	1.5209	0.000179	179.4	-0.0004	-441.2
1.5277	0.000178	178.3	-0.0004	-439.8	1.5309	0.000177	177.5	-0.0004	-438.8
1.5377	0.000176	176.3	-0.0004	-437.4	1.5409	0.000176	175.5	-0.0004	-436.4
1.5477	0.000174	174.4	-0.0004	-435.0	1.5509	0.000174	173.6	-0.0004	-434.0
1.5578	0.000172	172.5	-0.0004	-432.7	1.5609	0.000172	171.7	-0.0004	-431.7
1.5678	0.000171	170.6	-0.0004	-430.4	1.5709	0.000170	169.8	-0.0004	-429.4
1.5778	0.000169	168.7	-0.0004	-428.1	1.5809	0.000168	167.9	-0.0004	-427.2
1.5878	0.000167	166.8	-0.0004	-425.8	1.5909	0.000166	166.1	-0.0004	-424.9
1.5979	0.000165	165.0	-0.0004	-423.6	1.6009	0.000164	164.2	-0.0004	-422.7
1.6079	0.000163	163.1	-0.0004	-421.4	1.6109	0.000162	162.4	-0.0004	-420.5
1.6179	0.000161	161.3	-0.0004	-419.2	1.6208	0.000161	160.6	-0.0004	-418.4
1.6279	0.000159	159.5	-0.0004	-417.1	1.6308	0.000159	158.8	-0.0004	-416.3
1.6379	0.000158	157.7	-0.0004	-415.0	1.6408	0.000157	157.0	-0.0004	-414.2
1.6480	0.000156	155.9	-0.0004	-412.9	1.6508	0.000155	155.3	-0.0004	-412.1
1.6580	0.000154	154.2	-0.0004	-410.8	1.6608	0.000154	153.5	-0.0004	-410.0
1.6680	0.000152	152.4	-0.0004	-408.8	1.6708	0.000152	151.8	-0.0004	-408.0
1.6780	0.000151	150.7	-0.0004	-406.7	1.6808	0.000150	150.0	-0.0004	-406.0
1.6881	0.000149	148.9	-0.0004	-404.7	1.6908	0.000148	148.3	-0.0004	-404.0
1.6981	0.000147	147.2	-0.0004	-402.8	1.7008	0.000147	146.6	-0.0004	-402.0
1.7081	0.000145	145.5	-0.0004	-400.8	1.7108	0.000145	144.9	-0.0004	-400.1

1.7181	0.000144	143.8	-0.0004	-398.9	1.7207	0.000143	143.2	-0.0004	-398.2
1.7282	0.000142	142.1	-0.0004	-396.9	1.7307	0.000142	141.5	-0.0004	-396.3
1.7382	0.000140	140.4	-0.0004	-395.1	1.7407	0.000140	139.9	-0.0004	-394.4
1.7482	0.000139	138.7	-0.0004	-393.2	1.7507	0.000138	138.2	-0.0004	-392.5
1.7582	0.000137	137.1	-0.0004	-391.3	1.7607	0.000137	136.5	-0.0004	-390.7
1.7683	0.000135	135.4	-0.0004	-389.5	1.7707	0.000135	134.9	-0.0004	-388.9
1.7783	0.000134	133.8	-0.0004	-387.7	1.7807	0.000133	133.3	-0.0004	-387.1
1.7883	0.000132	132.1	-0.0004	-385.9	1.7907	0.000132	131.6	-0.0004	-385.3
1.7983	0.000131	130.5	-0.0004	-384.1	1.8007	0.000130	130.0	-0.0004	-383.5
1.8084	0.000129	128.9	-0.0004	-382.3	1.8107	0.000128	128.4	-0.0004	-381.8
1.8184	0.000127	127.3	-0.0004	-380.6	1.8207	0.000127	126.8	-0.0004	-380.0
1.8284	0.000126	125.7	-0.0004	-378.8	1.8306	0.000125	125.2	-0.0004	-378.3
1.8384	0.000124	124.0	-0.0004	-377.1	1.8406	0.000124	123.6	-0.0004	-376.6
1.8485	0.000122	122.4	-0.0004	-375.4	1.8506	0.000122	122.0	-0.0004	-374.9
1.8585	0.000121	120.8	-0.0004	-373.7	1.8606	0.000120	120.4	-0.0004	-373.2
1.8685	0.000119	119.2	-0.0004	-372.1	1.8706	0.000119	118.8	-0.0004	-371.6
1.8785	0.000118	117.6	-0.0004	-370.4	1.8806	0.000117	117.2	-0.0004	-369.9
1.8885	0.000116	116.1	-0.0004	-368.8	1.8906	0.000116	115.6	-0.0004	-368.3
1.8986	0.000114	114.5	-0.0004	-367.1	1.9006	0.000114	114.0	-0.0004	-366.7
1.9086	0.000113	112.9	-0.0004	-365.5	1.9106	0.000112	112.5	-0.0004	-365.0
1.9186	0.000111	111.3	-0.0004	-363.9	1.9206	0.000111	110.9	-0.0004	-363.4
1.9286	0.000110	109.7	-0.0004	-362.3	1.9305	0.000109	109.3	-0.0004	-361.8
1.9387	0.000108	108.1	-0.0004	-360.7	1.9405	0.000108	107.7	-0.0004	-360.3
1.9487	0.000107	106.5	-0.0004	-359.1	1.9505	0.000106	106.2	-0.0004	-358.7
1.9587	0.000105	104.9	-0.0004	-357.5	1.9605	0.000105	104.6	-0.0004	-357.1
1.9687	0.000103	103.4	-0.0004	-356.0	1.9705	0.000103	103.0	-0.0004	-355.6
1.9788	0.000102	101.8	-0.0004	-354.4	1.9805	0.000101	101.4	-0.0004	-354.0
1.9888	0.000100	100.2	-0.0004	-352.8	1.9905	0.000100	99.8	-0.0004	-352.5
1.9988	0.000099	98.6	-0.0004	-351.3	2.0005	0.000098	98.2	-0.0004	-350.9
2.0088	0.000097	97.0	-0.0003	-349.8	2.0105	0.000097	96.6	-0.0003	-349.4
2.0189	0.000095	95.4	-0.0003	-348.2	2.0205	0.000095	95.0	-0.0003	-347.9
2.0289	0.000094	93.8	-0.0003	-346.7	2.0305	0.000093	93.4	-0.0003	-346.4
2.0389	0.000092	92.2	-0.0003	-345.2	2.0404	0.000092	91.8	-0.0003	-344.8
2.0489	0.000091	90.5	-0.0003	-343.7	2.0504	0.000090	90.2	-0.0003	-343.3
2.0590	0.000089	88.9	-0.0003	-342.2	2.0604	0.000089	88.6	-0.0003	-341.8
2.0690	0.000087	87.3	-0.0003	-340.6	2.0704	0.000087	87.0	-0.0003	-340.3
2.0790	0.000086	85.6	-0.0003	-339.1	2.0804	0.000085	85.3	-0.0003	-338.8
2.0890	0.000084	84.0	-0.0003	-337.6	2.0904	0.000084	83.7	-0.0003	-337.3
2.0990	0.000082	82.3	-0.0003	-336.1	2.1004	0.000082	82.1	-0.0003	-335.8
2.1091	0.000081	80.7	-0.0003	-334.6	2.1104	0.000080	80.4	-0.0003	-334.3
2.1191	0.000079	79.0	-0.0003	-333.1	2.1204	0.000079	78.7	-0.0003	-332.8
2.1291	0.000077	77.3	-0.0003	-331.6	2.1304	0.000077	77.0	-0.0003	-331.3
2.1391	0.000076	75.6	-0.0003	-330.1	2.1403	0.000075	75.3	-0.0003	-329.8
2.1492	0.000074	73.9	-0.0003	-328.6	2.1503	0.000074	73.6	-0.0003	-328.3
2.1592	0.000072	72.2	-0.0003	-327.1	2.1603	0.000072	71.9	-0.0003	-326.8

2.1692	0.000070	70.4	-0.0003	-325.6	2.1703	0.000070	70.2	-0.0003	-325.3
2.1792	0.000069	68.7	-0.0003	-324.0	2.1803	0.000068	68.4	-0.0003	-323.8
2.1893	0.000067	66.9	-0.0003	-322.5	2.1903	0.000067	66.7	-0.0003	-322.3
2.1993	0.000065	65.1	-0.0003	-321.0	2.2003	0.000065	64.9	-0.0003	-320.7
2.2093	0.000063	63.3	-0.0003	-319.5	2.2103	0.000063	63.1	-0.0003	-319.2
2.2193	0.000062	61.5	-0.0003	-317.9	2.2203	0.000061	61.3	-0.0003	-317.7
2.2294	0.000060	59.7	-0.0003	-316.4	2.2303	0.000059	59.5	-0.0003	-316.1
2.2394	0.000058	57.8	-0.0003	-314.8	2.2403	0.000058	57.6	-0.0003	-314.6
2.2494	0.000056	56.0	-0.0003	-313.2	2.2502	0.000056	55.8	-0.0003	-313.0
2.2594	0.000054	54.1	-0.0003	-311.7	2.2602	0.000054	53.9	-0.0003	-311.5
2.2695	0.000052	52.2	-0.0003	-310.1	2.2702	0.000052	52.0	-0.0003	-309.9
2.2795	0.000050	50.2	-0.0003	-308.5	2.2802	0.000050	50.0	-0.0003	-308.3
2.2895	0.000048	48.3	-0.0003	-306.9	2.2902	0.000048	48.1	-0.0003	-306.7
2.2995	0.000046	46.3	-0.0003	-305.3	2.3002	0.000046	46.1	-0.0003	-305.1
2.3095	0.000044	44.3	-0.0003	-303.6	2.3102	0.000044	44.1	-0.0003	-303.4
2.3196	0.000042	42.2	-0.0003	-302.0	2.3202	0.000042	42.1	-0.0003	-301.8
2.3296	0.000040	40.2	-0.0003	-300.3	2.3302	0.000040	40.0	-0.0003	-300.1
2.3396	0.000038	38.1	-0.0003	-298.6	2.3402	0.000038	37.9	-0.0003	-298.5
2.3496	0.000036	36.0	-0.0003	-296.9	2.3501	0.000036	35.8	-0.0003	-296.8
2.3597	0.000034	33.8	-0.0003	-295.2	2.3601	0.000034	33.7	-0.0003	-295.1
2.3697	0.000032	31.6	-0.0003	-293.5	2.3701	0.000032	31.5	-0.0003	-293.4
2.3797	0.000029	29.4	-0.0003	-291.7	2.3801	0.000029	29.3	-0.0003	-291.6
2.3897	0.000027	27.2	-0.0003	-290.0	2.3901	0.000027	27.1	-0.0003	-289.8
2.3998	0.000025	24.9	-0.0003	-288.2	2.4001	0.000025	24.8	-0.0003	-288.1
2.4098	0.000023	22.6	-0.0003	-286.4	2.4101	0.000023	22.5	-0.0003	-286.2
2.4198	0.000020	20.2	-0.0003	-284.5	2.4201	0.000020	20.2	-0.0003	-284.4
2.4298	0.000018	17.9	-0.0003	-282.7	2.4301	0.000018	17.8	-0.0003	-282.6
2.4399	0.000015	15.4	-0.0003	-280.8	2.4401	0.000015	15.4	-0.0003	-280.7
2.4499	0.000013	13.0	-0.0003	-278.8	2.4501	0.000013	12.9	-0.0003	-278.8
2.4599	0.000010	10.5	-0.0003	-276.9	2.4600	0.000010	10.4	-0.0003	-276.8
2.4699	0.000008	7.9	-0.0003	-274.9	2.4700	0.000008	7.9	-0.0003	-274.9
2.4800	0.000005	5.3	-0.0003	-272.9	2.4800	0.000005	5.3	-0.0003	-272.9
2.4900	0.000003	2.7	-0.0003	-270.9	2.4900	0.000003	2.7	-0.0003	-270.8
2.5000	0.000000	0.0	-0.0003	-268.8	2.5000	0.000000	0.0	-0.0003	-268.8

ALL EARTH					CAPITAL DEMOLITION				
Pavement depth,m	E11	µm	E22	µm	Pavement depth,m	E11	µm	E22	µm
0.0000	-0.000778	-778.1	0.0001	147.4	0.0000	-0.000731	-730.6	0.0001	127.2
0.0100	-0.000567	-567.0	0.0001	58.9	0.0100	-0.000551	-551.2	0.0001	51.9
0.0200	-0.000366	-366.0	0.0000	-21.8	0.0200	-0.000381	-380.6	0.0000	-16.7
0.0300	-0.000172	-172.2	-0.0001	-97.3	0.0300	-0.000217	-217.0	-0.0001	-80.1
0.0400	0.000018	17.8	-0.0002	-170.1	0.0400	-0.000058	-58.1	-0.0001	-140.0
0.0500	**0.000207**	**207.3**	**-0.0002**	**-243.0**	**0.0500**	**0.000098**	**98.0**	**-0.0002**	**-198.3**
0.0500	**0.000208**	**208.3**	**-0.0008**	**-775.4**	**0.0500**	**0.000099**	**98.6**	**-0.0005**	**-530.0**
0.0602	0.000275	275.2	-0.0008	-776.4	0.0602	0.000167	167.1	-0.0005	-539.4
0.0704	0.000333	332.7	-0.0008	-771.8	0.0704	0.000228	228.3	-0.0005	-544.3
0.0806	0.000384	384.0	-0.0008	-764.3	0.0806	0.000285	284.8	-0.0005	-546.9
0.0908	0.000432	431.7	-0.0008	-755.8	0.0908	0.000339	339.0	-0.0005	-548.9
0.1010	0.000478	478.3	-0.0007	-748.2	0.1010	0.000393	393.2	-0.0006	-552.1
0.1112	0.000526	525.9	-0.0007	-743.1	0.1112	0.000449	449.2	-0.0006	-558.0
0.1214	0.000577	576.6	-0.0007	-742.1	0.1214	0.000509	509.2	-0.0006	-568.2
0.1316	0.000632	632.4	-0.0007	-746.5	0.1316	0.000575	575.1	-0.0006	-584.1
0.1418	0.000695	695.3	-0.0008	-758.0	0.1418	0.000649	649.1	-0.0006	-607.4
0.1520	**0.000768**	**767.8**	**-0.0008**	**-778.3**	**0.1520**	**0.000734**	**733.7**	**-0.0006**	**-639.9**
0.1520	**0.000769**	**768.5**	**-0.0013**	**-1268.2**	**0.1520**	**0.000735**	**734.5**	**-0.0012**	**-1204.5**
0.1620	0.000751	750.8	-0.0012	-1221.7	0.1620	0.000717	717.4	-0.0012	-1161.1
0.1720	0.000734	734.5	-0.0012	-1178.1	0.1720	0.000702	701.9	-0.0011	-1120.6
0.1820	0.000720	719.6	-0.0011	-1137.5	0.1820	0.000688	687.8	-0.0011	-1082.9
0.1920	0.000706	706.1	-0.0011	-1099.5	0.1920	0.000675	675.3	-0.0010	-1047.8
0.2020	0.000694	694.1	-0.0011	-1064.2	0.2020	0.000664	664.2	-0.0010	-1015.2
0.2120	0.000684	683.6	-0.0010	-1031.2	0.2120	0.000655	654.6	-0.0010	-984.9
0.2220	0.000674	674.5	-0.0010	-1000.6	0.2220	0.000646	646.4	-0.0010	-956.7
0.2320	0.000667	666.8	-0.0010	-972.3	0.2320	0.000640	639.7	-0.0009	-930.7
0.2420	0.000661	660.6	-0.0009	-946.0	0.2420	0.000634	634.3	-0.0009	-906.6
0.2520	0.000656	655.9	-0.0009	-921.7	0.2520	0.000630	630.3	-0.0009	-884.5
0.2620	0.000653	652.5	-0.0009	-899.5	0.2620	0.000628	627.7	-0.0009	-864.1
0.2720	0.000651	650.7	-0.0009	-879.1	0.2720	0.000627	626.6	-0.0008	-845.5
0.2820	0.000650	650.4	-0.0009	-860.5	0.2820	0.000627	626.8	-0.0008	-828.7
0.2920	0.000652	651.5	-0.0008	-843.8	0.2920	0.000628	628.5	-0.0008	-813.5
0.3020	0.000654	654.3	-0.0008	-828.9	0.3020	0.000632	631.6	-0.0008	-800.0
0.3120	0.000659	658.7	-0.0008	-815.8	0.3120	0.000636	636.3	-0.0008	-788.2
0.3220	0.000665	664.8	-0.0008	-804.6	0.3220	0.000643	642.5	-0.0008	-778.1
0.3320	0.000673	672.7	-0.0008	-795.1	0.3320	0.000650	650.5	-0.0008	-769.6
0.3420	0.000682	682.5	-0.0008	-787.6	0.3420	0.000660	660.2	-0.0008	-763.0
0.3520	0.000694	694.3	-0.0008	-782.0	0.3520	0.000672	671.7	-0.0008	-758.1
0.3620	0.000708	708.2	-0.0008	-778.5	0.3620	0.000685	685.2	-0.0008	-755.1
0.3720	0.000724	724.4	-0.0008	-777.1	0.3720	0.000701	700.8	-0.0008	-754.1

0.3820	0.000743	743.1	-0.0008	-778.0	0.3820	0.000719	718.7	-0.0008	-755.2
0.3920	0.000764	764.5	-0.0008	-781.3	0.3920	0.000739	739.1	-0.0008	-758.4
0.4020	**0.000789**	**788.8**	**-0.0008**	**-787.2**	**0.4020**	**0.000762**	**762.1**	**-0.0008**	**-764.1**
0.4020	**0.000789**	**789.0**	**-0.0013**	**-1331.2**	**0.4020**	**0.000762**	**762.3**	**-0.0013**	**-1295.0**
0.4120	0.000772	771.9	-0.0013	-1305.7	0.4120	0.000746	746.4	-0.0013	-1271.1
0.4220	0.000756	755.6	-0.0013	-1281.3	0.4220	0.000731	731.1	-0.0012	-1248.1
0.4320	0.000740	739.9	-0.0013	-1257.8	0.4320	0.000717	716.5	-0.0012	-1226.1
0.4420	0.000725	724.9	-0.0012	-1235.2	0.4420	0.000702	702.5	-0.0012	-1204.8
0.4520	0.000710	710.4	-0.0012	-1213.5	0.4520	0.000689	688.9	-0.0012	-1184.4
0.4619	0.000697	696.5	-0.0012	-1192.6	0.4619	0.000676	675.9	-0.0012	-1164.7
0.4719	0.000683	683.2	-0.0012	-1172.5	0.4719	0.000663	663.3	-0.0011	-1145.7
0.4819	0.000670	670.3	-0.0012	-1153.0	0.4819	0.000651	651.2	-0.0011	-1127.3
0.4919	0.000658	657.8	-0.0011	-1134.3	0.4919	0.000640	639.5	-0.0011	-1109.6
0.5019	0.000646	645.8	-0.0011	-1116.2	0.5019	0.000628	628.2	-0.0011	-1092.5
0.5119	0.000634	634.2	-0.0011	-1098.7	0.5119	0.000617	617.3	-0.0011	-1075.9
0.5219	0.000623	623.0	-0.0011	-1081.8	0.5219	0.000607	606.7	-0.0011	-1059.8
0.5319	0.000612	612.2	-0.0011	-1065.4	0.5319	0.000596	596.5	-0.0010	-1044.3
0.5419	0.000602	601.7	-0.0010	-1049.5	0.5419	0.000587	586.6	-0.0010	-1029.2
0.5519	0.000591	591.5	-0.0010	-1034.2	0.5519	0.000577	576.9	-0.0010	-1014.6
0.5618	0.000582	581.6	-0.0010	-1019.3	0.5618	0.000568	567.6	-0.0010	-1000.4
0.5718	0.000572	572.1	-0.0010	-1004.8	0.5718	0.000559	558.5	-0.0010	-986.6
0.5818	0.000563	562.8	-0.0010	-990.8	0.5818	0.000550	549.7	-0.0010	-973.3
0.5918	0.000554	553.7	-0.0010	-977.2	0.5918	0.000541	541.1	-0.0010	-960.3
0.6018	0.000545	545.0	-0.0010	-964.0	0.6018	0.000533	532.8	-0.0009	-947.6
0.6118	0.000536	536.5	-0.0010	-951.1	0.6118	0.000525	524.7	-0.0009	-935.3
0.6218	0.000528	528.2	-0.0009	-938.7	0.6218	0.000517	516.8	-0.0009	-923.4
0.6318	0.000520	520.1	-0.0009	-926.5	0.6318	0.000509	509.1	-0.0009	-911.7
0.6418	0.000512	512.3	-0.0009	-914.7	0.6418	0.000502	501.6	-0.0009	-900.4
0.6518	0.000505	504.6	-0.0009	-903.2	0.6518	0.000494	494.3	-0.0009	-889.3
0.6618	0.000497	497.1	-0.0009	-891.9	0.6618	0.000487	487.2	-0.0009	-878.6
0.6717	0.000490	489.9	-0.0009	-881.0	0.6717	0.000480	480.2	-0.0009	-868.1
0.6817	0.000483	482.8	-0.0009	-870.4	0.6817	0.000473	473.4	-0.0009	-857.8
0.6917	0.000476	475.9	-0.0009	-860.0	0.6917	0.000467	466.8	-0.0008	-847.8
0.7017	0.000469	469.1	-0.0008	-849.9	0.7017	0.000460	460.3	-0.0008	-838.1
0.7117	0.000462	462.5	-0.0008	-840.0	0.7117	0.000454	454.0	-0.0008	-828.6
0.7217	0.000456	456.0	-0.0008	-830.3	0.7217	0.000448	447.8	-0.0008	-819.3
0.7317	0.000450	449.7	-0.0008	-820.9	0.7317	0.000442	441.7	-0.0008	-810.2
0.7417	0.000444	443.6	-0.0008	-811.7	0.7417	0.000436	435.8	-0.0008	-801.3
0.7517	0.000438	437.5	-0.0008	-802.7	0.7517	0.000430	430.0	-0.0008	-792.6
0.7617	0.000432	431.6	-0.0008	-793.9	0.7617	0.000424	424.3	-0.0008	-784.1
0.7716	0.000426	425.8	-0.0008	-785.3	0.7716	0.000419	418.7	-0.0008	-775.8
0.7816	0.000420	420.2	-0.0008	-776.9	0.7816	0.000413	413.2	-0.0008	-767.7
0.7916	0.000415	414.6	-0.0008	-768.7	0.7916	0.000408	407.9	-0.0008	-759.7
0.8016	0.000409	409.2	-0.0008	-760.7	0.8016	0.000403	402.6	-0.0008	-751.9
0.8116	0.000404	403.9	-0.0008	-752.8	0.8116	0.000397	397.5	-0.0007	-744.3

0.8216	0.000399	398.7	-0.0007	-745.1	0.8216	0.000392	392.5	-0.0007	-736.8
0.8316	0.000394	393.5	-0.0007	-737.6	0.8316	0.000387	387.5	-0.0007	-729.5
0.8416	0.000389	388.5	-0.0007	-730.2	0.8416	0.000383	382.6	-0.0007	-722.4
0.8516	0.000384	383.6	-0.0007	-723.0	0.8516	0.000378	377.9	-0.0007	-715.3
0.8616	0.000379	378.8	-0.0007	-715.9	0.8616	0.000373	373.2	-0.0007	-708.4
0.8716	0.000374	374.0	-0.0007	-708.9	0.8716	0.000369	368.6	-0.0007	-701.7
0.8815	0.000369	369.4	-0.0007	-702.1	0.8815	0.000364	364.1	-0.0007	-695.1
0.8915	0.000365	364.8	-0.0007	-695.5	0.8915	0.000360	359.6	-0.0007	-688.6
0.9015	0.000360	360.3	-0.0007	-688.9	0.9015	0.000355	355.3	-0.0007	-682.2
0.9115	0.000356	355.9	-0.0007	-682.5	0.9115	0.000351	351.0	-0.0007	-676.0
0.9215	0.000352	351.5	-0.0007	-676.2	0.9215	0.000347	346.8	-0.0007	-669.9
0.9315	0.000347	347.3	-0.0007	-670.1	0.9315	0.000343	342.6	-0.0007	-663.8
0.9415	0.000343	343.1	-0.0007	-664.0	0.9415	0.000339	338.5	-0.0007	-657.9
0.9515	0.000339	339.0	-0.0007	-658.1	0.9515	0.000335	334.5	-0.0007	-652.1
0.9615	0.000335	334.9	-0.0007	-652.2	0.9615	0.000331	330.6	-0.0006	-646.4
0.9715	0.000331	330.9	-0.0006	-646.5	0.9715	0.000327	326.7	-0.0006	-640.9
0.9814	0.000327	327.0	-0.0006	-640.9	0.9814	0.000323	322.9	-0.0006	-635.4
0.9914	0.000323	323.1	-0.0006	-635.3	0.9914	0.000319	319.1	-0.0006	-630.0
1.0014	0.000319	319.4	-0.0006	-629.9	1.0014	0.000315	315.4	-0.0006	-624.7
1.0114	0.000316	315.6	-0.0006	-624.6	1.0114	0.000312	311.7	-0.0006	-619.5
1.0214	0.000312	311.9	-0.0006	-619.4	1.0214	0.000308	308.1	-0.0006	-614.4
1.0314	0.000308	308.3	-0.0006	-614.2	1.0314	0.000305	304.6	-0.0006	-609.3
1.0414	0.000305	304.7	-0.0006	-609.2	1.0414	0.000301	301.1	-0.0006	-604.4
1.0514	0.000301	301.2	-0.0006	-604.2	1.0514	0.000298	297.7	-0.0006	-599.5
1.0614	0.000298	297.8	-0.0006	-599.3	1.0614	0.000294	294.3	-0.0006	-594.7
1.0714	0.000294	294.4	-0.0006	-594.5	1.0714	0.000291	291.0	-0.0006	-590.0
1.0814	0.000291	291.0	-0.0006	-589.8	1.0814	0.000288	287.7	-0.0006	-585.4
1.0913	0.000288	287.7	-0.0006	-585.2	1.0913	0.000284	284.4	-0.0006	-580.9
1.1013	0.000284	284.4	-0.0006	-580.6	1.1013	0.000281	281.2	-0.0006	-576.4
1.1113	0.000281	281.2	-0.0006	-576.1	1.1113	0.000278	278.1	-0.0006	-572.0
1.1213	0.000278	278.0	-0.0006	-571.7	1.1213	0.000275	275.0	-0.0006	-567.7
1.1313	0.000275	274.9	-0.0006	-567.4	1.1313	0.000272	271.9	-0.0006	-563.4
1.1413	0.000272	271.8	-0.0006	-563.1	1.1413	0.000269	268.9	-0.0006	-559.2
1.1513	0.000269	268.8	-0.0006	-558.9	1.1513	0.000266	265.9	-0.0006	-555.1
1.1613	0.000266	265.8	-0.0006	-554.8	1.1613	0.000263	263.0	-0.0006	-551.1
1.1713	0.000263	262.8	-0.0006	-550.7	1.1713	0.000260	260.1	-0.0005	-547.1
1.1813	0.000260	259.9	-0.0005	-546.7	1.1813	0.000257	257.2	-0.0005	-543.1
1.1913	0.000257	257.0	-0.0005	-542.8	1.1913	0.000254	254.4	-0.0005	-539.3
1.2012	0.000254	254.2	-0.0005	-538.9	1.2012	0.000252	251.6	-0.0005	-535.5
1.2112	0.000251	251.4	-0.0005	-535.1	1.2112	0.000249	248.8	-0.0005	-531.7
1.2212	0.000249	248.6	-0.0005	-531.3	1.2212	0.000246	246.1	-0.0005	-528.0
1.2312	0.000246	245.9	-0.0005	-527.6	1.2312	0.000243	243.4	-0.0005	-524.4
1.2412	0.000243	243.2	-0.0005	-524.0	1.2412	0.000241	240.8	-0.0005	-520.8
1.2512	0.000241	240.5	-0.0005	-520.4	1.2512	0.000238	238.1	-0.0005	-517.3
1.2612	0.000238	237.9	-0.0005	-516.9	1.2612	0.000236	235.5	-0.0005	-513.8

1.2712	0.000235	235.3	-0.0005	-513.4	1.2712	0.000233	233.0	-0.0005	-510.4
1.2812	0.000233	232.7	-0.0005	-509.9	1.2812	0.000230	230.5	-0.0005	-507.0
1.2912	0.000230	230.2	-0.0005	-506.6	1.2912	0.000228	228.0	-0.0005	-503.7
1.3011	0.000228	227.7	-0.0005	-503.2	1.3011	0.000226	225.5	-0.0005	-500.4
1.3111	0.000225	225.2	-0.0005	-500.0	1.3111	0.000223	223.1	-0.0005	-497.2
1.3211	0.000223	222.8	-0.0005	-496.7	1.3211	0.000221	220.7	-0.0005	-494.0
1.3311	0.000220	220.4	-0.0005	-493.5	1.3311	0.000218	218.3	-0.0005	-490.8
1.3411	0.000218	218.0	-0.0005	-490.4	1.3411	0.000216	215.9	-0.0005	-487.8
1.3511	0.000216	215.6	-0.0005	-487.3	1.3511	0.000214	213.6	-0.0005	-484.7
1.3611	0.000213	213.3	-0.0005	-484.3	1.3611	0.000211	211.3	-0.0005	-481.7
1.3711	0.000211	211.0	-0.0005	-481.3	1.3711	0.000209	209.0	-0.0005	-478.7
1.3811	0.000209	208.7	-0.0005	-478.3	1.3811	0.000207	206.8	-0.0005	-475.8
1.3911	0.000206	206.4	-0.0005	-475.4	1.3911	0.000205	204.6	-0.0005	-472.9
1.4011	0.000204	204.2	-0.0005	-472.5	1.4011	0.000202	202.4	-0.0005	-470.1
1.4110	0.000202	202.0	-0.0005	-469.7	1.4110	0.000200	200.2	-0.0005	-467.3
1.4210	0.000200	199.8	-0.0005	-466.9	1.4210	0.000198	198.0	-0.0005	-464.6
1.4310	0.000198	197.7	-0.0005	-464.1	1.4310	0.000196	195.9	-0.0005	-461.8
1.4410	0.000196	195.5	-0.0005	-461.4	1.4410	0.000194	193.8	-0.0005	-459.1
1.4510	0.000193	193.4	-0.0005	-458.7	1.4510	0.000192	191.7	-0.0005	-456.5
1.4610	0.000191	191.3	-0.0005	-456.1	1.4610	0.000190	189.6	-0.0005	-453.9
1.4710	0.000189	189.2	-0.0005	-453.5	1.4710	0.000188	187.6	-0.0005	-451.3
1.4810	0.000187	187.2	-0.0005	-450.9	1.4810	0.000186	185.6	-0.0004	-448.8
1.4910	0.000185	185.2	-0.0004	-448.3	1.4910	0.000184	183.6	-0.0004	-446.3
1.5010	0.000183	183.2	-0.0004	-445.8	1.5010	0.000182	181.6	-0.0004	-443.8
1.5109	0.000181	181.2	-0.0004	-443.4	1.5109	0.000180	179.6	-0.0004	-441.3
1.5209	0.000179	179.2	-0.0004	-440.9	1.5209	0.000178	177.7	-0.0004	-438.9
1.5309	0.000177	177.2	-0.0004	-438.5	1.5309	0.000176	175.7	-0.0004	-436.5
1.5409	0.000175	175.3	-0.0004	-436.1	1.5409	0.000174	173.8	-0.0004	-434.2
1.5509	0.000173	173.4	-0.0004	-433.8	1.5509	0.000172	171.9	-0.0004	-431.9
1.5609	0.000171	171.5	-0.0004	-431.5	1.5609	0.000170	170.1	-0.0004	-429.6
1.5709	0.000170	169.6	-0.0004	-429.2	1.5709	0.000168	168.2	-0.0004	-427.3
1.5809	0.000168	167.7	-0.0004	-426.9	1.5809	0.000166	166.3	-0.0004	-425.1
1.5909	0.000166	165.9	-0.0004	-424.7	1.5909	0.000165	164.5	-0.0004	-422.9
1.6009	0.000164	164.0	-0.0004	-422.5	1.6009	0.000163	162.7	-0.0004	-420.7
1.6109	0.000162	162.2	-0.0004	-420.3	1.6109	0.000161	160.9	-0.0004	-418.5
1.6208	0.000160	160.4	-0.0004	-418.1	1.6208	0.000159	159.1	-0.0004	-416.4
1.6308	0.000159	158.6	-0.0004	-416.0	1.6308	0.000157	157.3	-0.0004	-414.3
1.6408	0.000157	156.8	-0.0004	-413.9	1.6408	0.000156	155.6	-0.0004	-412.2
1.6508	0.000155	155.1	-0.0004	-411.8	1.6508	0.000154	153.8	-0.0004	-410.2
1.6608	0.000153	153.3	-0.0004	-409.8	1.6608	0.000152	152.1	-0.0004	-408.2
1.6708	0.000152	151.6	-0.0004	-407.8	1.6708	0.000150	150.4	-0.0004	-406.2
1.6808	0.000150	149.9	-0.0004	-405.8	1.6808	0.000149	148.6	-0.0004	-404.2
1.6908	0.000148	148.1	-0.0004	-403.8	1.6908	0.000147	146.9	-0.0004	-402.2
1.7008	0.000146	146.4	-0.0004	-401.8	1.7008	0.000145	145.3	-0.0004	-400.3

1.7108	0.000145	144.7	-0.0004	-399.9	1.7108	0.000144	143.6	-0.0004	-398.4
1.7207	0.000143	143.0	-0.0004	-398.0	1.7207	0.000142	141.9	-0.0004	-396.5
1.7307	0.000141	141.4	-0.0004	-396.1	1.7307	0.000140	140.2	-0.0004	-394.6
1.7407	0.000140	139.7	-0.0004	-394.2	1.7407	0.000139	138.6	-0.0004	-392.7
1.7507	0.000138	138.0	-0.0004	-392.3	1.7507	0.000137	137.0	-0.0004	-390.9
1.7607	0.000136	136.4	-0.0004	-390.5	1.7607	0.000135	135.3	-0.0004	-389.1
1.7707	0.000135	134.8	-0.0004	-388.7	1.7707	0.000134	133.7	-0.0004	-387.3
1.7807	0.000133	133.1	-0.0004	-386.9	1.7807	0.000132	132.1	-0.0004	-385.5
1.7907	0.000131	131.5	-0.0004	-385.1	1.7907	0.000130	130.5	-0.0004	-383.7
1.8007	0.000130	129.9	-0.0004	-383.3	1.8007	0.000129	128.9	-0.0004	-382.0
1.8107	0.000128	128.3	-0.0004	-381.6	1.8107	0.000127	127.3	-0.0004	-380.2
1.8207	0.000127	126.6	-0.0004	-379.8	1.8207	0.000126	125.7	-0.0004	-378.5
1.8306	0.000125	125.0	-0.0004	-378.1	1.8306	0.000124	124.1	-0.0004	-376.8
1.8406	0.000123	123.4	-0.0004	-376.4	1.8406	0.000122	122.5	-0.0004	-375.1
1.8506	0.000122	121.8	-0.0004	-374.7	1.8506	0.000121	120.9	-0.0004	-373.5
1.8606	0.000120	120.3	-0.0004	-373.1	1.8606	0.000119	119.3	-0.0004	-371.8
1.8706	0.000119	118.7	-0.0004	-371.4	1.8706	0.000118	117.8	-0.0004	-370.2
1.8806	0.000117	117.1	-0.0004	-369.7	1.8806	0.000116	116.2	-0.0004	-368.5
1.8906	0.000116	115.5	-0.0004	-368.1	1.8906	0.000115	114.6	-0.0004	-366.9
1.9006	0.000114	113.9	-0.0004	-366.5	1.9006	0.000113	113.0	-0.0004	-365.3
1.9106	0.000112	112.3	-0.0004	-364.9	1.9106	0.000111	111.5	-0.0004	-363.7
1.9206	0.000111	110.8	-0.0004	-363.3	1.9206	0.000110	109.9	-0.0004	-362.1
1.9305	0.000109	109.2	-0.0004	-361.7	1.9305	0.000108	108.4	-0.0004	-360.5
1.9405	0.000108	107.6	-0.0004	-360.1	1.9405	0.000107	106.8	-0.0004	-359.0
1.9505	0.000106	106.0	-0.0004	-358.5	1.9505	0.000105	105.2	-0.0004	-357.4
1.9605	0.000104	104.5	-0.0004	-357.0	1.9605	0.000104	103.7	-0.0004	-355.8
1.9705	0.000103	102.9	-0.0004	-355.4	1.9705	0.000102	102.1	-0.0004	-354.3
1.9805	0.000101	101.3	-0.0004	-353.9	1.9805	0.000101	100.5	-0.0004	-352.8
1.9905	0.000100	99.7	-0.0004	-352.3	1.9905	0.000099	99.0	-0.0004	-351.2
2.0005	0.000098	98.1	-0.0004	-350.8	2.0005	0.000097	97.4	-0.0003	-349.7
2.0105	0.000097	96.5	-0.0003	-349.2	2.0105	0.000096	95.8	-0.0003	-348.2
2.0205	0.000095	94.9	-0.0003	-347.7	2.0205	0.000094	94.2	-0.0003	-346.7
2.0305	0.000093	93.3	-0.0003	-346.2	2.0305	0.000093	92.6	-0.0003	-345.2
2.0404	0.000092	91.7	-0.0003	-344.7	2.0404	0.000091	91.0	-0.0003	-343.7
2.0504	0.000090	90.1	-0.0003	-343.2	2.0504	0.000089	89.4	-0.0003	-342.2
2.0604	0.000089	88.5	-0.0003	-341.7	2.0604	0.000088	87.8	-0.0003	-340.7
2.0704	0.000087	86.9	-0.0003	-340.2	2.0704	0.000086	86.2	-0.0003	-339.2
2.0804	0.000085	85.3	-0.0003	-338.7	2.0804	0.000085	84.6	-0.0003	-337.7
2.0904	0.000084	83.6	-0.0003	-337.2	2.0904	0.000083	83.0	-0.0003	-336.2
2.1004	0.000082	82.0	-0.0003	-335.7	2.1004	0.000081	81.3	-0.0003	-334.7
2.1104	0.000080	80.3	-0.0003	-334.2	2.1104	0.000080	79.7	-0.0003	-333.3
2.1204	0.000079	78.6	-0.0003	-332.7	2.1204	0.000078	78.0	-0.0003	-331.8
2.1304	0.000077	77.0	-0.0003	-331.2	2.1304	0.000076	76.4	-0.0003	-330.3
2.1403	0.000075	75.3	-0.0003	-329.7	2.1403	0.000075	74.7	-0.0003	-328.8
2.1503	0.000074	73.6	-0.0003	-328.2	2.1503	0.000073	73.0	-0.0003	-327.3

2.1603	0.000072	71.8	-0.0003	-326.7	2.1603	0.000071	71.3	-0.0003	-325.8
2.1703	0.000070	70.1	-0.0003	-325.2	2.1703	0.000070	69.6	-0.0003	-324.3
2.1803	0.000068	68.4	-0.0003	-323.7	2.1803	0.000068	67.8	-0.0003	-322.8
2.1903	0.000067	66.6	-0.0003	-322.2	2.1903	0.000066	66.1	-0.0003	-321.3
2.2003	0.000065	64.8	-0.0003	-320.6	2.2003	0.000064	64.3	-0.0003	-319.8
2.2103	0.000063	63.0	-0.0003	-319.1	2.2103	0.000063	62.6	-0.0003	-318.3
2.2203	0.000061	61.2	-0.0003	-317.6	2.2203	0.000061	60.8	-0.0003	-316.8
2.2303	0.000059	59.4	-0.0003	-316.0	2.2303	0.000059	59.0	-0.0003	-315.2
2.2403	0.000058	57.6	-0.0003	-314.5	2.2403	0.000057	57.1	-0.0003	-313.7
2.2502	0.000056	55.7	-0.0003	-312.9	2.2502	0.000055	55.3	-0.0003	-312.2
2.2602	0.000054	53.8	-0.0003	-311.4	2.2602	0.000053	53.4	-0.0003	-310.6
2.2702	0.000052	51.9	-0.0003	-309.8	2.2702	0.000052	51.5	-0.0003	-309.0
2.2802	0.000050	50.0	-0.0003	-308.2	2.2802	0.000050	49.6	-0.0003	-307.5
2.2902	0.000048	48.0	-0.0003	-306.6	2.2902	0.000048	47.7	-0.0003	-305.9
2.3002	0.000046	46.0	-0.0003	-305.0	2.3002	0.000046	45.7	-0.0003	-304.3
2.3102	0.000044	44.0	-0.0003	-303.3	2.3102	0.000044	43.7	-0.0003	-302.7
2.3202	0.000042	42.0	-0.0003	-301.7	2.3202	0.000042	41.7	-0.0003	-301.0
2.3302	0.000040	40.0	-0.0003	-300.1	2.3302	0.000040	39.7	-0.0003	-299.4
2.3402	0.000038	37.9	-0.0003	-298.4	2.3402	0.000038	37.6	-0.0003	-297.7
2.3501	0.000036	35.8	-0.0003	-296.7	2.3501	0.000036	35.5	-0.0003	-296.1
2.3601	0.000034	33.6	-0.0003	-295.0	2.3601	0.000033	33.4	-0.0003	-294.4
2.3701	0.000031	31.5	-0.0003	-293.3	2.3701	0.000031	31.2	-0.0003	-292.7
2.3801	0.000029	29.3	-0.0003	-291.5	2.3801	0.000029	29.0	-0.0003	-290.9
2.3901	0.000027	27.0	-0.0003	-289.8	2.3901	0.000027	26.8	-0.0003	-289.2
2.4001	0.000025	24.8	-0.0003	-288.0	2.4001	0.000025	24.6	-0.0003	-287.4
2.4101	0.000022	22.5	-0.0003	-286.2	2.4101	0.000022	22.3	-0.0003	-285.6
2.4201	0.000020	20.1	-0.0003	-284.3	2.4201	0.000020	20.0	-0.0003	-283.8
2.4301	0.000018	17.8	-0.0003	-282.5	2.4301	0.000018	17.6	-0.0003	-282.0
2.4401	0.000015	15.4	-0.0003	-280.6	2.4401	0.000015	15.2	-0.0003	-280.1
2.4501	0.000013	12.9	-0.0003	-278.7	2.4501	0.000013	12.8	-0.0003	-278.2
2.4600	0.000010	10.4	-0.0003	-276.8	2.4600	0.000010	10.3	-0.0003	-276.3
2.4700	0.000008	7.9	-0.0003	-274.8	2.4700	0.000008	7.8	-0.0003	-274.3
2.4800	0.000005	5.3	-0.0003	-272.8	2.4800	0.000005	5.3	-0.0003	-272.4
2.4900	0.000003	2.7	-0.0003	-270.8	2.4900	0.000003	2.7	-0.0003	-270.4
2.5000	0.000000	0.0	-0.0003	-268.7	2.5000	0.000000	0.0	-0.0003	-268.3

CRUSHED ROCK BASE									
depth	E11	µm	E22	µm	depth	E11	µm	E22	µm
0.0000	-0.000791	-790.8	0.0002	152.8	1.2426	0.000229	229.3	-0.0005	-504.6
0.0100	-0.000548	-547.9	0.0001	51.2	1.2526	0.000227	226.8	-0.0005	-501.2
0.0200	-0.000317	-316.9	0.0000	-41.3	1.2625	0.000224	224.2	-0.0005	-497.8
0.0300	-0.000093	-92.8	-0.0001	-128.8	1.2725	0.000222	221.7	-0.0005	-494.5
0.0400	0.000130	129.7	-0.0002	-215.3	1.2825	0.000219	219.2	-0.0005	-491.2
0.0500	**0.000356**	**355.5**	**-0.0003**	**-304.9**	1.2925	0.000217	216.8	-0.0005	-488.0
0.0500	**0.000358**	**357.5**	**-0.0013**	**-1290.3**	1.3025	0.000214	214.4	-0.0005	-484.8
0.0602	0.000416	415.8	-0.0013	-1277.9	1.3124	0.000212	212.0	-0.0005	-481.7
0.0703	0.000458	457.8	-0.0013	-1256.0	1.3224	0.000210	209.6	-0.0005	-478.7
0.0805	0.000487	487.2	-0.0012	-1227.5	1.3324	0.000207	207.3	-0.0005	-475.6
0.0907	0.000507	507.2	-0.0012	-1194.7	1.3424	0.000205	205.0	-0.0005	-472.7
0.1008	0.000520	520.0	-0.0012	-1159.5	1.3524	0.000203	202.8	-0.0005	-469.7
0.1110	0.000528	527.6	-0.0011	-1123.0	1.3623	0.000201	200.5	-0.0005	-466.8
0.1212	0.000531	531.4	-0.0011	-1086.3	1.3723	0.000198	198.3	-0.0005	-464.0
0.1313	0.000533	532.5	-0.0011	-1050.1	1.3823	0.000196	196.1	-0.0005	-461.2
0.1415	0.000532	531.9	-0.0010	-1014.8	1.3923	0.000194	194.0	-0.0005	-458.4
0.1517	**0.000530**	**530.2**	**-0.0010**	**-980.7**	1.4022	0.000192	191.8	-0.0005	-455.7
0.1618	**0.000528**	**527.8**	**-0.0009**	**-948.1**	1.4122	0.000190	189.7	-0.0005	-453.0
0.1720	0.000525	525.3	-0.0009	-917.2	1.4222	0.000188	187.6	-0.0005	-450.4
0.1822	0.000523	522.9	-0.0009	-888.0	1.4322	0.000186	185.6	-0.0004	-447.7
0.1923	0.000521	520.9	-0.0009	-860.5	1.4422	0.000184	183.5	-0.0004	-445.2
0.2025	0.000519	519.5	-0.0008	-834.9	1.4521	0.000182	181.5	-0.0004	-442.6
0.2127	0.000519	518.9	-0.0008	-811.0	1.4621	0.000180	179.5	-0.0004	-440.1
0.2228	0.000519	519.2	-0.0008	-789.1	1.4721	0.000178	177.5	-0.0004	-437.7
0.2330	0.000521	520.7	-0.0008	-769.0	1.4821	0.000176	175.6	-0.0004	-435.2
0.2432	0.000523	523.5	-0.0008	-750.9	1.4921	0.000174	173.6	-0.0004	-432.8
0.2533	0.000528	527.7	-0.0007	-734.7	1.5020	0.000172	171.7	-0.0004	-430.5
0.2635	0.000534	533.6	-0.0007	-720.6	1.5120	0.000170	169.8	-0.0004	-428.1
0.2737	0.000541	541.3	-0.0007	-708.6	1.5220	0.000168	168.0	-0.0004	-425.8
0.2838	0.000551	551.0	-0.0007	-698.9	1.5320	0.000166	166.1	-0.0004	-423.6
0.2940	**0.000563**	**563.0**	**-0.0007**	**-691.6**	1.5420	0.000164	164.3	-0.0004	-421.3
0.2940	**0.000563**	**563.1**	**-0.0008**	**-847.1**	1.5519	0.000162	162.4	-0.0004	-419.1
0.3040	0.000554	554.1	-0.0008	-824.5	1.5619	0.000161	160.6	-0.0004	-416.9
0.3140	0.000546	546.0	-0.0008	-803.3	1.5719	0.000159	158.8	-0.0004	-414.8
0.3240	0.000539	538.7	-0.0008	-783.3	1.5819	0.000157	157.1	-0.0004	-412.6
0.3340	0.000532	532.2	-0.0008	-764.5	1.5919	0.000155	155.3	-0.0004	-410.5
0.3440	0.000527	526.6	-0.0007	-746.9	1.6018	0.000154	153.6	-0.0004	-408.4
0.3540	0.000522	521.7	-0.0007	-730.3	1.6118	0.000152	151.8	-0.0004	-406.4
0.3640	0.000518	517.7	-0.0007	-714.8	1.6218	0.000150	150.1	-0.0004	-404.4
0.3740	0.000514	514.5	-0.0007	-700.4	1.6318	0.000148	148.4	-0.0004	-402.4
0.3840	0.000512	512.1	-0.0007	-686.9	1.6418	0.000147	146.7	-0.0004	-400.4

0.3940	0.000510	510.5	-0.0007	-674.4	1.6517	0.000145	145.1	-0.0004	-398.4
0.4040	0.000510	509.7	-0.0007	-662.9	1.6617	0.000143	143.4	-0.0004	-396.5
0.4140	0.000510	509.7	-0.0007	-652.4	1.6717	0.000142	141.8	-0.0004	-394.6
0.4240	0.000511	510.6	-0.0006	-642.8	1.6817	0.000140	140.1	-0.0004	-392.7
0.4340	0.000512	512.4	-0.0006	-634.1	1.6917	0.000139	138.5	-0.0004	-390.9
0.4440	0.000515	515.1	-0.0006	-626.4	1.7016	0.000137	136.9	-0.0004	-389.0
0.4540	0.000519	518.7	-0.0006	-619.7	1.7116	0.000135	135.3	-0.0004	-387.2
0.4640	0.000523	523.3	-0.0006	-613.9	1.7216	0.000134	133.7	-0.0004	-385.4
0.4740	0.000529	528.9	-0.0006	-609.2	1.7316	0.000132	132.1	-0.0004	-383.6
0.4840	0.000536	535.6	-0.0006	-605.4	1.7416	0.000131	130.5	-0.0004	-381.9
0.4940	0.000543	543.4	-0.0006	-602.8	1.7515	0.000129	129.0	-0.0004	-380.1
0.5040	0.000552	552.3	-0.0006	-601.2	1.7615	0.000127	127.4	-0.0004	-378.4
0.5140	0.000563	562.6	-0.0006	-600.8	1.7715	0.000126	125.9	-0.0004	-376.7
0.5240	0.000574	574.1	-0.0006	-601.6	1.7815	0.000124	124.3	-0.0004	-375.0
0.5340	0.000587	587.1	-0.0006	-603.6	1.7915	0.000123	122.8	-0.0004	-373.3
0.5440	**0.000602**	**601.6**	**-0.0006**	**-607.0**	1.8014	0.000121	121.3	-0.0004	-371.7
0.5440	**0.000602**	**601.7**	**-0.0010**	**-1031.8**	1.8114	0.000120	119.7	-0.0004	-370.0
0.5540	0.000590	590.3	-0.0010	-1015.6	1.8214	0.000118	118.2	-0.0004	-368.4
0.5640	0.000579	579.4	-0.0010	-999.9	1.8314	0.000117	116.7	-0.0004	-366.8
0.5739	0.000569	568.8	-0.0010	-984.7	1.8414	0.000115	115.2	-0.0004	-365.2
0.5839	0.000559	558.6	-0.0010	-970.0	1.8513	0.000114	113.7	-0.0004	-363.6
0.5939	0.000549	548.7	-0.0010	-955.8	1.8613	0.000112	112.2	-0.0004	-362.1
0.6039	0.000539	539.1	-0.0009	-942.0	1.8713	0.000111	110.7	-0.0004	-360.5
0.6139	0.000530	529.8	-0.0009	-928.7	1.8813	0.000109	109.2	-0.0004	-359.0
0.6238	0.000521	520.8	-0.0009	-915.7	1.8913	0.000108	107.8	-0.0004	-357.4
0.6338	0.000512	512.1	-0.0009	-903.2	1.9012	0.000106	106.3	-0.0004	-355.9
0.6438	0.000504	503.6	-0.0009	-891.0	1.9112	0.000105	104.8	-0.0004	-354.4
0.6538	0.000495	495.4	-0.0009	-879.1	1.9212	0.000103	103.3	-0.0004	-352.9
0.6638	0.000487	487.4	-0.0009	-867.6	1.9312	0.000102	101.8	-0.0004	-351.4
0.6737	0.000480	479.6	-0.0009	-856.4	1.9411	0.000100	100.4	-0.0003	-349.9
0.6837	0.000472	472.0	-0.0008	-845.6	1.9511	0.000099	98.9	-0.0003	-348.4
0.6937	0.000465	464.7	-0.0008	-835.0	1.9611	0.000097	97.4	-0.0003	-347.0
0.7037	0.000457	457.5	-0.0008	-824.7	1.9711	0.000096	95.9	-0.0003	-345.5
0.7137	0.000451	450.5	-0.0008	-814.7	1.9811	0.000094	94.4	-0.0003	-344.1
0.7236	0.000444	443.7	-0.0008	-804.9	1.9910	0.000093	92.9	-0.0003	-342.6
0.7336	0.000437	437.1	-0.0008	-795.4	2.0010	0.000091	91.5	-0.0003	-341.2
0.7436	0.000431	430.6	-0.0008	-786.1	2.0110	0.000090	90.0	-0.0003	-339.8
0.7536	0.000424	424.3	-0.0008	-777.1	2.0210	0.000088	88.5	-0.0003	-338.4
0.7636	0.000418	418.2	-0.0008	-768.2	2.0310	0.000087	87.0	-0.0003	-336.9
0.7735	0.000412	412.1	-0.0008	-759.6	2.0409	0.000085	85.5	-0.0003	-335.5
0.7835	0.000406	406.3	-0.0008	-751.2	2.0509	0.000084	84.0	-0.0003	-334.1
0.7935	0.000401	400.5	-0.0007	-743.0	2.0609	0.000082	82.5	-0.0003	-332.7
0.8035	0.000395	394.9	-0.0007	-735.0	2.0709	0.000081	80.9	-0.0003	-331.3
0.8134	0.000389	389.4	-0.0007	-727.2	2.0809	0.000079	79.4	-0.0003	-329.9
0.8234	0.000384	384.1	-0.0007	-719.5	2.0908	0.000078	77.9	-0.0003	-328.5

0.8334	0.000379	378.8	-0.0007	-712.1	2.1008	0.000076	76.3	-0.0003	-327.1
0.8434	0.000374	373.7	-0.0007	-704.7	2.1108	0.000075	74.8	-0.0003	-325.7
0.8534	0.000369	368.7	-0.0007	-697.6	2.1208	0.000073	73.2	-0.0003	-324.3
0.8633	0.000364	363.8	-0.0007	-690.6	2.1308	0.000072	71.7	-0.0003	-322.9
0.8733	0.000359	358.9	-0.0007	-683.8	2.1407	0.000070	70.1	-0.0003	-321.5
0.8833	0.000354	354.2	-0.0007	-677.1	2.1507	0.000068	68.5	-0.0003	-320.1
0.8933	0.000350	349.6	-0.0007	-670.5	2.1607	0.000067	66.9	-0.0003	-318.7
0.9033	0.000345	345.0	-0.0007	-664.1	2.1707	0.000065	65.3	-0.0003	-317.3
0.9132	0.000341	340.6	-0.0007	-657.8	2.1807	0.000064	63.6	-0.0003	-315.9
0.9232	0.000336	336.2	-0.0007	-651.6	2.1906	0.000062	62.0	-0.0003	-314.5
0.9332	0.000332	331.9	-0.0006	-645.6	2.2006	0.000060	60.3	-0.0003	-313.1
0.9432	0.000328	327.7	-0.0006	-639.7	2.2106	0.000059	58.7	-0.0003	-311.6
0.9532	0.000324	323.6	-0.0006	-633.9	2.2206	0.000057	57.0	-0.0003	-310.2
0.9631	0.000320	319.5	-0.0006	-628.2	2.2306	0.000055	55.3	-0.0003	-308.8
0.9731	0.000316	315.5	-0.0006	-622.6	2.2405	0.000054	53.6	-0.0003	-307.3
0.9831	0.000312	311.6	-0.0006	-617.1	2.2505	0.000052	51.8	-0.0003	-305.9
0.9931	0.000308	307.8	-0.0006	-611.8	2.2605	0.000050	50.1	-0.0003	-304.4
1.0031	0.000304	304.0	-0.0006	-606.5	2.2705	0.000048	48.3	-0.0003	-303.0
1.0130	0.000300	300.3	-0.0006	-601.3	2.2805	0.000046	46.5	-0.0003	-301.5
1.0230	0.000297	296.7	-0.0006	-596.2	2.2904	0.000045	44.7	-0.0003	-300.0
1.0330	0.000293	293.1	-0.0006	-591.3	2.3004	0.000043	42.8	-0.0003	-298.5
1.0430	0.000290	289.5	-0.0006	-586.4	2.3104	0.000041	41.0	-0.0003	-297.0
1.0530	0.000286	286.1	-0.0006	-581.6	2.3204	0.000039	39.1	-0.0003	-295.4
1.0629	0.000283	282.7	-0.0006	-576.9	2.3303	0.000037	37.2	-0.0003	-293.9
1.0729	0.000279	279.3	-0.0006	-572.2	2.3403	0.000035	35.2	-0.0003	-292.4
1.0829	0.000276	276.0	-0.0006	-567.7	2.3503	0.000033	33.3	-0.0003	-290.8
1.0929	0.000273	272.7	-0.0006	-563.2	2.3603	0.000031	31.3	-0.0003	-289.2
1.1029	0.000270	269.5	-0.0006	-558.8	2.3703	0.000029	29.3	-0.0003	-287.6
1.1128	0.000266	266.4	-0.0006	-554.5	2.3802	0.000027	27.2	-0.0003	-286.0
1.1228	0.000263	263.3	-0.0006	-550.3	2.3902	0.000025	25.1	-0.0003	-284.3
1.1328	0.000260	260.2	-0.0005	-546.1	2.4002	0.000023	23.0	-0.0003	-282.7
1.1428	0.000257	257.2	-0.0005	-542.0	2.4102	0.000021	20.9	-0.0003	-281.0
1.1528	0.000254	254.2	-0.0005	-538.0	2.4202	0.000019	18.7	-0.0003	-279.3
1.1627	0.000251	251.3	-0.0005	-534.0	2.4301	0.000017	16.5	-0.0003	-277.6
1.1727	0.000248	248.4	-0.0005	-530.1	2.4401	0.000014	14.3	-0.0003	-275.8
1.1827	0.000246	245.6	-0.0005	-526.3	2.4501	0.000012	12.0	-0.0003	-274.0
1.1927	0.000243	242.8	-0.0005	-522.5	2.4601	0.000010	9.7	-0.0003	-272.2
1.2027	0.000240	240.0	-0.0005	-518.8	2.4701	0.000007	7.3	-0.0003	-270.4
1.2126	0.000237	237.3	-0.0005	-515.2	2.4800	0.000005	4.9	-0.0003	-268.6
1.2226	0.000235	234.6	-0.0005	-511.6	2.4900	0.000002	2.5	-0.0003	-266.7
1.2326	0.000232	232.0	-0.0005	-508.1	2.5000	0.000000	0.0	-0.0003	-264.8

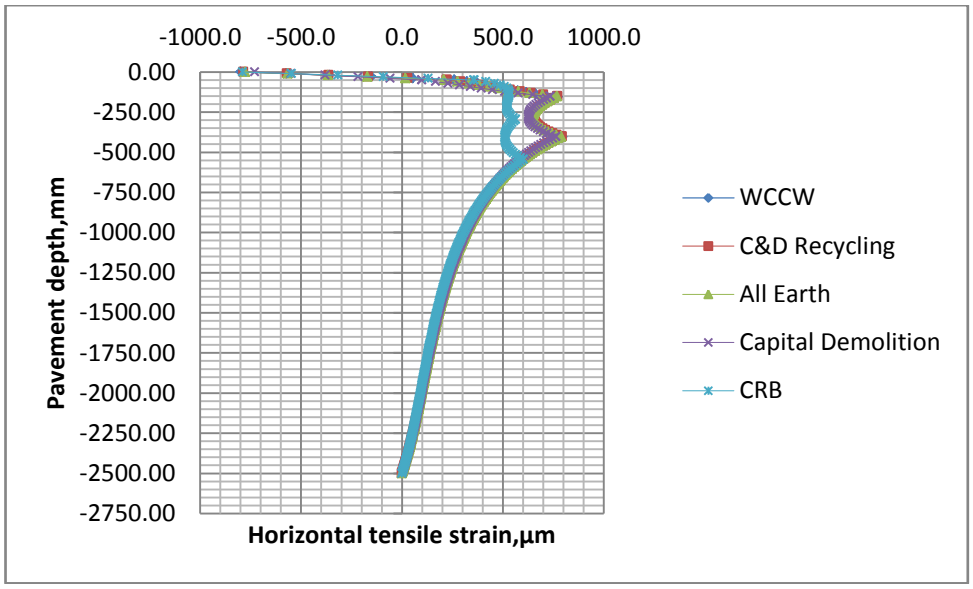

Figure D-1-1: Horizontal tensile strain at depth of modelled pavement depth

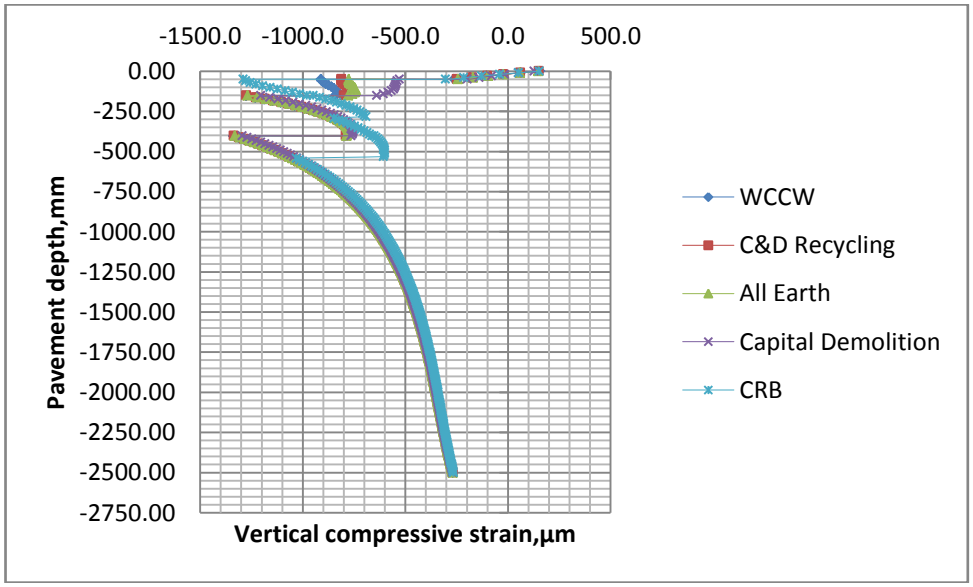

Figure D-1-2: Vertical compressive strain at depth of modelled pavement