University of Southern Queensland
Faculty of Engineering and Surveying

Cost Effective Pavement Reconstruction or Rehabilitation Profile(s) in Townsville

A 'Dissertation' submitted by

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In partial fulfilment of the requirements for the degree of

Bachelor of Engineering (Civil)

ABSTRACT

Councils all over Australia face the same issue; cost effectively reconstructing or rehabilitating trunk roads under traffic. In recent years, the Townsville City Council has undertaken numerous pavement reconstruction or rehabilitation projects of varying profiles. The identification of a cost effective and successful reconstruction or rehabilitation profile would, from a planning perspective, assist a Council in preparing their works programs and securing the appropriate funding required. This project has sought to determine the most cost effective and successful reconstruction or rehabilitation of four (4) varying profiles constructed within Townsville.

A cost-benefit analysis has considered the following criteria;

- pavement design and expected design life;
- in-service performance;
- costs associated with the project.

The pavement profiles analysed consisted of cement treated subbase (CTSB), cement modified base (CMB) and asphalt surfacing along with in-situ stabilisation works utilising cement and foam bitumen.

Whilst the concept of being able to accurately determine a cost effective profile that could be blindly adopted within the local region appears to be useful, the complexities behind pavement design, evaluation, construction and general overall variability of materials result in an extremely complicated procedure.

Via simplification of the original intended analysis, it was observed that there were significant cost savings when in-situ stabilisation can be undertaken, however the ability to construct a consistent CMB modulus within the design envelope appears to be significantly difficult. This is supported by the mean back-analysed base layer modulus being well above 2500 MPa, suggesting its performing more like a cement treated base (CTB) layer as opposed to the design intent of a CMB.

LIMITATIONS OF USE

CERTIFICATION

I certify that the ideas, designs and experimental work, results, analysis and conclusions set out in this dissertation are entirely my own efforts, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

John Single
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Thanks must be given to the Townsville City Council for their assistance in funding the FWD testing and providing access to their databases in order to collate the necessary information. Special thanks must also go to Northern Pavement Consultants for their assistance in developing and undertaking the FWD testing regime and my supervisor Prof. Ron Ayers for his advice and guidance. Lastly, thanks must go to Northern Consulting Engineers for their understanding and support during this time.

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GLOSSARY OF TERMS

The following abbreviations have been used throughout the text:-

CBR	California Bearing Ratio
CMB	Cement Modified Base
CTB	Cement Treated Base
DCP	Dynamic Cone Penetrometers
DESA	Design Equivalent Standard Axles
FBS	Foam Bitumen Stabilised
FWD	Falling Weight Deflectometer
GB	General purpose Blended cement
GP	General purpose Portland cement
LL	Liquid Limit
MPa	Mega Pascals
NPC	Northern Pavement Consultants
PI	Plasticity Index
PSD	Particle Size Distribution
QDTMR	Queensland Department of Transport and Main Roads
RSL	Remaining Service Life
SAR	Standard Axle Repetitions
TCC	Townsville City Council
TLD	Traffic Load Distribution
UCS	Unconfined Compressive Strength

CHAPTER 1 - INTRODUCTION

1.1 Project Definition

The development of pavement reconstruction and rehabilitation works has come a long way in recent years, with new design ideas and various construction practices successfully implemented. As with any project, the general aim in these works is to deliver a project in the most cost effective manner possible. To an organisation such as a local Council, which has many and various assets to maintain, cost effective pavement reconstruction or rehabilitation works are paramount.

The identification of a cost effective and successful reconstruction or rehabilitation profile would, from a planning perspective, assist a Council in preparing their works programs and securing the appropriate funding required. All the profiles being analysed in this project have been constructed in the recent past and firsthand knowledge of their performance has been developed, which provides a reasonable level of confidence in relation to the best design and construction practices to be adopted.

1.2 Background

Townsville is located on the eastern coast of North Queensland, Australia, and has expanded rapidly in the last few decades. This expansion has generated a substantial increase in traffic loads on an aging road network. It is evident that the original pavement design did not anticipate the future traffic loads being experienced today and many have reached the end of their design life. Consequently, substantial pavement reconstruction or rehabilitation works are required on numerous trunk and collector roads to provide an acceptable level of service to the public.

Figure 1-1 below shows the location of Townsville, relative to Queensland.

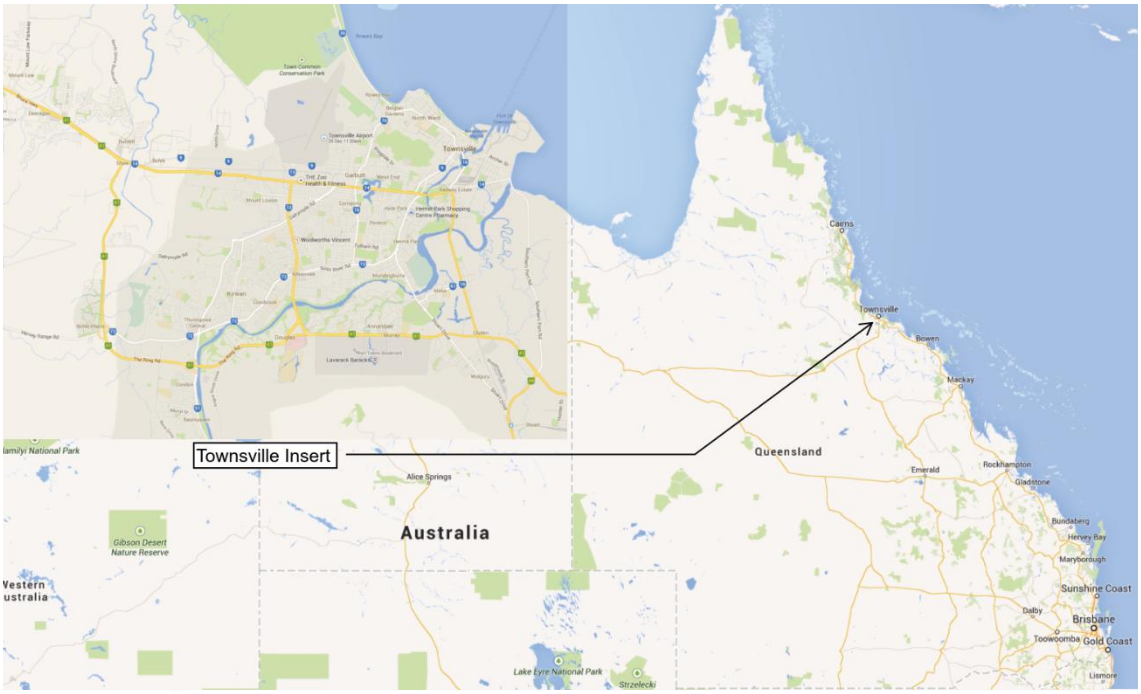

Figure 1-1 Locality map of Townsville (Google Maps, 2014)

Undertaking reconstruction or rehabilitation works on such roads has added complexity and costs due to high traffic volumes. Investigation shows that the majority of these types of works only focus on the costs associated with design and construction and not the overall costs. Overall costs are considered to consist of;

- design and construction;
- maintenance;
- the in-service performance and life of the reconstructed or rehabilitated pavement.

Subsequently, this investigation looks to identify and analyse pavement reconstruction or rehabilitation works under traffic in accordance with overall cost impacts.

1.3 Scope of the Study

The key objective of this project is to:

determine the most cost effective reconstruction or rehabilitation (under traffic) pavement profile(s) of those adopted in Townsville within the past ten (10) years.

It was also a request of the Townsville City Council (TCC), that findings be related back to the current 'Pavement Design Manual', that is under review as of April 2014. This comparison is anticipated to provide TCC with information which will assist with re-defining pavement design parameters and specifications that may be adopted for future pavement design.

To achieve the above objective and request, consideration of the following is required:

- design and construction of pavement profiles
- traffic volumes
- design parameters
- in-service performance
- construction costs

Based on the key objectives and considerations, the scope of the project has been defined as;

1. undertake a literature review that considers pavement design parameters and associated testing of these parameters, current technical design methods, reconstruction (and/or rehabilitation) of road pavements under traffic, theoretical pavement design life for various profiles, typical specifications and standards of pavement and cost-benefit issues associated with choice of pavement type, design methods and construction techniques relating to pavements within the Townsville Region. This research will need to be undertaken on a broader scale, i.e. Queensland/Australia and correlated appropriately to the Townsville Region.

2. identify up to four (4) collector/substantial road sites within the Townsville Region that have been reconstructed under traffic within the past 1-10 years. Each site should have a varying pavement profile, be similar in traffic loads.
3. obtain and collate design testing data, pavement design, construction testing data, construction duration, number of complaints received during construction, construction methodology, design cost, construction cost and any other data consider relevant for undertaking a cost benefit analysis.
4. obtain or undertake traffic counts and analysis to determine current traffic volumes and predicted traffic volumes.
5. undertake non-destructive testing such as Falling Weight Deflectometer (FWD) to analyse the performance and expected constructed pavement life.
6. evaluate constructed pavement profiles using computer software (CIRCLY) to establish current pavement life versus theoretical pavement life and predicted constructed pavement life.
7. evaluate all data and undertake a cost-benefit analysis of pavement profile taking into consideration pavement design life, predicted pavement life, design and construction costs
8. compare findings with the specifications and standards of Townsville City Council's Pavement Design Manual (currently in draft, however due for release this year).
9. present project findings in the required written and oral formats.

1.4 Research Objectives

The key objective of the project is to determine the most cost effective pavement reconstruction or rehabilitation profile(s) of a collector roadway within Townsville City Council region.

1.5 Document Structure

This document is structured as follows:

- **Chapter 1** (this chapter) – details the background, scope and objectives of the project.
- **Chapter 2** – features a literature review that investigates the key components of pavement theory such as design parameters, specifications, standards, design methods, construction, evaluation and associated by products.
- **Chapter 3** – outlines the methodology proposed in order to achieve the aim of the project which entails research, data collation, testing and analysis.
- **Chapter 4** – presents the results of the design, deflection and evaluation analysis of each site and provides interpretations of these results.
- **Chapter 5** – offers conclusion and recommendations regarding further research.

CHAPTER 2 – LITERATURE REVIEW

2.0 Introduction

Pavements have been continuously modified over the years with the aim of improving their durability and life span whilst maintaining costs at a minimum. The improvements in pavement profiles have lead to changes in design methodologies, specifications, materials and construction techniques. This chapter explores basic pavement design, materials, evaluation, specifications, standards, construction and cost along with the current pavement design methodologies commonly adopted by the engineering industry.

2.1 Pavement Materials

The choice of pavement materials is dependent upon the intended function of the road, anticipated traffic, environment, availability of materials, economics, durability and future maintenance requirements. Austroads (AGPT02/12) classifies pavement materials into five (5) categories according to their fundamental behaviour under loading:

- unbound granular;
- modified granular;
- cemented;
- asphalt;
- concrete.

Austroads (AGPT02/12), Table 6.1, p47 provides a brief summary of the typical material types, behaviour characteristics, distress modes, design input parameters and performance criteria for each of the above material categories. For convenience this table has been reproduced below in **Table 2-6**. For discussion purposes, the categorisation of pavement materials has been reduced to four (4) categories:

- unbound granular;
- bound granular;
- asphalt;
- rigid or cement.

Unbound and bound granular materials are discussed further in Sections 2.1.1 and 2.1.2 respectively. Discussions associated with asphalt or rigid pavements have not been presented as part of this project as the pavement profiles investigated consist of unbound or bound materials supplemented with a thin asphalt wearing course, < 50mm.

2.1.1 Unbound Granular Materials

Typically unbound granular materials comprise of crushed rock, coarse gravel and fines that are blended together to form a mechanically stable matrix. Their performance is directly associated with their strength (shear resistance), stiffness (modulus) and durability (ability to resist deformation or breakdown under repeated loading).

Material Properties

Blending of these materials is also referred to as gradings which are classified according to their particle size distribution (PSD). The Queensland Department of Transport and Main Roads (QDTMR) have categorised the gradings as Type 1, 2, 3 and 4 with subtypes ranging from 1 to 5, i.e. Type 2.1 material, refer to QDTMR specification MTRS05 for further details. Typically in Townsville, pavement materials are prepared in accordance with QDTMR specifications and to gain an appreciation between national recommendation and more local requirements, a comparison between QDTMR's grading envelopes and Austroads (AGPT04A/08) has been undertaken. This comparison indicates that QDTMR's envelope provides a slightly larger range, however there is favourable correlation between the other material properties, i.e. liquid limit (LL), plasticity index (PI), etc. It is considered that this variance between the grading envelopes may be reflective of the typical quarry materials within Queensland. **Figure 2-1** below illustrates this comparison.

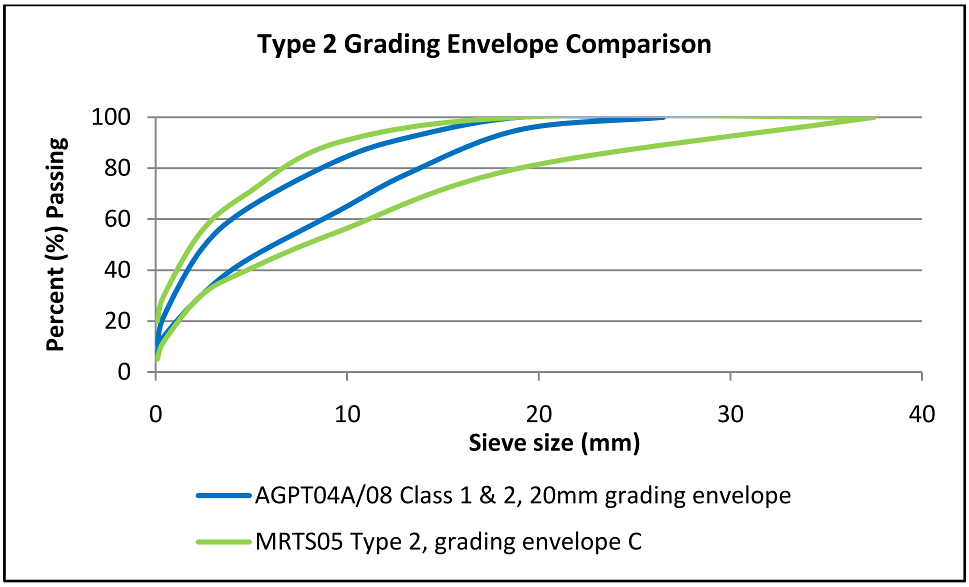

Figure 2-1 AGPT04A/08 and MRTS05 Type 2 grading envelope comparison.

Research shows that the PSD ultimately determines the performance of a granular material based on its shear strength (mechanical interlock), density (for a given compactive effort) and permeability. For example, gradings containing too many fines can prevent the interlock of larger particles, reducing the shear strength of the material due to the reduction in friction between the interlocking particles. Likewise, if there are too few fines (generally defined as a 'boney' finish) the compacted density of the material is reduced and in turn increases permeability. This boney finish can result in a higher modulus (stiffness) due to aggregate point-to-point load transfer, however a loss of shear strength may also be experienced as a result of a inferior mechanically stable matrix. While it is acknowledged that the PSD of granular material has an effect on stiffness (modulus), it has been demonstrated in past research that this effect is minor in nature.

Unbound granular materials are described as cross-anisotropic, i.e. different elastic parameters (modulus and Poisson's ratio) are assigned to the vertical and horizontal directions. Austroads (AGPT02/12) indicates the vertical to horizontal modulus ratio in the mechanistic design is 2:1, i.e the vertical modulus is twice the horizontal modulus with Poisson ratio values between 0.1 and 0.5. It has previously been found that Poisson ratios within this range have negligible impact on pavement thickness requirements, consequently Austroads (AGPT02/12) recommends an assumed value of 0.35 for unbound granular materials being analysed via the mechanistic design method. This is also supported by Tutumluer and Thompson (1998) where a constant shear stiffness ratio value of 35% of the vertical modulus gave reasonably good predictions of up to eight different response variables. This study also found, in general, that as horizontal and shear stiffness increased, nearly all of the critical pavement responses predicted, i.e surface and subgrade deflections, vertical subgrade strains and deviator stresses and asphalt strains, decreased to some extent. Consequently this is where the use of various geotextiles and geogrids assist in reinforcing an unbound granular material which increases the horizontal and shear stiffness, reducing the potential of permanent deformation of the subgrade.

Studies have also found that construction techniques (placement and compaction of pavement materials in horizontal layers) induce an apparent anisotropy resulting in the layer becoming stiffer in the vertical direction due to compaction equipment. In-service traffic loads then impose further anisotropic loading, hence supporting the use of cross-anisotropic properties in modelling of unbound granular material.

Material Parameters

Determination of a materials modulus can be undertaken via one of two (2) methods; direct measurement or assigning presumptive values. The latter is typically adopted in pavement design. Austroads (AGPT02/12) provides adequate guidance in relation to presumptive values via varies studies and is also well recognised and excepted within the industry.

Table 2-1 provides a summary of the typical presumptive unbound materials parameters adopted for pavement design, however reference to Austroads (AGPT02/12) is still recommended for additional guidance on when and how these parameters may be varied.

Table 2-1 Summary of typical presumptive unbound material parameters

Elastic property	Base quality materials			Subbase quality materials
	High standard crushed rock	Normal standard crushed rock	Base quality gravel	
Range of vertical modulus (MPa)	300-700	200-500	150-400	150-400
Typical vertical modulus (E_v) (MPa)	500	350	300	250[(1)]
Degree of anisotropy	2			
Typical Poisson's ratio	0.35			

1 This value is that at typical subbase stress level in unbound granular pavements with thin bituminous surfacing.

(Source: Modified from Austroads (2012). *Guide to Pavement Technology – Part 2: Pavement Structural Design*, AGPT02/12, Table 6.3, p53, Austroads, Sydney, Australia.)

2.1.2 Bound Granular Materials

Bound granular materials can be described as unbound granular materials with the addition of a stabilising agent (such as cement, lime, bitumen or a variation of these binders) that is mixed together with water to produce a bound material that has a significant increase in tensile strength. Bound materials are also commonly referred to as stabilised materials. Although there is an increase in tensile strength, bound materials still maintain certain flexible pavement characteristics and vary based on the extent of stabilisation. In this discussion, bound materials have been categorised into two (2) types; modified and cemented. The main difference between these two (2) types is the amount of stabilising agent added to a granular material which is discussed further below.

Modified Material Properties

Modified materials contain small amounts of stabilising agents that increase the materials modulus and can also be used to correct existing deficiencies in granular materials. Typically a modified material maintains the characteristics of a flexible pavement with the added benefit of reducing its permeability. Due to the small amount of stabilising agent, modified materials do not develop tensile strain under load (in theory), however in practice this is difficult to ensure for numerous reasons. For example, QDTMR specifications stipulate that the minimum cement percentage for a modified material is 1.5% by weight with a maximum 28-day unconfined compressive strength (UCS) of 1.5 MPa, however from experience the addition of 1.5% cement to granular materials can result in a UCS > 1.5MPa. Consequently modified materials exceeding this value begin to fall under the category of stabilised materials which may result in unexpected pavement failures, particularly if the layer was model as a modified material.

To limit the likelihood of this occurring, Austroads (AGPT02/12) recommends a maximum 28-day UCS of 1.0 MPa for modified materials at which point it is still considered to behave similar to an unbound material, hence modelled in the same manner. Consideration should be given to the effect a stabilising agent has on a granular material in relation to a potential increase in horizontal and shear stiffness. However, there is limited research into the effect of modified materials and it is therefore recommended that further investigation be undertaken in relation to the vertical to horizontal ratio (currently 2:1 for unbound granular materials) for modified materials.

Modified Material Parameters

Austroads (AGPT02/12) suggests that modified materials behave in a similar manner to unbound materials, consequently they have the same defining parameters as unbound materials, refer to above. Notwithstanding, it is recommended that the higher modulus value of the typical ranges suggested in Section 6.2.3 of Austroads (AGPT02/12) are adopted. As previously mentioned, upon further investigation into the potential development of tensile strain in modified materials, consideration should be given to modifying the vertical to horizontal modulus ratio to reflect the improved nature of the modified material.

Cemented Material Properties

Cemented granular materials are described as isotropic, i.e. identical elastic parameters (modulus and Poisson's ratio) in all directions. Larger amounts of binder in comparison to modified materials, are added to the granular materials in order to produce a bound layer than has significant tensile strength. Typically general purpose Portland cement (GP) or general purpose blended cement (GB) are used as the binding agent.

Unlike unbound granular materials, cemented materials have a certain window of workability, i.e they generally need to be batched, delivered to site, placed, compacted and trimmed all within a typical working time of four (4) hours. As GB cements contain a larger quantity of cementitious binders, i.e fly ash, iron and steel slabs, silica fume, the typical window of workability may be extended. Additionally, there is also a cost saving associated with the use GB cements due to the use of recycled cementitious binders.

Typically cemented materials are constructed and compacted in a single layer to eliminate the early pavement deterioration that can result when sublayers are not bound together (Austroads 2012). Depending on the type of compaction equipment being used, the thickness of a cemented layer should generally be limited to 200mm to ensure adequate compaction throughout the entire thickness is achieved and performance is reflective of the design model. When cemented layers exceed this thickness, Austroads recommends the design model of the cemented layer is sublayered to account for poorer densities in the lower half of the layer. Notwithstanding the above, it is still preferable (Austroads 2014) to construct cemented materials in thicker layers rather than two (2) or more thin layers. This results from the potential of a substantially reduced pavement performance should debonding occur between these two (2) thinner layers. Consequently, both the designer and construction engineer need to keep this in mind when designing and constructing cemented layers of a pavement.

Cemented Material Parameters

Cemented materials are characterised by their elastic modulus and Poisson's ratio with the flexural modulus and flexural strength being the preferred design inputs due to similarities with the loading regime of in-service conditions (Austroads 2014). Previous investigations have shown that the Poisson's ratio, within the normal range of 0.1-0.3, have relatively little influence on the thickness of cemented layers with the material's flexural modulus and strength largely influencing the fatigue characteristics.

Typical practice is to specify a cemented layer in terms of its 28 day unconfined compressive strength (UCS) with equation (2-**1**) describing the typical relationship between the flexural modulus and UCS value.

$$E_{FLEX} = k\ UCS \tag{2-1}$$

where a recently adopted revision to Austroads 2012 (Austroads 2014, AP-R463/14) states:

E_{FLEX} = flexural modulus of laboratory-manufactured beams at 90 days (MPa), unsoaked (previously Austroads 2012 stated; flexural modulus of field beams at 28 days moist curing)

UCS = unconfined compressive strength of laboratory specimens at 28 days (MPa)

k = a constant. Values of 1150 to 1400 are typically used for GP cements, the value depending on laboratory testing practices and construction specifications for cemented materials (previously Austroads 2012 stated; values of 1000 to 1250).

Although the k value has been revised in Austroads 2014, the original value of 1000 will be adopted throughout the investigation as original designs would have been undertaken based on this assumption. It is also noted that equation (2-**1**) is only applicable for values up to 5000 MPa.

Table 2-2 provides a summary of the typical presumptive cemented material parameters adopted for pavement design and reflects the revised parameters of Austroads 2014, AP-R463/14. In addition to Austroads recommendations, DTMR specifies their own parameters that are to be adopted for pavements designed within their jurisdiction and are reproduced in **Table 2-3**. The Austroads parameters have been adopted throughout this investigation as the QDTMR parameters are only application to state controlled roads and none of the sites are under QDTMR's jurisdiction.

Table 2-2 Summary of typical presumptive cemented material parameters

Elastic property	Base quality materials			Subbase quality materials
	High standard crushed rock	Normal standard crushed rock	Base quality gravel	
Range of vertical modulus (MPa)	300-700	200-500	150-400	150-400
Typical vertical modulus (E_v) (MPa)	500	350	300	250(1)
Degree of anisotropy	2			
Typical Poisson's ratio	0.35			

1 This value is that at typical subbase stress level in unbound granular pavements with thin bituminous surfacing.

(Source: Modified from Austroads (2012). *Guide to Pavement Technology – Part 2: Pavement Structural Design*, AGPT02/12, Table 6.3, p53, Austroads, Sydney, Australia.)

Table 2-3 QDTMR presumptive cemented material parameters

Category	Design Modulus (MPa)[1, 2]	Material to be stabilised (MRTS05 Type)	Typical minimum UCS (28 day) (MPa)[3]
Category 1	3500	1.1, 2.1	3.5 to 4.5
Category 2	2500	1.1, 2.1, 2.2, 3.1[4] or 3.2[4]	2.5 to 3.5

Notes:

1 These design modulus values assume seven (7) days initial curing with negligible trafficking.

2 Design modulus values are based on the specified compaction standard being achieved over the full depth of the layer.

3 The minimum 28 day UCS values shown are based on a cementitious blend of 75% cement and 25% flyash.

4 Type 3 materials are only suitable for use in relatively dry environments.

(Source: DTMR, November 2013. *Pavement Design Supplement - Supplement to ' Part 2: Pavement Structural Design' of the Austroads Guide to Pavement Technology*, Table Q6.4, p34.)

2.1.3 Foam Bitumen Materials

Foam bitumen materials is typically an in-situ stabilisation process where bitumen and water are injected into the existing material causing rapid expansion of the bitumen and coating the finer particles. However it can also be plant mixed and delivered to site in a similar manner to cemented materials. Unlike cemented materials, foam bitumen has a longer working duration and it can be topped up and re-trimmed if necessary. Austroads (AP-T188/11) reviewed and compared four (4) foam bitumen design methods in order to provided an interim design procedure that produces a bound layer with significant tensile strength, similar to cemented materials.

The elastic parameters of foam bitumen materials is similar to asphalt, subsequently it is susceptible to high temperatures. However it has the added benefit of being trafficable within a much shorter duration (typically three (3) hours) than cemented materials. The elastic modulus of foam bitumen stabilisation is determined via indirect tensile testing and typically this type of testing is not undertaken at the design phase of a pavement. Subsequently the interim design method provides presumptive initial and long term modulus values that need to be adjusted according to temperature and rate of loading. Table 2-4 and Table 2-5 detail these minimum requirements.

Table 2-4 Minimum mix design limit for initial modulus

Average daily ESA in design year of opening	Initial modulus (MPa)
< 100	500
≥ 100	700

(Source: Austroads 2011. *Review of Structural Design Procedures for Foamed Bitumen Pavements*, AP-T188/11, Table 7.1, p38, Austroads, Sydney, Australia.)

Confirmation of the initial modulus is required to ensure the risk of the pavement prematurely rutting, as a result of being opened to traffic within hours after placement, is reduce.

Table 2-5 Minimum mix design limits for dry modulus for foamed bitumen base

Average daily ESA in design year of opening	Minimum dry modulus (MPa)	Minimum soaked modulus (MPa)	Minimum retained modulus ratio
< 100	2500	1500	40%
100 - 1000	3000	1800	45%
> 1000	4000	2000	50%

(Source: Austroads 2011. *Review of Structural Design Procedures for Foamed Bitumen Pavements*, AP-T188/11, Table 7.2, p39, Austroads, Sydney, Australia.)

Due to its susceptibility to temperature, the presumptive design modulus needs to be adjusted to account for in-service pavement temperatures. Austroads (AP-T188/11) recommends this adjustment is undertaken in accordance with equation (2-**2**):

$$\text{Modulus at WMAPT / Modulus at test temperature (T)} = \exp(-0.025[\text{WMAPT} - \text{T}]) \tag{2-2}$$

where

WMAPT = Weighted Mean Annual Pavement Temperature (ºC) and can be obtained from Appendix B of Austroads AGPT02/12 for various locations around Australia.

T = Temperature of indirect tensile resilient modulus test (ºC), typically 25 ºC.

Further to the temperature adjustment, the in-service rate of loading (traffic speed) needs to be accounted for in terms of the in-service heavy vehicle traffic speed. This adjustment is described by equation (2-**3**):

$$\text{Modulus at V / Modulus at 40 ms rise time loading rate} = 0.46V^{0.16} \tag{2-3}$$

Foam bitumen layers are then model as per asphalt layers with the traffic multipliers and performance criteria as detailed later.

Table 2-6 Pavement material categories and characteristics

Characteristics	Pavement material category				
	Unbound granular	**Modified granular**	**Cemented**	**Asphalt**	**Concrete**
Material types	Crushed rock Gravel Soil aggregate Granular-stabilised	Bitumen-stabilised Chemically-modified Cemented, lime, lime/fly ash or slag-modified	Lime-stabilised Cement-stabilised Slag-stabilised Slag/lime-stabilised	Asphalt	Concrete
Behaviour characteristics	Development of shear strength through particle interlock. No significant tensile strength.	Development of shear strength through particle interlock. No significant tensile strength.	Development of shear strength through particle interlock and chemical bonding. Significant tensile strength.	Development of shear strength through particle interlock and cohesion. Significant tensile strength. Properties are temperature sensitive.	Development of shear strength through chemical bonding and particle interlock. Very significant tensile strength.
Distress mode	Deformation through shear and densification. Disintegration through breakdown.	Deformation through shear and densification. Disintegration through breakdown.	Cracking developed through shrinkage, fatigue and over-stressing. Erosion and pumping in the presence of moisture.	Cracking developed through fatigue, overloading. Permanent deformation.	Cracking developed through shrinkage, fatigue and erosion of subbase/subgrade.
Input parameters for design	Modulus Poisson's ratio Degree of anisotropy	Modulus Poisson's ratio Degree of anisotropy	Modulus Poisson's ratio	Modulus Poisson's ratio	28-day flexural strength or 28-day compressive strength.
Performance criteria	Current material specifications (grading criteria, i.e. type 2.1)	Current material specifications (grading criteria, i.e. type 2.1)	Fatigue relationships	Fatigue relationships	Fatigue and erosion relationships

(Source: Austroads (2012). *Guide to Pavement Technology – Part 2: Pavement Structural Design*, AGPT02/12, Table 6.1, p47, Austroads, Sydney, Australia.)

2.2 Pavement Design Overview

A pavement profile (structure) comprises of various layers of material supported by a natural foundation, otherwise known as the subgrade. **Figure 2-2** illustrates a typical pavement profile.

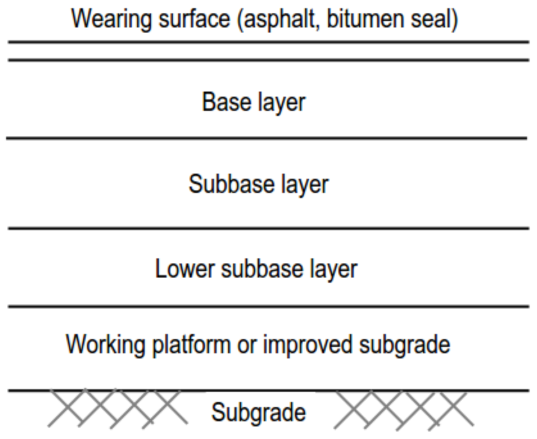

Figure 2-2 A typical pavement profile.

When beginning an investigation into pavements, whether it be performance, design or comparison, it is important to understand the nature and fundamentals of pavement design. The process for the design of pavements involves numerous inputs, analysis and decisions to be made and is best represented in the flow chart depicted in **Figure 2-3**.

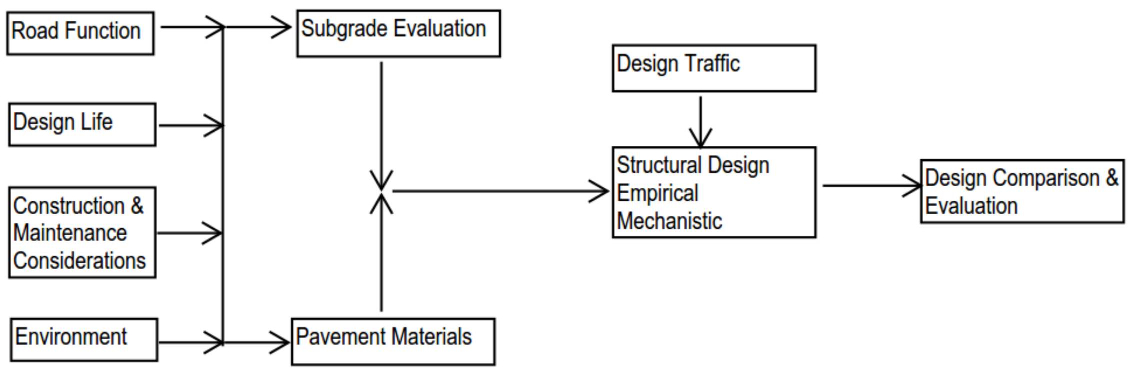

Figure 2-3 Pavement design process (Austroads, AGPT02/12)

2.2.1 Road Function

The road function sets the criteria and reliability level for pavement design. Typically in Australia each local authority has a set road hierarchy based around various higher authorities such as Austroads, Queensland Streets (or equivalent) or QDTMR. Currently TCC is reviewing their typical road cross section and hierarchy however they typically fall under the following categories; motorway, arterial, sub-arterial, major collector, minor collector, access street and access place.

2.2.2 Types of Pavements

Figure 2-2 illustrated the typical structure of a pavement regardless of the type of pavement. Pavements are typically categorised as flexible or rigid and can be combination of various materials. **Figure 2-4** depicts examples of combinations that may be adopted when design a pavement.

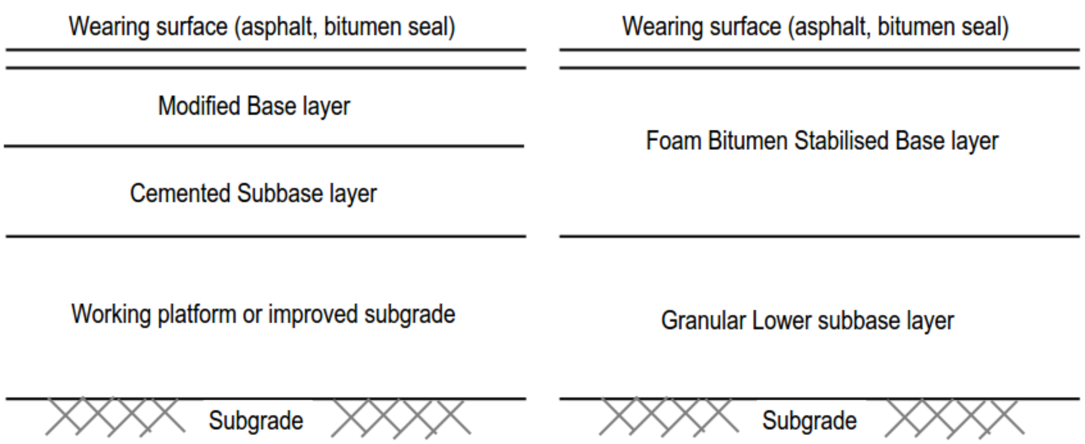

Figure 2-4 Example pavement structures

2.2.3 Design Life

Design life is the first component required when estimating the design traffic loads for a pavement. This parameter sets the duration for which the pavement is anticipated to function prior to requiring major reconstruction or rehabilitation works. Austroads (AGPT02/12) also states that in addition to the preceding statement, the design life sets the baseline of expectation on how the constructed pavement will perform.

Design life for flexible pavements can range from 20-40 years and is dependant of the intended function of the road. In Townsville, the typical design life of a pavement is set at 20 years for flexible pavements for road categorised below a major collector. Road categorised as major collector and higher are to be designed for a 35 year life for flexible pavements. As this manual was not in affect during this project, the original design life of 20 years will be adopted throughout this investigation.

2.2.4 Design Traffic

It is widely established and accepted that light vehicles, such as cars and motorbikes, contribute little to the structural deterioration of a pavement, consequently only the effect of heavy vehicles are considered in pavement design. Consequently it is excepted that the damaged caused by these heavy vehicles is not only related to their weight but also how many axles are on the vehicle, the grouping of axles and the weight distribution over the axles. It is also important to note that typical design traffic loading does not account for shear or load transfer forces applied to a pavement which should be incorporated or at the least considered during the design process. The effects of shear and load transfer forces have not been investigated within this project.

The typical procedure to estimate the design traffic loading is based around the concept of a single Equivalent Standard Axle (ESA) and is defined by Austroads (2012) as:

$$N_{DT} = 365 \text{ x } AADT \text{ x } DF \text{ x } \%HV/100 \text{ x } LDF \text{ x } CGF \text{ x } N_{HVAG} \qquad (2\text{-}4)$$

where

AADT = Annual Average Daily Traffic in vehicles per day in the first year. This data can be readily obtained from traffic counts.

DF = Direction Factor is the proportion of the two-way AADT travelling in the direction of the design lane. If data is obtained from a pneumatic tube traffic counter, the AADT in the direction of travel is typically identified, resulting in a DF value of 1.

%HV = average percentage of heavy vehicles. This is also readily obtained from pneumatic tube traffic counter data.

LDF = Lane Distribution Factor, proportion of heavy vehicles in the design lane for roads with two (2) or more lanes in each direction. If there is only a single lane in each direction, this value is set to 1.

N_{HVAG} = average number of axle groups per heavy vehicle.

CGF = Cumulative Growth Factor described by equation (2-**5**):

$$CGF = (1 + 0.01R)^{P} / 0.01R \text{ for } R > 0\text{; or}$$
$$= P \text{ for } R = 0 \tag{2-5}$$

where

R = annual growth rate (%)

P = design period (years)

In greenfield sites where traffic count data is not available, it is typical of a local authority to stipulate minimum design loading based on the road function. For example in TCC draft pavement manual a Type A urban residential street shall have a minimum 20 year design life loading equivalent to a design ESA of 2 x 10^4 and varied as required to suit the particulars of the new development. This also extends to typical %HV values, growth rates, ESA per heavy vehicle (ESA/HVAG also referred to as the Traffic Load Distribution (TLD)) and N_{HVAG}.

Austroads 2012 states that whilst the use and determine of the design traffic loading as described above is a well-entrenched and useful practice, it does not, by itself, contain enough information for the design of pavements containing one or more bound layers. Additional information is required to describe the three (3) distinct types of damage caused to a pavement; fatigue damage to asphalt, rutting and loss of surface shape and fatigue damage to cemented materials. Therefore the design traffic loading is converted into Standard Axle Repetitions (SAR). Firstly, the design ESA (DESA) is factored by the TLD via equation (2-**6**):

$$DESA = TLD \times N_{DT}$$

(2-6)

where

TLD = ESA/HVAG

N_{DT} = as determined via equation (2-**4**)

The DESA is then converted into an equivalent design SAR (DSAR) based on the damage type. This conversion is undertaken by multiplying the DESA by the corresponding SAR_m traffic multiplier, i.e:

- Fatigue of asphalt = SAR_5 = a traffic multiplier of 1.1
- Rutting and loss of surface shape (subgrade deformation) = SAR_7 = a traffic multiplier of 1.6
- Fatigue of cemented materials = SAR_{12} = a traffic multiplier of 12.

These traffic multiplier values represent typical values adopted for urban road design and are in accordance with values previously outlined in Austroads AGPT02/10. For lightly traffic roads, Austroads 2012 recommends values of SAR_5 = 1, SAR_7 = 1 and SAR_{12} = 3 or 12 for roads without and with buses respectively.

2.2.5 Subgrade

It is widely recognised that the support provided by the subgrade is generally the most import factor in defining the pavement profile and performance of the pavement. There are numerous aspects that affect subgrade performance, namely;

- natural variability, such as moisture variance and lenses of different material;
- material characteristics, such as cohesion, plastic limit (PL), swell, liquid limit (LL) and plasticity index (PI);
- changes in moisture content, both during construction and service life, such as volume changes associated with exposure to excessive moisture conditions;
- construction techniques.

Subgrade support is typically expressed in terms of its California Bearing Ratio (CBR) and is the value adopted in the empirical method for pavement design. The CBR value of a subgrade can be obtained via in-situ (Dynamic Cone Penetrometer (DCP) test) and/or laboratory testing in accordance with Australian Standard AS 1289. The CBR value provides a measure of the strength of a non-stabilised cohesive material by comparing the bearing capacity of the material to that of a well-graded crushed stone. The higher the CBR value the greater the support, i.e. subgrade CBR values greater than 10% are consider to represent reasonable support where a poor subgrade is generally referred to as CBR values of ≤ 3%.

The mechanistic method is based on a materials elastic modulus with Austroads (AGPT02/12) recommending that the empirical relationship (equation (2-**7**)) is adopted.

$$\text{Modulus, E (MPa)} = 10 \times CBR \tag{2-7}$$

Although this relationship is also supported and adopted by Nataatmadja 2012 [3], Sparks & Potter 1982 found that the modulus can vary between 5 x CBR to 20 x CBR, hence should only be used as an approximation. It is also noted that equation (2-**7**) should only be used for CBR values ≤ 15% with Austroads (AGPT02/12) recommending this value (CBR 15% or E 150 MPa) as a maximum for subgrade.

The subgrade needs to have sufficient support to:

- prevent excess rutting and shoving during construction;
- provide adequate support for the placement and compaction of pavement layers;
- minimise the effect of permanent deformation (rutting) during the service life of the pavement.

When a subgrade fails to provide this support, typically for CBR values < 3%, corrective action or subgrade improvement is required. This can be achieved via:

- removal and replacement (over excavation) of poor material;
- stabilisation with lime, cement or bitumen binders;

- capping and bridging layers inclusive of capping poor material with a higher quality material, geotextiles and reinforcement (geogrid/tensar).

Regardless of the improvement method, consideration of the underlying material, cost and benefits is required to ensure value for money is provided. The 2010 revision of Austroads (AGPT02/10) had indicated that any effect of CBR improvement to subgrades with CBR values < 3% was ignored and a design CBR of 3% adopted following treatment. This statement has since been removed in the Austroads (AGPT02/12) and replaced with "it is essential that the potential effects of any weak layers below the design subgrade level are considered in the pavement process, particularly for low-strength materials occurring to depths of about 1 metre". Beyond a depth of 1 metre, the effect of applied stress is assumed to be negligible. This is reflected in the equation (2-**8**), otherwise known as the Japan Equation.

$$E_E = \left[\frac{\sum_i h_i E_i^{1/3}}{T}\right]^3$$

(2-8)

where

E_E = equivalent modulus of total thickness of bound material (MPa)

E_i = modulus of layer (MPa)

h_i = thickness of layer (mm)

T = total thickness of equivalent modulus (mm) = 1000mm

Equation (2-**8**) implicitly assumes:

- all layers are isotropic and have the same Poisson's ratio
- both the original structure and the equivalent structure have the same stress strain distribution, i.e. f = 1
- the existence of a semi-infinite subgrade thickness is ignored.

2.2.6 Structural Design - Empirical Method

The empirical method is only suitable for pavements that comprise solely of unbound layers of granular material with a thin bituminous surfacing, resulting in only one (1) assessed damage type, namely permanent subgrade deformation. The charts depicted in **Figure 2-5** and **Figure 2-6** where developed from observations of pavement performance under various traffic loadings and represents a 'best-fit' approach. Consequently only three (3) inputs are required, subgrade CBR, DESA as determined via equation (2-**6**) and the CBR of the proposed base and subbase gravel materials.

This method has been successfully used in the past to design unbound granular pavements, however there is a general movement towards all pavement designs being undertaken via the mechanistic method. From a large scale planning or preliminary assessment perspective, the use of the empirical methods still provides a quick and adequate indication of the overall pavement thickness that may be required. The final design and composition of the pavement can then be undertaken via the mechanistic method during the detailed design phase.

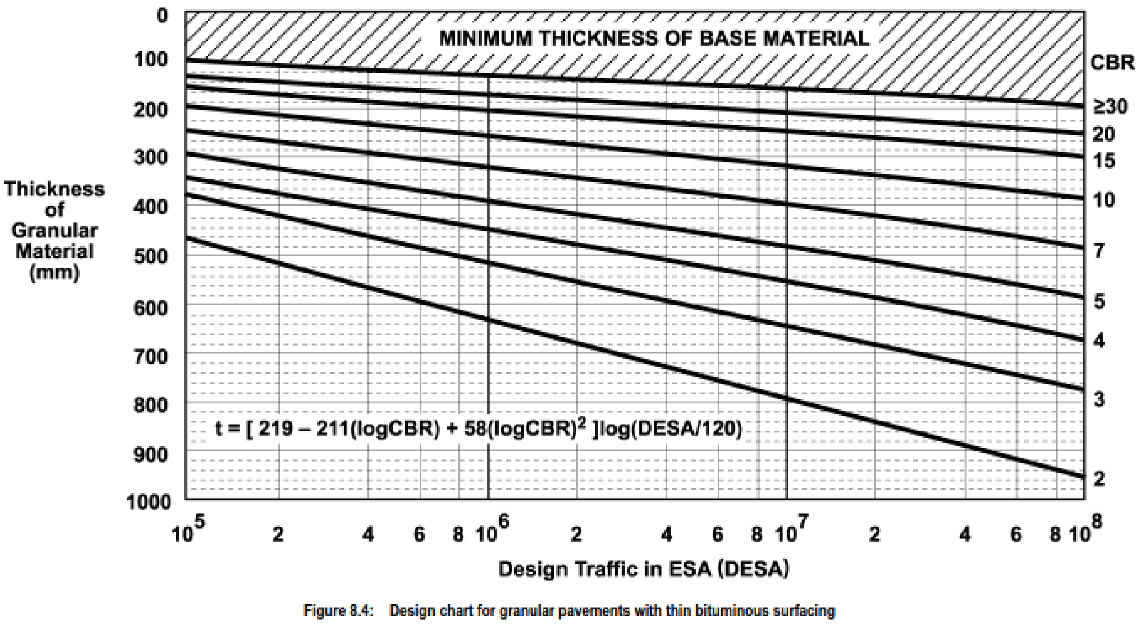

Figure 2-5 Heavily trafficked (DESA $1x10^5$ to $1x10^8$) empirical pavement thickness design chart (Austroads, AGPT02/12, Figure 8.4)

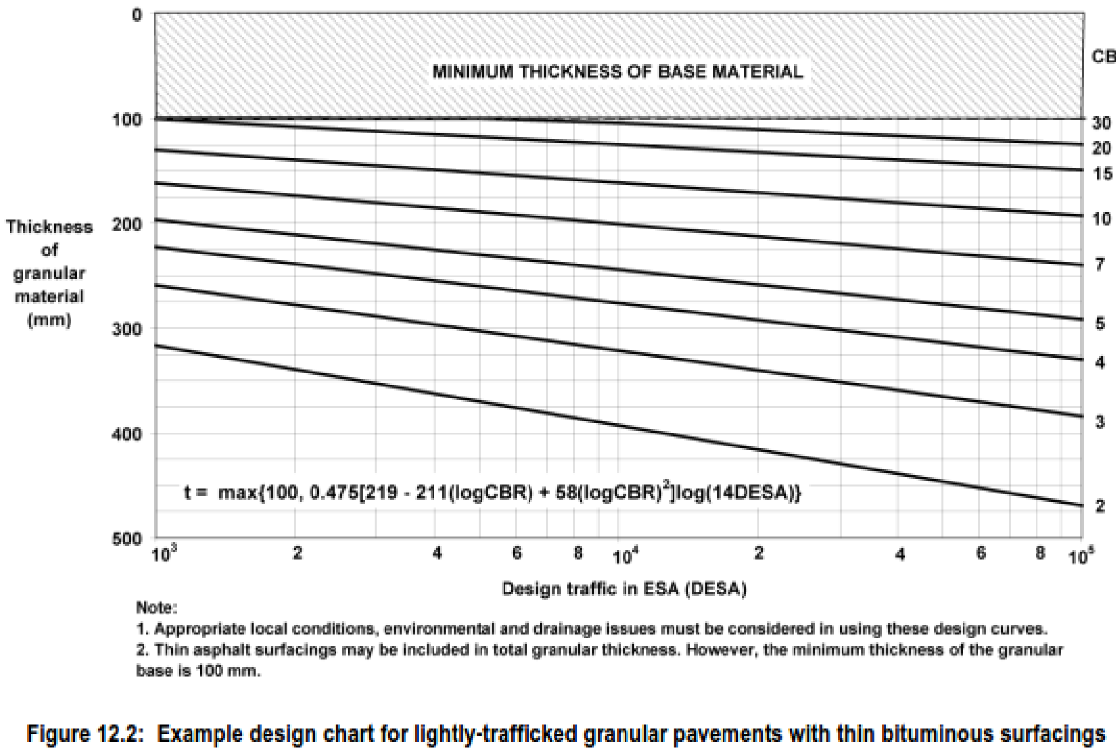

Figure 2-6 Lightly trafficked (DESA $1x10^3$ to $1x10^5$) empirical pavement thickness design chart (Austroads, AGPT02/12, Figure 12.2)

2.2.7 Structural Design - Mechanistic Method

Using the theory of mechanics, the mechanistic method expands on the empirical method by introducing the state of stress and strain experienced in a pavement under traffic loading. The relationships established from the results of experiments and/or observations of the pavements' in-service performances (empirical) are adopted in the mechanistic approach in order to provide correlation between theoretical calculations and actual pavement performance. Hence similar results are obtained from both the mechanistic and empirical methods for unbound granular pavements This approach to pavement design is becoming more commonly adopted with the evolution of computing power available.

Simply explained, the mechanistic approach uses a multi-layered elastic model, subject to traffic loading, to calculate the stress, strain and deflections at subgrade level and the underside of asphalt and stabilised layers within a pavement. Empirical equations are then used to define pavements' performance by relating the calculated stress, strain and deflections to various pavement failure criterions. Subsequently this approach dictates that pavement design is undertaken as an iterative trial and error process, namely assessing an assumed pavement profile and refining this profile to meet the desired pavement performance criteria. Consequently various computer programs, such as CIRCLY, have been continuously developed overtime to assist designers with this iterative process.

Due to the complexity of this model, Austroads (AGPT02/12) has established key assumptions for this approach to simplify the procedure whilst providing results that are consistent with observed behaviour. Key assumptions include, as defined by Austroads (AGPT02/12):

1. *Pavement materials are considered to be homogeneous, elastic and isotropic (expect for unbound granular materials and subgrades which, as discussed in Section 5 and 6, are considered to be anisotropic).*
2. *Response to load is calculated using a linear elastic model, such as the computer program CIRCLY.*
3. *The critical responses assessed for pavement and subgrade materials are:*
    a. *asphalt and cemented - horizontal tensile strain at the bottom of the layer*
    b. *unbound granular - not considered in model*
    c. *subgrade and selected subgrade materials - vertical compressive strain at the top of the layer.*
4. *Standard Axle loading consists of a dual-wheeled single axle, applying a load of 80 kN. For flexible pavements, the critical responses within the pavement occur either along the vertical axis directly below the inner-most wheel of the dual wheel group or along the vertical axis located symmetrically between a pair of dual wheels (Figure 8.2)*
5. *Standard Axle loading is represented by four uniformly-loaded circular areas of equal area separated by centre-to-centre distances of 330 mm, 1470 mm, and 330 mm respectively as illustrated in Figure 8.2*

6. *The contact stress is assumed to be uniform over the loaded area and, for the purpose of design, is taken to be 750 kPa. The contact stress is related to the air pressure in the tyre in service which for highway traffic is assumed to be in the range 500 - 1000 kPa*

7. *Some variations to the above may be appropriate for other than normal axle types and loadings; for example, where sharp turning movements or acceleration or braking occur. A model which more closely corresponds to the actual axle configuration and loading should be adopted in such cases. The computer program CIRCLY can accommodate these variations. However, this is rarely undertaken for most pavement design situations and there is little case study experience to relate the calculated pavement responses to pavement performance*

8. *For some projects, the mechanistic modelling may indicate that both a thin (< 50 mm) and thick asphalt surfaced pavement can be adopted. Caution is advised in adopting the thin asphalt surfaced pavement option because the dominant damage types are not necessarily those addressed by the design model and as a consequence mechanistic modelling of asphalt layers less than 40 mm thick is less certain than for thicker asphalt layers (Section 8.2.5)*

When undertaking pavement designs based on a rutting failure criterion, it is assumed that the majority of surface rutting occurs due to subgrade deformation and is related to the magnitude of the elastic strain transferred through the pavement to the top of the subgrade.

The typical mechanistic design procedure documented in Austroads (2012) is based on assessing pavement performance from a vertical 'load case'. Although this load case is the dominate force applicable throughout the majority of the pavement (resulting from linear travel), consideration should also be given to the forces applied when;

- breaking / acceleration and linear travel on steeper gradients - resulting in horizontal forces and moments about the horizontal axis;
- turning and screwing - resulting in moments about the vertical axis and radial shear stress.

Wardle (CIRCLY theory and background manual) provides further explanation on the theory and impacts of these other loading cases and how these forces can be considered and analysed in CIRCLY.

Design Procedure

Austroad (AGPT02/12) has recommended and detailed an eighteen (18) step design procedure for the mechanistic method that can be used with or without the aid of computer software, such as CIRCLY. The procedure is effectively a trial and error process that is broken into three (3) categories; design inputs, analysis and interpretation. Refer to Austroads (AGPT02/2012) for further details on the step by procedure.

Wardle (2003) states that sensible designs will only be produced when the derived failure criterion is used as part of the same procedure, otherwise the empirical link between the design and original performance data used to calibrate the criterion is broken. Consequently it is up to the designer to ensure the appropriate criteria is adopted. For typical scenarios, i.e. standard residential and highway design, the criteria specified below will provide sensible designs.

Unbound layers are sub-layered in order to better model their non-linear response. Austroads (AGPT02/12) suggests that sublayering of unbound granular materials is only required when placed directly on in-situ or selected subgrades. Sub-layering is not required when unbound granular material is placed directly onto a bound cemented layer. When sublayering, the unbound material is divided into five (5) equi-thick sublayers with the vertical modulus (E_v) of the top of the granular layer determined in accordance with equation (2-**9**). The ratio of moduli of adjacent sub-layers is determined via equation (2-**10**) which can then be used to assign the elastic vertical modulus to each of the five (5) equi-sub-layers of the unbound layer.

$$E_{v\ \text{top of granular layer}} = E_{V\ \text{underlying material}} \times 2^{(\text{total granular thickness / 125})}$$

(2-9)

$$R = \left[\frac{E_{V\ \text{top granular sub-layer}}}{E_{\text{underlying material}}}\right]^{\frac{1}{5}}$$

(2-10)

Performance Criterion

The performance criteria (also referred to as fatigue criteria) is the link between the mechanistic method and experimental findings (empirical). This means that the performance criteria has been established via best-fit solutions of experimental results and observations and the mechanistic component is the theoretical analysis of material behaviour under loading.

In accordance with Austroads (AGPT02/12) recommendations, a summary of the each of the performance criterion is outlined below. It is noted that performance criteria is only applicable to asphalt, cemented material, rigid and subgrade layers of a pavement. Whilst it is recognised (Austroads (AGPT02/12)) that permanent deformation is a primary stress mode for granular layers over time, where the material's stability decreases, there is not a suitable model to reliably predict the development of rutting in a granular material. Consequently, performance analysis of granular layers are excluded from the mechanistic design method. Similarly, modified materials are excluded from performance assessment due to Austroads (AGPT02/12) recommending these materials be treated as unbound materials. Refer to Section 2.1.2 for further details.

Subgrade

The subgrade performance criteria represents a 'best fit' relationship between the application of the mechanistic method to a range of pavements derived from the empirical method charts. This suggests that the criteria given in equation (2-**11**), will generally produce design that are reflective of observed pavement performances.

The subgrade performance criteria limits the vertical compressive strain at the top of the subgrade to an allowable number of repetitions of a Standard Axle Repetitions prior to permanent deformations occurring, i.e. rutting.

$$N = \left[\frac{9300}{\mu\epsilon}\right]^7 \tag{2-11}$$

where

$\mu\varepsilon$ = the vertical compressive strain at the top on the subgrade in microstrain.

N = the allowable number of repetitions of a Standard Axle.

Cemented materials

The fatigue criteria for cemented materials is given by equation (2-**12**) and indicates the number of allowable repetitions that can be sustained by the cement prior to cracking. Once cracked, Austroads recommends that this layer is then assess as a granular layer with a presumptive E_v of 500 MPa. The only exception to this is that the post-cracked layer is not sublayered.

$$N = RF\left[\frac{(\frac{113000}{E^{0.804}} + 191}{\mu\varepsilon}\right]^{12}$$

(2-12)

where

N = the allowable number of repetitions of a Standard Axle.

$\mu\varepsilon$ = horizontal tensile strain at base of cemented material (microstrain)

E = cemented material modulus (MPa), determined in accordance with equation (2-**1**)

RF = reliability factor in accordance with **Table 2-7**

Table 2-7 Suggested reliability factors for cemented materials fatigue

Desired project reliability				
80%	85%	90%	95%	97.5%
4.7	3.3	2.0	1.0	0.5

(Source: Austroads (2012). *Guide to Pavement Technology – Part 2: Pavement Structural Design*, AGPT02/12, Table 6.8, p64, Austroads, Sydney, Australia.)

Foam Bitumen

Austroads interim design procedure recommends foam bitumen layers are modelled as a bound layer and the performance assessed based on the asphalt fatigue relationship as detailed in equation **(2-13)**.

$$N = \left[\frac{(6918(1.08 + 0.856V_b)}{E^{0.36}\mu\varepsilon}\right]^5$$

(2-13)

where

N = the allowable number of repetitions of a Standard Axle.

$\mu\varepsilon$ = horizontal tensile strain at base of foam bitumen material (microstrain)

E = foam bitumen modulus as detailed in Section 2.1.3

V_b = percentage by volume of bitumen in the bitumen layer (typically 3.5%)

2.3 Pavement Evaluation

Pavement evaluation is a critical component of predicting the structural deterioration and remaining service life (RSL) of a pavement. This information assists asset managers in developing maintenance, reconstruction and rehabilitation programs whilst providing adequate lead time to secure the necessary funding. A detailed pavement evaluation should consider the following:

- Structural adequacy
- Roughness
- Surface defects such as cracking, potholes, edge defects, deformation, etc
- Surface deterioration such as stripping, flushing, etc
- Skid resistance
- Surface texture

Due to available resources, only the structural adequacy will be investigated in the project. Following is a review of available structural testing and how this information can be adopted in assessing the RSL of the pavement.

2.3.1 Falling Weight Deflectometer (FWD)

Back-analysis of pavements can provide valuable insight into the in-service performance of a pavement profile. In-service pavement testing assists designers in understanding the performance by providing clarity to assumptions adopted during the design process. Various methods of in-service testing are available but can be categorised into two (2) main categroies, non-destructive testing (NDT) and destructive testing. Examples of these methods include:

- Non-destructive testing
  - Falling Weight Deflectometer (FWD)
  - Benkelman Beam
- Destructive testing
  - Bore logs
  - Core samples for various parameter testing, i.e. in-service modulus.

Destructive testing is generally more expensive due to the pavement repair works that are required following testing.

The Falling Weight Deflectometer (FWD) test measures a pavements bearing capacity under load by measuring the vertical deflection. The magnitude, duration and area of the impulse load is calibrated to reflect the loading effect of a standard axle. As FWD testing in non destructive, this method is commonly adopted in practice to assess the in service structural integrity of a pavement.

The key information obtained from the FWD testing is the deflection bowl. The data obtained from the deflection bowl provides invaluable insight into the performance and structural capacity of a pavement.

2.3.2 Structural Number

The structural number (SN) was originally determined with the help of the American Association of State Highway Officials (AASHO) in order to provide a parameter that would assist in determining the overall strength of the pavement. The strength of the pavement is highly dependent on the overall subgrade support, thus the development of the modified structural number (SNC). Use of the SNC has since become the preferred way of describing the strength of the pavement due to its inclusion of the effect of the subgrade.

The literature review revealed numerous methods that are available for determining the SN and SNC of a pavement from various parameters of the deflection bowl. As discussed by Schonoor and Horak 2012, SNC is calculated via equation (2-**14**) which includes the effect of the subgrade. Determination of the subgrade structural number (SNSG) referred to by Schonoor and Horak 2012 is evaluated via equation (2-**15**).

$$SNC_i = SN + SNSG \tag{2-14}$$

$$SNSG = -0.85(\log CBR)^2 + 3.51(\log CBR) - 1.43 \tag{2-15}$$

Where CBR is the California Bearing Ratio of the subgrade expressed in percent.

These two (2) governing equations were adopted as the basis for determining the SNC.

Schonoor and Horak 2012 referred to an analysis completed by Rhode where Jameson's and Rhode's methods demonstrated improved correlation between the SNC and total pavement response. These two (2) methods were chosen to assess the strength of the subject pavements in this project. For comparison purposes, Paterson's, referred to in Austroads (AP-T159/10), was also included in the analysis. Each of these methods are detailed below.

Rhode's

Rhode's is applicable when the pavement thickness is known and the SN is determined from the Structural Index of the Pavement (SIP) and the Structural Index of the Subgrade (SIS) parameters which in turn utilises various aspects of the deflection bowl. In developing equations **(2-16)** and **(2-17)** Schonoor and Horak 2012 report that Rhode had found a correlation between the pavement subgrade response and the results of surface deflection at an offset of 1.5 times the pavement thickness from the applied load.

$$SIP = D_0 - D_{1.5Hp} \tag{2-16}$$

$$SIS = D_{1.5Hp} - D_{1.5Hp + 450} \tag{2-17}$$

Using the SIP and SIS parameters, the SN and subgrade modulus (E_{sg}) can be calculated the following equations:

$$SN = a0\ SIP^{a1}\ HP^{a2} \tag{2-18}$$

$$E_{sg} = 10^{a3}\ SIS^{a4}\ HP^{a5} \tag{2-19}$$

where

D_0 = peak surface deflection measure (in microns) under a standard 40kN FWD load. This is equivalent to the old Benkelman beam testing method.

$D_{1.5Hp}$ = surface deflection measure (in microns) at an offset of 1.5 times the pavement thickness (Hp) under a standard 40kN FWD load.

$D_{1.5Hp\ +450}$ = surface deflection measure (in microns) at an offset of 1.5 times the Hp + 450mm under a standard 40kN FWD load.

a0, a1 and a2 = Rhode's SN-SIP relationship coefficients as shown in **Table 2-8** below.

a3, a4 and a5 = Rhode's E_{sg} - SIS relationship coefficients as shown in **Table 2-9** below.

Table 2-8 Coefficients for SN-SIP Relationship (Schnooor and Horak, 2012)

Surface Type	a0	a1	a2
Surface seals	0.1165	-0.3248	0.8241
Asphalt concrete	0.4728	-0.4810	0.7581

Table 2-9 Coefficients for E_{sg} - SIS Relationship (Schnooor and Horak, 2012)

Surface Type	a3	a4	a5
HP≤380mm	9.138	-1.236	-1.903
380mm<HP≤525mm	8.756	-1.213	-1.780
525mm<HP	10.655	-1.254	-2.453

Jameson's

Jameson's method only requires surface deflection results from FWD testing in order to determine the SN. The deflection results required in equations (2-**20**) and (2-**21**) are expressed in microns under a standard 50kN load.

$$SN = 1.69 + 842.8/(D_0 - D_{1500}) + 42.94/D_{900} \tag{2-20}$$

$$\text{Subgrade CBR} = 3.264 - 1.018 \log(D_{900}) \tag{2-21}$$

where

D_{900} = surface deflection measure (in microns) at an offset of 900mm from the centre of loading

D_{1500} = surface deflection measure (in microns) at an offset of 1500mm from the centre of loading

All other parameters as previously defined.

Paterson's

As defined in Austroads (AP-T159/10), Paterson's method for cemented or bitumen stabilised pavements is described by equation (2-**22**):

$$SNC_i = 2.2 \times D_0^{-0.63} \tag{2-22}$$

where

SNC_i = is the modified structural number of the pavement at its current age

Austroads (AP-T159/10), also discussed the strength ratio of a pavement based on SNC_i/SNC_0. This ratio is to be used to a the dependent variable in estimating the structural deterioration of the pavement at each site. It is also noted that the SNC_0 can be estimated from the SNC_i, current pavement age (AGE_i) and the original design life (DL) via the relationship:

$$SNC_0 = SNC_i/0.96[2\text{-}\exp(0.33 \text{ x } AGE_i/DL)] \quad (2\text{-}23)$$

2.4 Construction Methodology

Construction methodology can have a significant impact on the as constructed performance of the pavement. Poor techniques of lack of attention to detail can be the difference between a pavement exceeding or failing to reach its design life. It is therefore crucial that specifications and guidelines that have been developed over the years followed. When designing a pavement it is beneficial for the designer to have an understanding of how the works will be constructed and an appreciation for potential construction issues that may arise. This will provide the designer with a sound platform for ensuring the appropriate amount of tolerance is incorporated into designs.

Likewise it is also important for construction supervisors to have a basic understanding of design requirements. Together, a pavement can be designed in a manner that caters for the construction environment, resulting in a pavement be constructed in accordance with the design intent.

2.5 Pavement Profiles, Specifications and Standards

Specifications have been continuously compiled and modified over the years and provide guidance for pavement design, construction and materials. In the Townsville Region, Austroads is considered to be the overarching specification/authority for pavement design standards with individual authorities (Department of Transport and Main Roads (DTMR), Townsville City Council (TCC)) compiling their own supplements which modify particular criteria to better suit local conditions.

In 2007, the Institute of Public Works Engineering Australia (IPWEA) and Standards Australia engaged the National Building Specification, NATSPEC, to develop and distribute what is known today as the AUS-SPEC Development Specifications. Similar to Austroads supplements, local authorities, including TCC, modify particular aspects to better suit the local conditions.

CHAPTER 3 - METHODOLOGY

3.0 Introduction

This chapter will go on to outline the process for site selection, collation of required data, testing and analysis necessary to justify the most cost effective pavement reconstruction / rehabilitation profile for the Townsville Region. Limitations due to the proposed methodology of the project are also discussed.

3.1 Limitations

This projected is limited to analysing pavement profiles adopted for reconstruction / rehabilitation works that were completed under traffic at four (4) sites around Townsville. There is reliance upon the accuracy of information sourced with assumptions note as required. Subsequently, findings over this analysis will be limited a profile type that has previously been adopted.

Variance of reconstruction / rehabilitation profiles adopted within the Townsville Region are also limited due to availability of materials, equipment and TCC's preferred methodology. Pavement analysis will be undertaken with the aid of computer software, CIRCLY. A brief background and summary of CIRCLY's limitations are provided below in Section 3.1.1.

3.1.1 CIRCLY

CIRCLY is a linear-elastic modelling program that incorporates the mechanistic method to assess a pavements structural integrity based on various performance criteria. The latest version of CIRCLY (5.1) is based on methods detailed in Austroads (2010, AGPT02/10), however as noted in Section 2.2.7, these changes do not affect the pavement modelling approach of CIRCLY.

3.2 Site Selection

Local knowledge and consultation with TCC staff from design and construction departments and staff of Northern Pavement Consultants (NPC) identified various sites around Townsville that had been reconstructed within the past ten (10) years. When finalising four (4) sites for this analysis, three (3) key criteria were adopted, namely;

- each site should have a varying pavement profile;
- traffic loads / volumes should be similar;
- construction works were completed under traffic.

The purpose behind the above criteria was to maintain a holistic view and not disregard a possible profile on the basis of constructability, costs or similar, in order to understand the benefits and impacts associated with various profiles. It is considered that the adoption of various profiles will provide a suitable basis for a cost-benefit analysis due to the variance in construction methodology, duration, material and resources associated with the reconstruction / rehabilitation works.

Sites with similar traffic volumes will provide a reasonable constant in relation to the magnitude of traffic management and social impacts. Similar traffic loads will also give insight into the performance of varying pavement profiles adopted for reconstruction / rehabilitation in the Townsville Region.

From initial investigations, it is understood that various testing had been conducted prior to the commencement of works for the selected sites described below in Section 3.2. A review of these test results are anticipated to allow an informative performance comparison assessment to be investigated. Further testing of the reconstructed / rehabilitated works will provided confirmation of the proposed design and calibration of the in service pavement analysis. In turn, this will lead to a cost versus performance assessment, yielding the overall cost effectiveness of the reconstructed profile.

Insight into the construction standards achieved, i.e. compaction effort, will provide a discussion point into the importance of construction standards and pavement performance / life.

Sections 3.2.1 to 3.2.4 provides a brief summary of the sites selected and the pavement profile that had been adopted for the rehabilitation / reconstruction works. At present, in depth details surrounding the design, traffic volumes, construction methodology, etc are still unknown, however collation of data outlined Section 3.3 will expose these unknowns. **Figure 3-1** provides an overview on the location of each site within Townsville (Google Earth, 2013, Queensland Globe, 2014).

Figure 3-1 Overview of site locations across Townsville (Google Earth, 2013, Queensland Globe, 2014)

3.2.1 Bamford Lane (Mill Drive to Dalrymple Road)

Bamford Lane is located in the suburb of Kirwan and is categorised as a trunk (major collector) road within Townsville. This portion of Bamford Lane (Mill Drive to Dalrymple Road) is a two-way (single lane in each direction, 3.5m wide) road that is separated by a large central landscaped median and is approximately 600m in length. It is also noted that this portion of the carriageway corridor contains a parking lane, 3.5m wide, adjacent each traffic lane. **Figure 3-2** below provides an aerial view of this site (Google Earth, 2013, Queensland Globe, 2014).

Initial investigation into the reconstruction / rehabilitation works undertaken at this site indicated that a full reconstruction, with a profile comprising of cement treated sub-base (CTSB), cement modified base (CMB) and asphalt surfacing was undertaken.

Figure 3-2 Bamford Lane (Mill Drive to Dalrymple Road) site (Google Earth, 2013, Queensland Globe, 2014)

3.2.2 Woodlands Service Road

Woodland Service Road is located in the suburb of Deeragun and provides access from the Bruce Highway to various commercial outlets and residential developments. The service road is a one-way carriageway that is approximately 5.0m wide (one-way cross fall) and is 240m in length. **Figure 3-3** below provides an aerial view of this site (Google Earth, 2013, Queensland Globe, 2014).

Initial investigations revealed that this site was rehabilitated via in-situ stabilisation using foam bitumen. In the Townsville Region, use of this technique has been limited and therefore provides the perfect opportunity to assess and compare its performance against the more commonly adopted reconstruction / rehabilitation methods.

Figure 3-3 Woodlands Service Road site (Google Earth, 2013, Queensland Globe, 2014)

3.2.3 Hugh Street (Bayswater Road to the Lakes turn off)

This portion of Hugh Street (Bayswater Road to the Lakes turn off) is located in the suburb of Currajong and provides access to various commercial outlets including the ‘Lakes’ precinct. The road is a four-way (two lanes, each 3.5m wide, both directions), approximately 360m in length and categorised as a trunk (major collector) road in the Townsville Region. **Figure 3-4** below provides an aerial view of this site (Google Earth, 2013, Queensland Globe, 2014).

Initial investigations revealed this site was reconstructed with a profile similar to that adopted for the Bamford Lane site, namely CTSB, CMB and an asphalt surfacing. Although similar to the Bamford Lane site, performance analysis of this pavement will provide an ideal comparison of the cost effectiveness in adopting a CTSB, CMB profile. Further, any cost variance between the two (2) sites is anticipated to highlight possible construction issues and / or efficiencies that have been learnt over time.

Figure 3-4 Hugh Street (Bayswater Road to the Lakes turn off) site (Google Earth, 2013, Queensland Globe, 2014)

3.2.4 Palmerston Street (Hugh Street to Kings Road)

Works undertaken in this portion of Palmerston Street (Hugh Street to Kings Road) were predominately located in the suburb of Pimlico and can be categorised as a minor collector road. The carriageway is two-way (single lane in each direction) with approximately 3.5m lanes, 3.0m parking lane (each side) and 800m in length. **Figure 3-5** below provides an aerial view of this site (Google Earth, 2013, Queensland Globe, 2014).

Initial investigations revealed that this site was rehabilitated via in-situ stabilisation using cement with isolated sections of sub-base fully reconstructed. Analysis of this site is expected to provide a suitable comparison of in-situ stabilisation methods with the Woodlands Service Road. Similar traffic volumes are also anticipated between this site and the Woodlands Service Road site.

Figure 3-5 Palmerston Street (Hugh Street to Kings Road) site (Google Earth, 2013, Queensland Globe, 2014)

3.3 Data Collation

As noted in Chapter 2, pavement design requires a variety of inputs, subsequently resulting in the collation of a large quantity of data. Sections 3.3.1 to 3.3.4 below outline the type of data required to complete this analysis.

3.3.1 Pavement Design and As Constructed Data

Pavement design and as constructed records are generally available from the local Council, subsequently this information will be sourced from TCC. It is also considered that additional background design information can be sourced from NPC as the pavement design consultant engaged by TCC. Information to be collated includes;

- design pavement profile;
- as constructed pavement profile which is anticipated to reflect any unforseen issues experienced during construction;
- results of testing undertaken prior to pavement design and during construction.

Collation of this information will provide the opportunity to back-analyse present pavement performance and predicted remaining pavement life. Subsequently this will give insight into the cost effectiveness of the adopted pavement profile.

Should as constructed data not be available, it will be assumed that the pavement was constructed as per the design. Back-analysing the pavement performance will allow the design pavement profile to be modified to establish a correlation between the current pavement performance testing and the actual pavement profile constructed.

3.3.2 Traffic Data

This information is typically collect over time by the local Council to assist with asset management and infrastructure planning. Subsequently, data for this project will be obtained from TCC as it is understood that the sites listed above in Section 3.2 have historic data prior to reconstruction / rehabilitation works being undertaken and recent data following the completion of works. Depending on currency of the traffic data on record, more recent data may require collecting. This will be undertaken with assistance from TCC via installation of pneumatic tubes. This is in accordance with TCC's typical method of traffic data collection and will provide information in relation to traffic volume, vehicle class and speed.

Using methods detailed in Austroads (2012, AGPT02/12), this traffic data can be analysed to determine current and future design traffic, growth rates, heavy vehicle percentage and average speed. It is important to understand the original assumptions of the design in order to compare against in-service performance and actual unforseen conditions experienced during construction. This will all assist with understanding a complete cost per profile.

3.3.3 Construction Details

Construction methodology / efficiency can greatly affect the costs associated with such works. Subsequently, construction data will be sourced from TCC's records an analysed in order to gain an understanding of the approach and potentially difficulties experienced. The type of data, if available, to be sourced includes;

- construction duration;
- traffic management practices implemented;
- construction methodology or program
- plant and procurement;
- results of testing undertaken during construction, i.e. compaction, material quality, etc.

Where records are unavailable, it is anticipated that discussions with TCC staff involved on these works may be able to provide valuable information in relation to site issues, changes to original works programs, etc. If unknowns are still present following data collation and discussions, assumptions will be made based on best practices.

3.3.4 Costs

Project cost are proposed to be obtained from TCC records. The type of costs to be acquired include;

- design costs
- construction costs
- variations associated with design and construction
- traffic management costs
- project coordination costs (if not factored into construction cost rates)
- maintenance costs (cost prior to and after reconstruction / rehabilitation)

It is also important to search records for public complaints and time spent by Council officers dealing with these complaints as this will provide a holistic view in relation to costs associated with completing reconstruction / rehabilitation works under traffic. Collation of these types of cost will allow a value to be placed on public perception to roadworks and provide a basis of comparison as to whether it is more cost effective to have a larger upfront cost that reduces construction time and potentially resulting in few complaints, or lower upfront costs that have extended construction times and potentially more complaints.

Assumptions will be required where information is not available and it is proposed that these assumption will be validate from average costs of importation obtain or via use of typical industry rates within the Townsville Region. With all costs collated and analysed, a unit rate, i.e. dollars per meter squared ($\$/m^2$) or dollars per meter ($/m), based either on the entire project cost divided by the area of works or broken down into various components, will be established. It is important that a component breakdown of costs has a common denominator to ensure a like for like comparison is achieved.

3.4 In-service Testing

Further to the collation of data noted above in Section 3.3, testing to assess the pavements' in service performance is required. This will assist in understanding the benefit of the adopted profile from a cost versus pavement life perspective.

Falling Weight Deflectometer (FWD) testing has been adopted as the preferred testing method due to its non-destructive nature and ability to back-analyse the pavement profile. NPC have the FWD equipment available and will undertake this testing.

It is proposed that FWD testing at each location is undertaken at 20m centres of both the inner and outer wheel paths. Testing locations should be staggered between the inner and outer wheel paths in order to provide a triangular grid pattern over the extent of the works, refer to **Figure 3-6**. This staggered approach is anticipated to map the current performance of the pavement with a reasonable level of confidence.

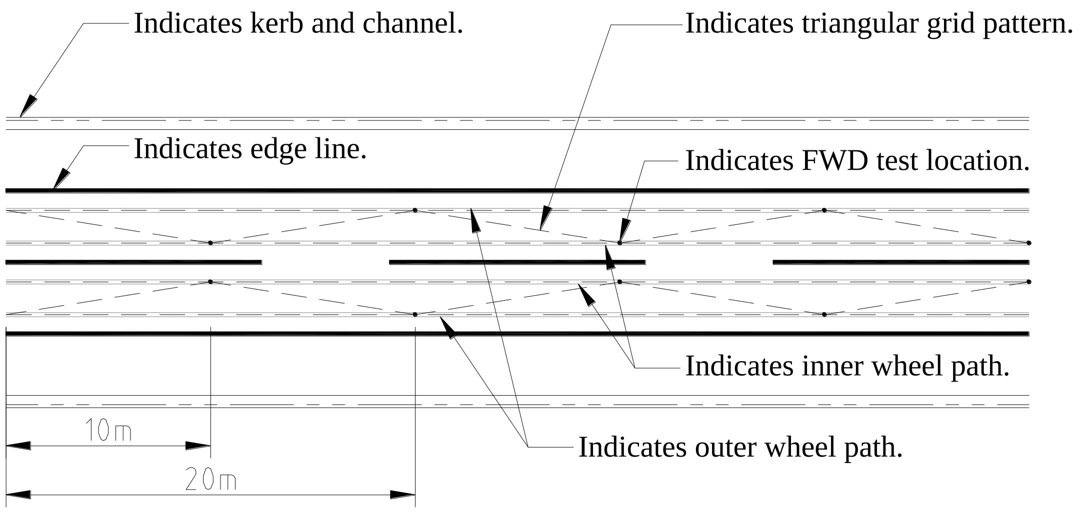

Figure 3-6 FWD proposed testing layout

3.5 Pavement Analysis (CIRCLY)

Back-analysis of the pavement performance will provide a common basis for comparison between each of the profiles. The pavements' current in-service age (as opposed to constructed age), performance and life expectancy is the type of information that will be sort from the back-analysis. This information is expected to assist in determining a weighted cost that is proportioned base on the calculated performance and life of the reconstructed / rehabilitated pavement.

Back-analysis will be undertaken with the aid of computer software, namely CIRCLY. Although CIRCLY has been updated to reflect Austroads (2010), all parameters and criteria adopted for the back-analysis will be in accordance with the later release of Austroads (2012, AGPT02/12) which will ensure compliance with TCC and industry standards.

Where FWD testing was undertaken prior to reconstruction / rehabilitation works being completed, back-analysis of the existing pavement performance is expected to provide insight into the in-service conditions of the subgrade. Results of this analysis is only anticipated to provide a discussion point associated with the impact that reconstruction / rehabilitation works have on subgrade support.

Visual analysis may also be undertaken as a validation/calibration of the performance criteria adopted in the CIRCLY analysis. If required, visual analysis will be undertaken in accordance with TCC's newly developed scoring weighted method that is based on the laser survey and assessment methodology. Further details surrounding this method will be outline as required.

3.6 Pavement Evaluation

The pavement evaluation is proposed to be undertaken via a structural deterioration model that incorporates the use of the pavements structural number. This is expected to provide a reasonable basis in order to compare the remaining service life of each profile type. However, should time not allow for this assessment to be completed a simplified assessment will be completed where the allowable number of repetitions of the load will be determined from which a theoretical expected design life can be calculated. Although not as in depth and detailed, this simplified analysis is expected to provide grounds for a reasonable comparison of the different pavement profiles.

3.7 Cost-Benefit Analysis

The purpose of a cost-benefit analysis is to provide a basis for comparing the adopted profiles of each site and provide justification to the discussions and findings of this project. With collation of costs and findings of the pavement analysis, a comprehensive cost-benefit assessment can be undertaken and provide valuable insight into a cost effective pavement reconstruction / rehabilitation profile for the Townsville Region.

This analysis is anticipated to provide answers to the following questions:

1. Does the type of profile adopted provide any maintenance benefits?
2. What is the cost impacts associated with construction durations versus public perception / complaints?
3. Is there a substantial cost benefit between reconstruction versus rehabilitation?
4. Of the profiles analysed, which one provides the greatest overall cost-benefit?

CHAPTER 4 - RESULTS AND DISCUSSION

4.0 Introduction

This chapter will outline the analysis undertaken and present the findings of this project. It will also provide discussions in relation to necessary assumptions and analysis simplifications that were required.

4.1 Data Collation

As noted in Section 3.3 information was sort from TCC and NPC in relation to:

- Pavement designs and parameters;
- Pavement as constructed records;
- Traffic data;
- Construction details, and;
- Costs.

Between TCC and NPC pavement design and parameters adopted in these design were obtained for all sites apart from Woodlands Service Road. The original design proposed by NPC consisted of cement stabilised profile, however during the construction phase, a variation request was proposed by the Contractor and the Council Project Manager at the time to adopt a foam bitumen stabilised profile. Consequently, even after contacting the Contractor, no design information had been kept and was therefore unavailable.

All of the construction works were undertaken by TCC's construction crew, apart from the in-situ stabilised portions which were supervised by site foreman, and in general as constructed information was extremely limited. Discussions with TCC construction crew members suggested that all works had been constructed in accordance with the designs, subsequently the design profiles documented on the construction drawings were assumed to be reflective of the as constructed pavement. The exception to this was an as constructed mark-up of unsuitable subgrade dig outs for the Palmerston Street site.

Obtaining traffic count data was an easy process as TCC had a reasonable program where data was collected periodically via the use of pneumatic tube counters. Data at each site was available as far back as the year 2000 and beyond, however not all sites had had counts conducted. This was not considered to be an issue as the data available was interpolated based on past and present trends to obtain relevant anticipated design loadings.

Detailed construction information was limited, including testing results, however the overall construction durations at each site were estimated based on the dates associated with the project finance expenditure records. As a result of the limited construction procedures, it has been assumed that best practices were adopted during the construction phase.

The project finance expenditure records provided be TCC were quite detailed and allowed for easy extraction of costs associated with various components of the project, i.e. design, survey, traffic management, construction, etc. The exception to this was the Hugh Street site where works beyond the boundaries of the subject site were undertaken in conjunction with works within the subject site boundaries. Therefore the cost for this project were pro-rated based on the proportional construction areas within and beyond the bounds of the subject site.

4.2 Deflection Analysis

The deflection bowl is defined following FWD testing and provides valuable insight into the performance of the pavement. Deflection bowl parameters are commonly adopted to analysis the structure performance of the pavement and estimate the as constructed layer modulus and structural number. Subsequently remaining service life (RSL) of the pavement can be predicted, giving asset managers the tools required to program and prioritise future works.

4.2.1 FWD Testing

FWD testing was completed at each site at 25m staggered intervals along each wheel path of each traffic lane as opposed to the original proposal of 20m staggered intervals. Staggering of the test locations effectively provided deflection results every 12.5m along each lane. **Figure 4-1** provides a diagrammatic summary of the testing pattern adopted. A load of 50kN, which represents a tyre contact pressure of 707kPa, was targeted during testing with a tolerance of +/- 5kN. Results were then normalised to 50kN by assuming a liner relationship.

Testing was conducted in July 2014 during the night, 8pm to 6am, to ensure as minimal disruption to traffic as possible. This resulted in testing being undertaken when the pavement was less likely to be affected by temperature, potentially showing bias towards the actual pavement performance. Testing during the middle of the day when temperatures are higher may have resulted in different results. The tabulated results of the FWD testing are available in **Appendix B**.

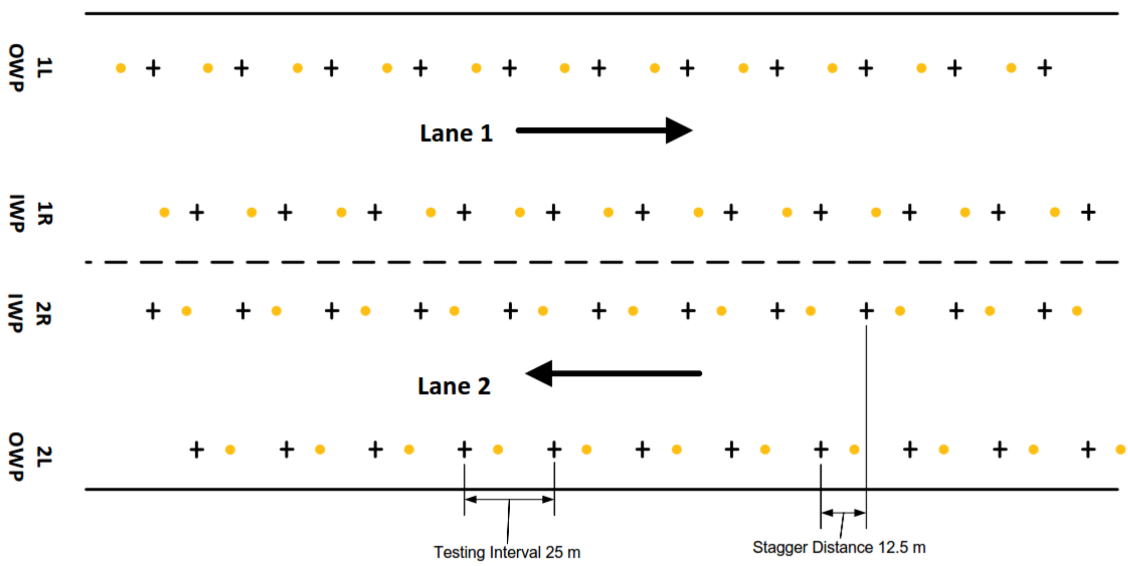

Figure 4-1 Typical FWD staggered testing layout.

4.2.2 Back-analysis of Layer Modulus

NPC have spent considerable time, resources and money in developing their own graphical user interface (GUI) program to back-analyse each pavement layer's modulus for each FWD test location. This program has been through various peer reviews and uses the background engines of industry approved pavement model programs, such as CIRCLY, to complete the analysis grunt works. Subsequently this GUI has been accepted as a suitable method for estimating the layer modulus and due to intellectual property rights, further details of this program cannot be discussed. To save time, as there were over 300 test locations, NPC used this program to undertake the back-analysis of each point and estimate the as constructed modulus of each layer at each test location. The raw results of this analysis is available in **Appendix B**.

As with the design process, a simplified model of the pavement profile is required and is extremely similar to that adopted for design purposes. The major difference is the inclusion of upper and lower (as required) subgrade layers, refer to **Figure 4-2** for a diagrammatic representation of the simplified pavement profile model.

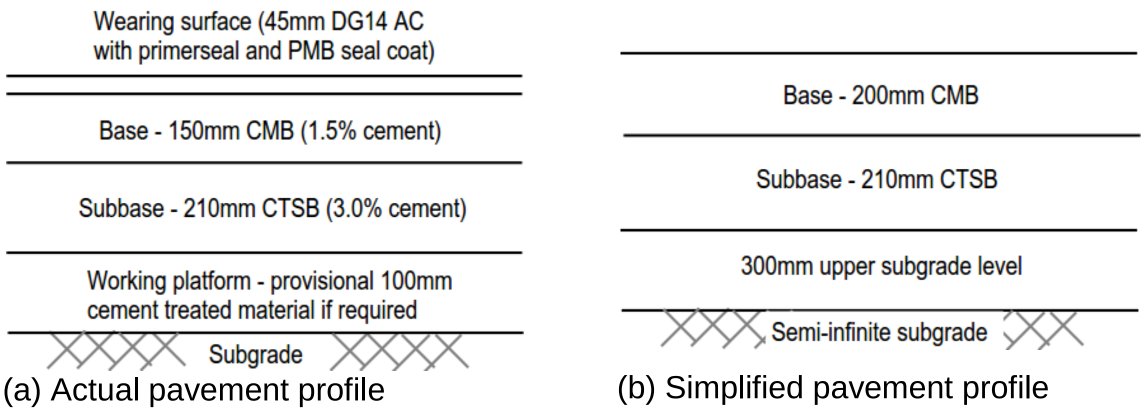

Figure 4-2 Typical pavement profile simplification adopted for back-analysis.

The inclusion of an upper subgrade level provides an allowance for the possibility of a working platform or unsuitable subgrade replacement dig out that may have been undertaken during construction and not picked up with as constructed records. For the Palmerston Street site, an additional 500mm lower subgrade was also incorporated into the model as it was known that unsuitable replacement depths varied from 100mm to 400mm. The semi-infinite subgrade layer aligns with the recommendations of Austroads.

The back-analysed modulus at each of the test locations for each of the pavement layers at each site was plotted against the road chainage. **Figure 4-3** to **Figure 4-6** are the plots of the average modulus for each layer at the four (4) sites. Plots of the individual layer moduli's are presented in **Appendix C**.

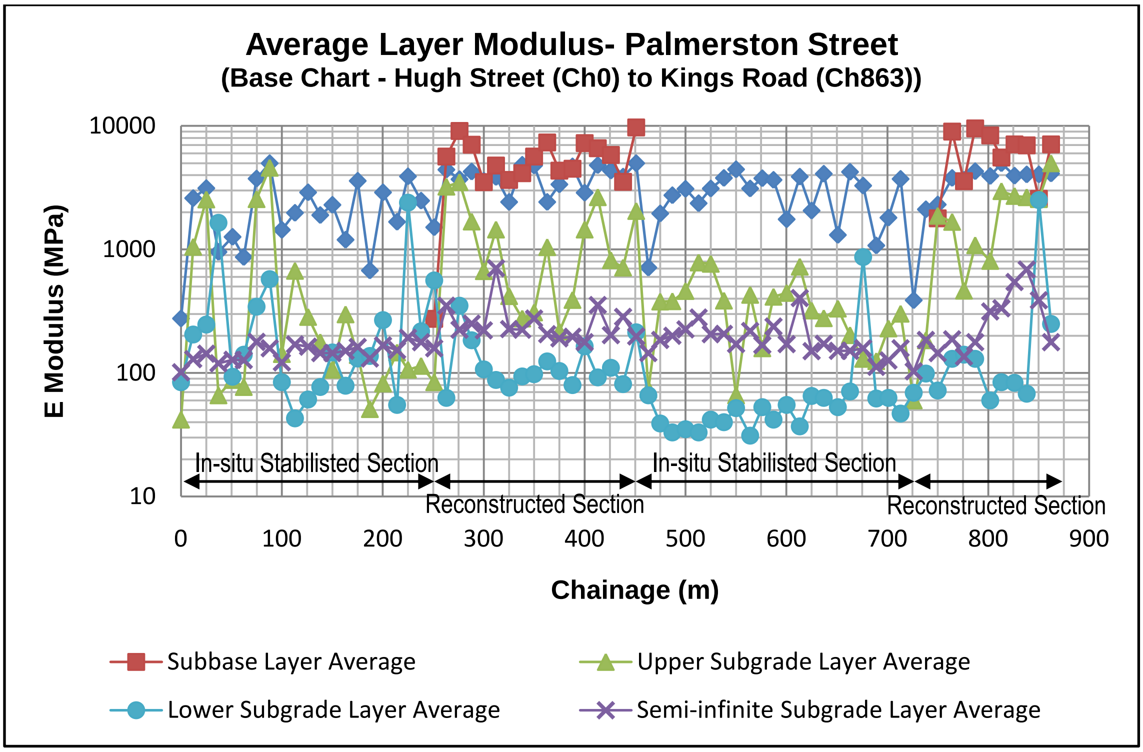

Figure 4-3 Palmerston Street average layer modulus.

Key observations from the Palmerston Street modulus plots include:

- Traverse joints in pavement or change in pavement profile are easily identified.
- There is a greater variance in the modulus of the rehabilitated (in-situ stabilised) profile as opposed to the reconstructed. There are two (2) factors that are considered to contribute to this variance. The first is associated with the achievable in-situ mix ability of the stabilising agent with the second linked to grading envelope and\or quality of the existing gravel material. This is in stark contrast to the more uniform modulus of the of the reconstructed sections were the CMB material has been plant mixed.

- Variance between inner and outer wheel paths within the same lane, not to mention between lanes is evident and emphasised more so in the in-situ stabilised sections. As definitive construction methodology was not available, it is concluded that the variance in the in-situ sections is attributed to the location of the stabilising machines longitudinal passes. Consistent overlap of the longitudinal path would result in double the amount of binder and explain the higher modulus results. On the other hand, lower modulus result may have been the result of inefficient overlap on the longitudinal runs.

- Of the 140 test locations, only a hand full of points fell within the target modulus range of 1500 MPa +/- 250 MPa for the base course where in comparison there were only a few points within the subbase layer that failed to achieve the minimum design target modulus of 3000 MPa. No correlation was evident as all the points that failed to achieve the subbase layer minimum target were within the reconstruction sections were the base layer modulus results generally exceed the design target envelope.

- Considerable modulus variance in the upper subgrade layer was present and is considered to be reflective construction tolerances and replacement dig outs of unsuitable subgrade material. Results became more consistent in the lower subgrade layer and even better again at the semi-infinite layer.

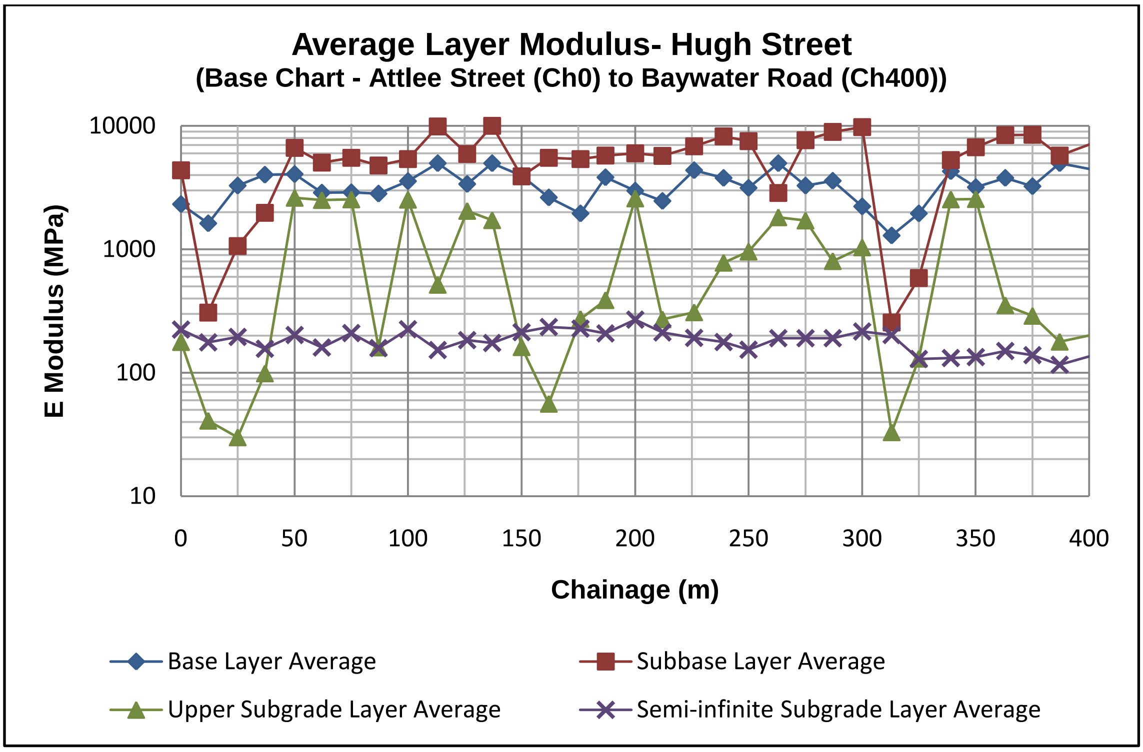

Figure 4-4 Hugh Street average layer modulus

Key observations from the Hugh Street modulus plots include:

- Unsuitable areas of upper subgrade are easily detected, i.e. approximate chainages of 25, 110, 160 and 310 and are areas that should have been excavated and replaced with a working platform layer as per the design. Without as constructed records to compare against, the back-analysis would suggest that working platforms were installed at approximate chainages of 50-75, 100, 125, 200, 260 and 335.

- There is correlation between the poor upper subgrade layer modulus and the decrease in modulus of the upper layers. This would suggest inefficient compaction of the subbase and base layers resulting from the founding layer's (upper subgrade) inadequate ability to provide the necessary support during compaction.

- The semi-infinite subgrade layer is relatively consistent, suggesting the natural material is fairly homogenous.

- The base course layer is general greater than the design target envelope of 1500 MPa +/- 250 MPa, suggesting that this layer is performing more like a bound material rather than modified. Similarly the subbase layer typically exceeds the minimum design target modulus of 3000 MPa, suggesting this layer is performing as intended.

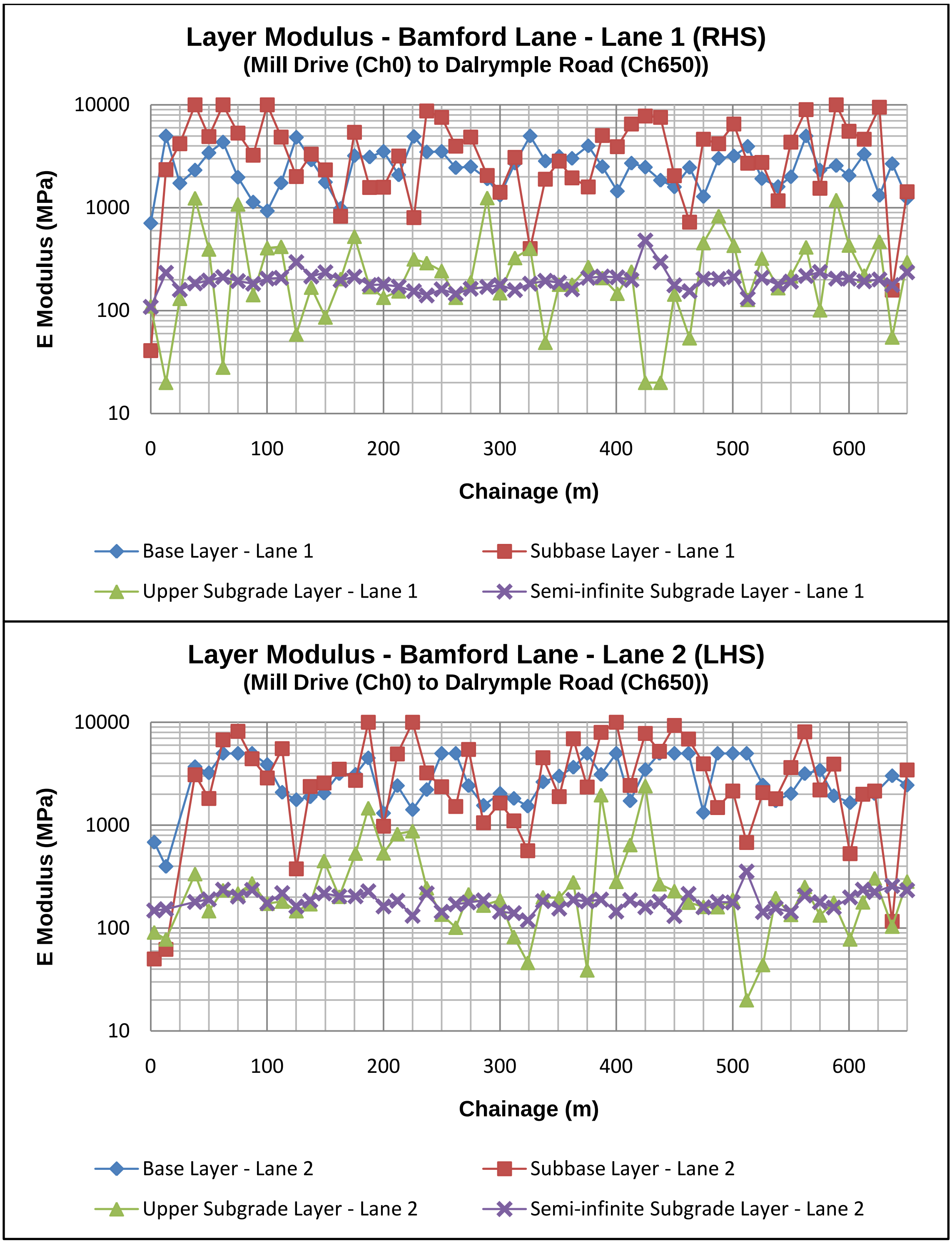

Figure 4-5 Bamford Lane layer modulus

Due to the substantial size of the landscaped median that seperates the two (2) lanes, the layer modulus plot analysed as individual lanes as opposed to the average across the carriageway. Key observations from the Bamford Lane modulus plots include:

- For Lane 2, it is evident where working platforms appear to have not been constructed within the upper subgrade layer, subsequently impacting the effective compaction of the upper layers. The upper subgrade layer of Lane 1 is considerably erratic, suggesting that majority of the subgrade at the time of construction was unsuitable and a working platform should have been adopted.
- Approximately 80% of base course layer modulus results greater than the design target envelope of 1500 MPa +/- 250 MPa, suggesting that this layer is performing more like a bound material rather than modified. Contrastingly approximately only 50% the subbase layer typically moduli exceeds the minimum design target modulus of 3000 MPa, suggesting this layer may already be performing as a post-cracked pavement. As the pavement has only been in service for approximately 4-5 years, cracking of the subbase layer may be a result of construction practices outside the norm, i.e. material not placed and compacted within allowable working time or the layer may have been trafficked sooner than the minimum recommended non-trafficked time frames.
- The semi-infinite subgrade layer is relatively consistent, suggesting the natural material is fairly homogenous.

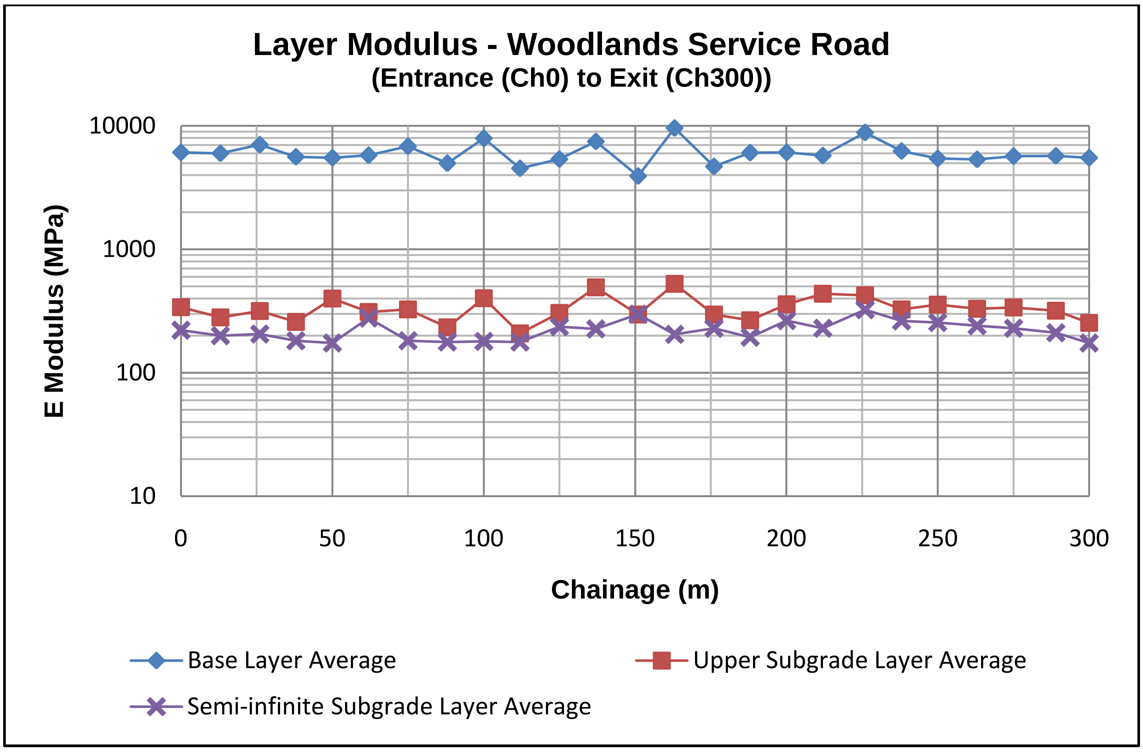

Figure 4-6 Woodlands Service Road layer modulus

Key observations from the Woodlands Service Road modulus plots include:

- Results across the board are fairly homogenous.
- With the extremely limited data surrounding the design and construction methodology, the results of the back-analysis suggest that the design and construction have been undertaken in accordance with documented practices. Consequently a consistent product has been provided.

Apart from the Woodlands Service Road site, **Figure 4-3** to **Figure 4-6** are noticeably noisy. To reduce this noise, a standard deviation envelope was established for each layer with all points outside this envelope disregarded. From the remaining points, the average modulus for each layer was determined and this value was adopted for further analysis via CIRCLY.

Table 4-1 provides a summary of this exercise and the average modulus for each layer that was adopted in the CIRCLY analysis.

Table 4-1 Summary of modulus noise reduction

Site	Direction of Travel	Statistic	Pavement Layer Modulus (MPa)					
			Combined Base Reconstructed	**Combined Base In-situ Stabilised**	**Subbase**	**Upper Subgrade**	**Lower Subgrade**	**Semi-infinite Subgrade**
Palmerston Street	East	1L Average	3311	2226	5064	814	458	188
		1R Average	4151	2509	5076	835	191	228
		Lane Average	3731	2368	5070	825	325	208
		Standard Deviation	1134	1596	3053	1332	896	168
	West	2L Lane Average	4231	2479	7503	1240	110	233
		2R Lane Average	3797	2836	5357	750	107	196
		Lane Average	4014	2658	6430	995	109	215
		Standard Deviation	1172	1462	3420	1521	124	146
	Overall	Site Average	3872	2512	5750	910	216	211
		Standard Deviation	1172	1462	3420	1521	124	146
		Upper Envelope Limit	5023	4041	9033	2337	863	368
		Lower Envelope Limit	2721	983	2467	0	0	54
		Average within envelope	**4245**	**2304**	**5381**	**440**	**108**	**173**
Hugh Street	South	1L Average	2520		4100	398		179
		1R Average	3323		4581	488		179
		Lane Average	2922		4341	443		179
		Standard Deviation	1637		3642	758		48
	South	2L Lane Average	3868		7549	1974		202
		2R Lane Average	3808		6524	1047		169
		Lane Average	3838		7037	1511		186
		Standard Deviation	1211		3582	1975		51
	Overall	Site Average	3374		5693	983		183
		Standard Deviation	1503		3837	1582		49
		Upper Envelope Limit	4877		9530	2565		232
		Lower Envelope Limit	1871		1856	0		134
		Average within envelope	**3321**		**5324**	**358**		**202**
Bamford Lane	North	1L Average	2498		3903	286		207
		1R Average	2761		4338	320		190
		Lane Average	2630		4121	303		199
		Standard Deviation	1131		2896	301		52
	South	2L Lane Average	3142		3833	346		201
		2R Lane Average	2894		3504	317		169
		Lane Average	3018		3669	332		185
		Standard Deviation	1393		2850	450		40
	Overall	Site Average	2821		3895	317		192
		Standard Deviation	1277		2868	380		47
		Upper Envelope Limit	4098		6763	697		239
		Lower Envelope Limit	1544		1027	0		145
		Average within envelope	**2578**		**3201**	**212**		**191**

Site	Direction of Travel	Statistic	Pavement Layer Modulus (MPa)					
			Combined Base Reconstructed	Combined Base In-situ Stabilised	Subbase	Upper Subgrade	Lower Subgrade	Semi-infinite Subgrade
Woodlands Service Road	West	1L Average	6079			340		229
		1R Average	6096			332		215
		Lane Average	6088			336		222
		Standard Deviation	1289			76		41
		Upper Envelope Limit	7377			412		263
		Lower Envelope Limit	4799			260		181
		Average within envelope	**5842**			**328**		**220**

From the above table and as observed in **Figure 4-3** to **Figure 4-6** average modulus for all CMB layers at each site is well above the target modulus of 1500 MPa +/- 250 MPa. As previously mentioned, this suggests that the layer is performing more like a bound layer (cement treated base (CTB)) rather than a modified layer as per the intent of the design. Subsequently this introduces the potential for reflective cracking to penetrate into the wearing surface of the pavement and accelerate the structural deterioration of the pavement by allowing the ingress of moisture into the underlying pavement layers and ultimately the subgrade.

4.3 CIRCLY Analysis

These days it is typical in the industry for pavement designs to be undertaken via the mechanistic approach with the aid of CIRCLY (or equivalent approved program), particularly when a pavement profile consists of a stabilised material. Due to issues surrounding the ability to accurately model thin asphalt layers via the mechanistic method, a simplified model of the profile was required. This simplification combined the thickness of the wearing surface with the base course layer and modelled with the parameters of the base course material. **Figure 4-7** depicts a typical model of a simplified pavement profile adopted for the design analysis. The simplified as constructed profile adopted was in accordance with **Figure 4-2**.

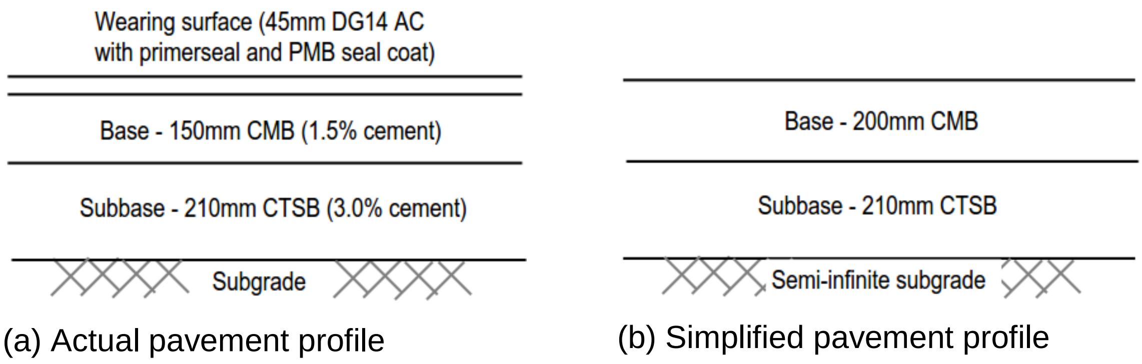

Figure 4-7 Typical pavement profile simplification for CIRCLY design analysis

An analysis, using CIRCLY, of the design reconstructed and rehabilitated profiles (hereinafter referred as "original designs/profiles") was undertaken to obtain a baseline comparison between the design intent and the as constructed profile. It was identified that these original profiles had been designed for a post cracked scenario were the following parameters had been adopted:

- Ev = 600 MPa with parameters as per Austroads (AGPT02/10) Clause 6.3 and a target UCS value of 1.5 MPa +/- 0.25 MPa for CMB materials.
- Ev = 500 MPa parameters as per Austroads (AGPT02/10) Clause 6.4.3 and a target UCS value of 3.0 MPa minimum for CTB and CTSB materials.

Although designed for posted cracked it is important to note the minimum cover over a CTSB (in accordance with Austroads, i.e. 0.75 x thickness of gravel material cover plus thickness of asphalt cover ≥ 175mm) has not been achieved hence the potential for reflective cracking to be observed within the wearing surface. However this risk has been reduced somewhat by the inclusion of a PMB seal and PMB AC wearing course, otherwise known as a Strain Alleviating Membrane Interlayer (SAMI).

4.3.1 Traffic Design Parameters

Traffic parameters for the original reconstruction and rehabilitation designs were obtained along with the expected design life and loading. This information is summarised below in **Table 4-2** and has been incorporated into the design analysis.

Table 4-3 details the new parameters adopted in the pavement performance assessment which account for the following:

- More recent traffic count data, collated via pneumatic tube counters, at the Bamford Lane and Woodlands Service Road sites;
- The average annual growth rate determined from past traffic count data collated over the previous ten (10) years;
- The average number of axles per heavy vehicle (NHVAG) was increased to 2.5 to align with the parameters Council are proposing in the new pavement design manual.
- In both scenarios, a Distribution Factor (DF) of 1 was adopted as each site.

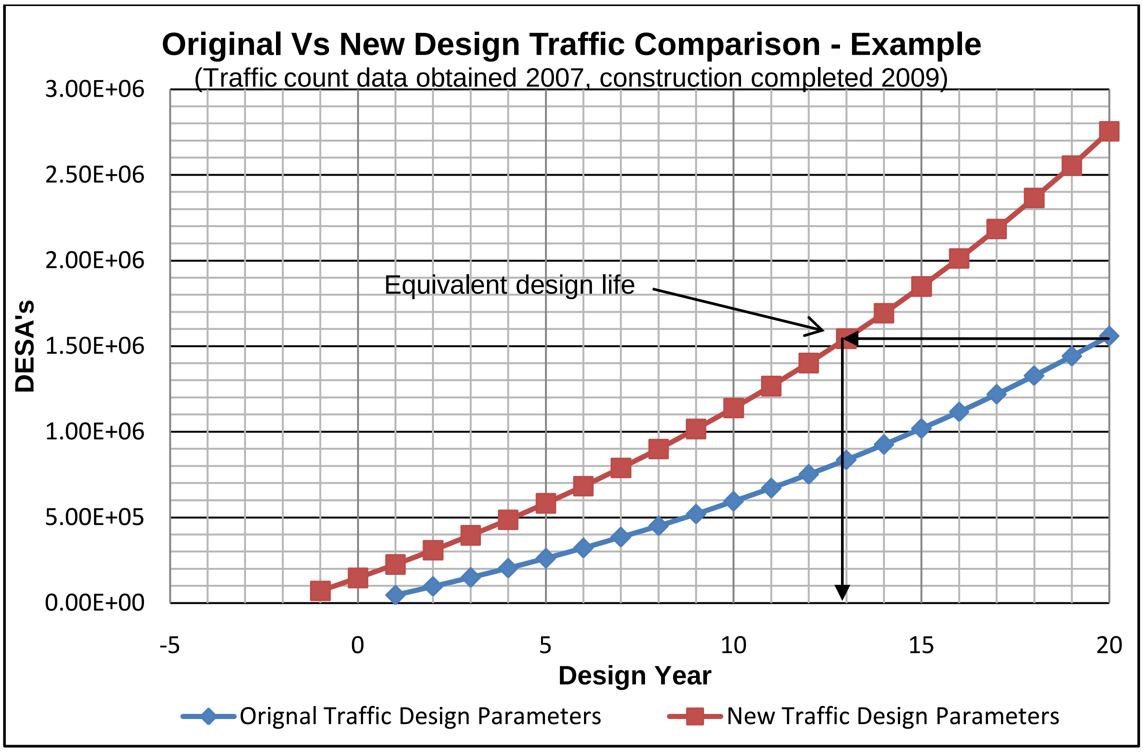

Figure 4-8 Example of the effect of modified traffic design parameters

During this assessment it was observed that on average there was a 53% increase in the Design Equivalent Standard Axles (DESA) which was attributed to the slight increase of the NHVAG parameter. To put this increase into perspective, the theoretical effect on pavement thickness and design life was investigated with the following noted:

- Based on the heavily trafficked empirical granular design chart (**Figure 2-5**) and a subgrade CBR 3%, the overall pavement thickness is required to increase by 15mm to 30mm.
- From **Figure 4-8** it can be seen that the equivalent design life of the pavement under the new parameters is approximately 13 years, representing a 7 year decrease to the original desired design life.
- This equivalent design life of the pavement under the new parameter guidelines is compounded by the fact that the original design was undertaken two (2) or more years in advance of the actual works being constructed. This theoretically suggests that in the pavements actual first year it is operating under third year or greater traffic loadings with the effective life of the pavement automatically decreased by the lapse in time between design and construction.

Subsequently this suggested that the original parameters and loadings adopted during the design were acceptable.

Table 4-2 Original traffic design parameters and design loading.

Road	**Year Constructed**	**Design Life (years)**	**One-way AADT**	**AADT Year**	**%HV**	**Annual Growth Rate**	**NHVAG**	**TLD**	**DESA**
Bamford Lane	2010	20	4344	2007	2.8%	2.0%	2.2	0.7	1.70E+06
Hugh Street	2012	20	10210	2010	4.5%	2.0%	2.2	0.7	5.10E+06
Woodlands	2009	20	3542	2007	7.3%	5.0%	NA	0.5	1.50E+06
Palmerston Street	2012	20	2800	2010	3.0%	1.0%	2	0.7	9.50E+05

Table 4-3 Traffic design parameters and design loading adopted for further analysis.

Road	Year Constructed	Design Life (years)	One-way AADT	AADT Year	%HV	Annual Growth Rate	NHVAG	TLD	DESA
Bamford Lane	2010	20	4752	2014	3.0%	2.0%	2.5	0.7	2.48E+06
Hugh Street	2012	20	10210	2010	4.5%	2.0%	2.5	0.7	7.98E+06
Woodlands	2009	20	2800	2008	4.0%	5.0%	2.5	0.7	2.56E+06
Palmerston Street	2012	20	2800	2010	3.0%	1.0%	2.5	0.7	1.31E+06

4.3.2 Material Parameters and Performance Criterion

Following is a summary of the parameters adopted for each site when undertaking the CIRCLY analysis of the design and as constructed profiles. Material parameters were in accordance with Austroad (AGPT02/12), namely:

Subgrade (upper, lower and semi-infinite):

- cross-anisotropic with a degree of anisotropy of 2;
- Poisson's ratio of 0.45 for semi-infinite and lower layers and 0.35 for upper layers;
- sublayering of the upper and lower layers;
- shear stress parameter of f = E_v / (1 + Poisson's ratio).

Modified material (CMB):

- cross-anisotropic with a degree of anisotropy of 2;
- Poisson's ratio of 0.35;
- sublayering;
- shear stress parameter of f = E_v / (1 + Poisson's ratio).
- E_v = 600 MPa;

- As constructed material was modelled as a bound material.

Bound material (cemented), pre-cracked:

- isotropic with a degree of anisotropy of 1;
- Poisson's ratio of 0.2;
- No sublayering;
- Design modulus of 3000 MPa and as constructed modulus equivalent to the site average within the standard deviation envelope.

Bound material (cemented), post-cracked:

- cross-anisotropic with a degree of anisotropy of 2;
- Poisson's ratio of 0.35;
- No sublayering;
- shear stress parameter of f = E_v / (1 + Poisson's ratio);
- E_v = 500 MPa.

FBS:

- isotropic with a degree of anisotropy of 1;
- Poisson's ration of 0.4;
- No sublayering;
- Design and as constructed modulus factored for temperature and rate of loading.

The fatigue criteria constant k was determined by re-arranging the performance criterion equations **(2-11)**, **(2-12)**, and **(2-13)** for the subgrade, bound (cemented) and foam bitumen stabilised (FBS) layers respectively. This rearrangement resulted in constant k being calculated via:

Subgrade (upper, lower and semi-infinite):

$$K = 9300 \times 10^{-6} = 0.0093 \quad (4\text{-}1)$$

Bound material (cemented):

$$(113000 / E^{0.804} + 191) \times 10^{-6} \tag{4-2}$$

FBS:

$$(6918(0.856\, V_b + 1.08) / E^{0.36}) \times 10^{-6} \tag{4-3}$$

where

E = modulus of material in MPa

V_b = percentage by volume of bitumen, i.e. 7% which is equivalent to twice the general design percentage of 3.5% by mass. This is a result of the typical density of granular material being around 2 tonne/m^3.

A fatigue criteria constant b of 7, 12 and 5 was adopted for the subgrade, bound and FBS materials respectively which is in accordance with the power function of each performance criteria equation. For each site a desired project reliability of 95% selected, resulting in a reliability factor (RF) of 1.

As there was no weigh in motion (WIM) data available for these sites, presumptive traffic multiplier factors were adopted from Austroads AGPT02/10. The values adopted were 1.1 (SAR5), 12 (SAR12) and 1.6 (SAR7) for FBS, bound materials, and subgrade respectively.

Table 4-4 to **Table 4-7** detail the CIRCLY input parameters adopted for the design and as constructed (both pre and post cracked scenarios) profiles for each site.

Table 4-4 Palmerston Street CIRCLY input parameters and assessment

Section Description	Thickness	Aniso/Iso	Modulus		Poisson		Shear (f)	Fatigue Criteria			Max Strain		Traffic Loading	
			Ev	Eh	vv	vh		RF	k	b	με	Location of strain	Allowable	DESA
Reconstructed Profile (Pre-fatigue cracking) - Design														
DG14 PBM AC (included in base layer)														
Base - Type 2.1 CMB (UCS 1.5±0.25 MPa)	170	Aniso	600	300	0.35	0.35	444.4	1	0.009300					
Subbase - Type 2.1 CTSB (UCS 3.0 MPa min)	200	Iso	3000	3000	0.2			1	0.000372	12	158	between the loaded wheels	2.89E+04	2.41E+03
Subgrade (CBR3.0)	Infinite	Aniso	30	15	0.45	0.45	20.7	1	0.009300	7	480	between the loaded wheels	1.02E+09	6.41E+08
Total	370													
Reconstructed Profile (Post-fatigue cracking) - Design														
DG14 PBM AC (included in base layer)														
Base - Type 2.1 CMB (UCS 1.5±0.25 MPa)	170	Aniso	600	300	0.35	0.35	444.4	1	0.009300					
Subbase - Type 2.1 CTSB (UCS 3.0 MPa min)	200	Aniso	500	250	0.35	0.35	370.4	1	0.009300	7				
Subgrade (CBR3.0)	Infinite	Aniso	30	15	0.45	0.45	20.7	1	0.009300	7	1088	between the loaded wheels	3.33E+06	2.08E+06
Total	370													
Reconstructed Profile (Pre-fatigue cracking) - As Con														
DG14 PBM AC (included in base layer)														
Base - Type 2.1 CMB (UCS 1.5±0.25 MPa)	170	Iso	4245	4245	0.2			1	0.000328	12	3	beneath a loaded wheel	2.90E+24	2.42E+23
Subbase - Type 2.1 CTSB (UCS 3.0 MPa min)	200	Iso	5381	5381	0.2			1	0.000304	12	44	between the loaded wheels	1.19E+10	9.90E+08
Upper Subgrade (inclusive of working platform)	300	Aniso	440	220	0.35	0.35	325.9	1	0.009300	7	62	between the loaded wheels	1.71E+15	1.07E+15
Lower Subgrade	500	Aniso	108	54	0.45	0.45	74.5	1	0.009300	7	107	between the loaded wheels	3.75E+13	2.34E+13
Subgrade	Infinite	Aniso	173	86.5	0.45	0.45	119.3	1	0.009300	7	43	inside the load wheel	2.21E+16	1.38E+16
Total	1170													
Rehabilitated Profile - Design														
DG14 PBM AC (included in base layer)														
Insitu Stabilised Modified Base (UCS 1.5±0.25 MPa)	300	Aniso	600	300	0.35	0.35	444.4	1	0.009300					
Existing pavement (assumed)	100	Aniso	150	75	0.35	0.35	111.1	1	0.009300	7				
Subgrade (CBR4.0)	Infinite	Aniso	40	20	0.45	0.45	27.6	1	0.009300	7	1504	between the loaded wheels	3.46E+05	2.16E+05
Total	400													
Rehabilitated Profile (Pre-fatigue cracking) - As Con														
DG14 PBM AC (included in base layer)														
Insitu Stabilised Modified Base (UCS 1.5±0.25 MPa)	300	Iso	2304	2304	0.2			1	0.000415	12	92	between the loaded wheels	7.03E+07	5.86E+06
Upper Subgrade (inclusive of working platform)	300	Aniso	440	220	0.35	0.35	325.9	1	0.009300	7	126	beneath a loaded wheel	1.19E+13	7.46E+12
Lower Subgrade	500	Aniso	108	54	0.45	0.45	74.5	1	0.009300	7	108	between the loaded wheels	3.51E+13	2.19E+13
Subgrade	Infinite	Aniso	173	86.5	0.45	0.45	119.3	1	0.009300	7	60	between the loaded wheels	2.15E+15	1.34E+15
Total	1100													
Rehabilitated Profile (Post-fatigue cracking) - As Con														
DG14 PBM AC (included in base layer)														
Insitu Stabilised Modified Base (UCS 1.5±0.25 MPa)	300	Aniso	500	250	0.35	0.35	370.4	1	0.009300					
Upper Subgrade (inclusive of working platform)	300	Aniso	440	220	0.35	0.35	325.9	1	0.009300	7	258	beneath a loaded wheel	7.91E+10	4.94E+10
Lower Subgrade	500	Aniso	108	54	0.45	0.45	74.5	1	0.009300	7	328	between the loaded wheels	1.47E+10	9.21E+09
Subgrade	Infinite	Aniso	173	86.5	0.45	0.45	119.3	1	0.009300	7	84	between the loaded wheels	2.04E+14	1.27E+14
Total	1100													

Table 4-5 Hugh Street CIRCLY input parameters.

Section Description	*Thickness*	*Aniso/Iso*	*Modulus*		*Poisson*		*Shear (f)*	*Fatigue Criteria*			Max Strain		Traffic Loading	
			Ev	Eh	vv	vh		RF	k	b	με	Location of strain	Allowable	DESA
Reconstructed Profile (Pre-fatigue cracking) - Design														
DG14 PBM AC (included in base layer)														
Base - Type 2.1 CMB (UCS 1.5±0.25 MPa)	180	Aniso	600	300	0.35	0.35	444.4	1	0.009300					
Subbase - Type 2.1 CTSB (UCS 3.0 MPa min)	180	Iso	3000	3000	0.2			1	0.000372	12	156	between the loaded wheels	3.37E+04	2.81E+03
Subgrade (CBR4.0)	Infinite	Aniso	40	20	0.45	0.45	27.6	1	0.009300	7	460	between the loaded wheels	1.38E+09	8.63E+08
Total	360													
Reconstructed Profile (Post-fatigue cracking) - Design														
DG14 PBM AC (included in base layer)														
Base - Type 2.1 CMB (UCS 1.5±0.25 MPa)	180	Aniso	600	300	0.35	0.35	444.4	1	0.009300					
Subbase - Type 2.1 CTSB (UCS 3.0 MPa min)	180	Aniso	500	250	0.35	0.35	370.4	1	0.009300					
Subgrade (CBR4.0)	Infinite	Aniso	40	20	0.45	0.45	27.6	1	0.009300	7	988	between the loaded wheels	6.55E+06	4.09E+06
Total	360													
Reconstructed Profile (Pre-fatigue cracking) - As Con														
DG14 PBM AC (included in base layer)														
Base - Type 2.1 CMB (UCS 1.5±0.25 MPa)	180	Iso	3321	3321	0.2			1	0.000358	12	3	beneath a loaded wheel	8.26E+24	6.88E+23
Subbase - Type 2.1 CTSB (UCS 3.0 MPa min)	180	Iso	5324	5324	0.2			1	0.000305	12	50	between the loaded wheels	2.66E+09	2.22E+08
Upper Subgrade (inclusive of working platform)	300	Aniso	358	179	0.35	0.35	265.2	1	0.009300	7	86	between the loaded wheels	1.73E+14	1.08E+14
Subgrade	Infinite	Aniso	202	101	0.45	0.45	139.3	1	0.009300	7	78	between the loaded wheels	3.43E+14	2.14E+14
Total	660													
Reconstructed Profile (Post-fatigue cracking) - As Con														
DG14 PBM AC (included in base layer)														
Base - Type 2.1 CMB (UCS 1.5±0.25 MPa)	180	Aniso	500	250	0.35	0.35	370.4	1	0.009300					
Subbase - Type 2.1 CTSB (UCS 3.0 MPa min)	180	Aniso	500	250	0.35	0.35	370.4	1	0.009300					
Upper Subgrade (inclusive of working platform)	300	Aniso	358	179	0.35	0.35	265.2	1	0.009300	7	253	between the loaded wheels	9.07E+10	5.67E+10
Subgrade	Infinite	Aniso	202	101	0.45	0.45	139.3	1	0.009300	7	174	between the loaded wheels	1.25E+12	7.79E+11
Total	660													

Table 4-6 Bamford Lane CIRCLY input parameters.

Section Description	*Thickness*	*Aniso/Iso*	*Modulus*		*Poisson*		*Shear (f)*	*Fatigue Criteria*			Max Strain		Traffic Loading	
			Ev	Eh	vv	vh		RF	k	b	με	Location of strain	Allowable	DESA
Reconstructed Profile (Pre-fatigue cracking) - Design														
DG14 PBM AC (included in base layer)														
Base - Type 2.1 CMB (UCS 1.5±0.25 MPa)	200	Aniso	600	300	0.35	0.35	444.4	1	0.009300					
Subbase - Type 2.1 CTSB (UCS 3.0 MPa min)	210	Iso	3000	3000	0.2			1	0.000372	12	137	between the loaded wheels	1.60E+05	1.34E+04
Subgrade (CBR3.0)	Infinite	Aniso	30	15	0.45	0.45	20.7	1	0.009300	7	422	between the loaded wheels	2.52E+09	1.58E+09
Total	410													
Reconstructed Profile (Post-fatigue cracking) - Design														
DG14 PBM AC (included in base layer)														
Base - Type 2.1 CMB (UCS 1.5±0.25 MPa)	200	Aniso	600	300	0.35	0.35	444.4	1	0.009300					
Subbase - Type 2.1 CTSB (UCS 3.0 MPa min)	210	Aniso	500	250	0.35	0.35	370.4	1	0.009300					
Subgrade (CBR3.0)	Infinite	Aniso	30	15	0.45	0.45	20.7	1	0.009300	7	936	between the loaded wheels	9.56E+06	5.97E+06
Total	410													
Reconstructed Profile (Pre-fatigue cracking) - As Con														
DG14 PBM AC (included in base layer)														
Base - Type 2.1 CMB (UCS 1.5±0.25 MPa)	200	Iso	2578	2578	0.2			1	0.000395	12	9	beneath a loaded wheel	5.17E+19	4.30E+18
Subbase - Type 2.1 CTSB (UCS 3.0 MPa min)	210	Iso	3201	3201	0.2			1	0.000363	12	52	between the loaded wheels	1.33E+10	1.11E+09
Upper Subgrade (inclusive of working platform)	300	Aniso	212	106	0.35	0.35	157.0	1	0.009300	7	122	between the loaded wheels	1.50E+13	9.35E+12
Subgrade	Infinite	Aniso	191	95.5	0.45	0.45	131.7	1	0.009300	7	77	between the loaded wheels	3.75E+14	2.34E+14
Total	710													
Reconstructed Profile (Post-fatigue cracking) - As Con														
DG14 PBM AC (included in base layer)														
Base - Type 2.1 CMB (UCS 1.5±0.25 MPa)	200	Aniso	500	250	0.35	0.35	370.4	1	0.009300					
Subbase - Type 2.1 CTSB (UCS 3.0 MPa min)	210	Aniso	500	250	0.35	0.35	370.4	1	0.009300					
Upper Subgrade (inclusive of working platform)	300	Aniso	212	106	0.35	0.35	157.0	1	0.009300	7	334	between the loaded wheels	1.30E+10	8.11E+09
Subgrade	Infinite	Aniso	191	95.5	0.45	0.45	131.7	1	0.009300	7	161	between the loaded wheels	2.15E+12	1.34E+12
Total	710													

Table 4-7 Woodlands Service Road CIRCLY input parameters.

Section Description	*Thickness*	*Aniso/Iso*	*Modulus*		*Poisson*		*Shear (f)*	*Fatigue Criteria*			Max Strain		Traffic Loading	
			Ev	Eh	vv	vh		RF	k	b	με	Location of strain	Allowable	DESA
Reconstructed Profile - Design														
DG14 PBM AC (included in base layer)														
Foam Bitumen Stabilised (Vb=7)	280	Iso	1970	1970	0.4			1	0.003188	5	195	between the loaded wheels	1.63E+06	1.49E+06
Existing pavement material	50	Aniso	150	75	0.35	0.35	111.1	1	0.009300					
Subgrade (CBR4.0)	Infinite	Aniso	40	20	0.45	0.45	27.6	1	0.009300	7	443	between the loaded wheels	1.80E+09	1.12E+09
Total	330													
Reconstructed Profile - As Con														
DG14 PBM AC (included in base layer)														
Foam Bitumen Stabilised (Vb=7)	280	Iso	5842	5842	0.4			1	0.002156	5	50	between the loaded wheels	4.31E+06	3.92E+06
Upper Subgrade (inclusive of working platform)	300	Aniso	328	164	0.35	0.35	243.0	1	0.009300	7	104	between the loaded wheels	4.57E+13	2.86E+13
Subgrade	Infinite	Aniso	220	110	0.45	0.45	151.7	1	0.009300	7	81	between the loaded wheels	2.63E+14	1.64E+14
Total	580													
Reconstructed Profile - As Con (factored for temperature)														
DG14 PBM AC (included in base layer)														
Foam Bitumen Stabilised (Vb=7)	280	Iso	3383	3383	0.4			1	0.002624	5	72	between the loaded wheels	2.08E+08	1.74E+07
Upper Subgrade (inclusive of working platform)	300	Aniso	328	164	0.35	0.35	243.0	1	0.009300	7	141	between the loaded wheels	5.43E+12	3.39E+12
Subgrade	Infinite	Aniso	220	110	0.45	0.45	151.7	1	0.009300	7	102	between the loaded wheels	5.24E+13	3.27E+13
Total	580													

4.4 Pavement Evaluation

Pavement evaluation has focused on the structural aspect of the pavement and has been divided into two (2) main components, namely the allowable number of repetitions the as constructed pavement can theoretically withstand and an analysis of the Structural Number (SN). Due to time restraints a full evaluation via the structural number was not completed, however enough work was completed in order to provide a comparison between recommended methods and is discussed further below.

Subsequently, the simplified evaluation based on the allowable number of repetitions was completed, with these results discussed below.

4.4.1 Allowable Number of Repetitions

Following input of the material parameters, the critical strains where obtained from CIRCLY. The critical strains were then used to determine the allowable traffic (N) loadings in accordance with the appropriated performance criteria equations detailed in Section 2.2.7 and converted back to the equivalent DESA. This data is also detailed in **Table 4-4** to **Table 4-7** above.

The lowest DESA value for each profile analysed in **Table 4-4** to **Table 4-7** was then used to back calculate, with the aid of the 'Goal Seek' tool within Microsoft Excel, the estimated equivalent design life. **Table 4-8** provides a summary of the assessment.

Table 4-8 Back calculated estimated equivalent design life summary

Site	Allowable No. Of Repetitions	Estimated Design Life (years)	Comments
Woodlands Service Road	3.92×10^6	27	Un-factored modulus
	1.74×10^7	58	Temperature and loading factored modulus
Bamford Lane	5.97×10^6	40	Actual design life of the original post-cracked design
	1.34 x 104	<1	Cracking of the CTSB layer in the original design to occur within the

Site	Allowable No. Of Repetitions	Estimated Design Life (years)	Comments
			initial year of operation.
	1.11×10^9	240	As constructed pre-cracking of CTSB
	8.11×10^9	323	As constructed post-cracking of CTSB
Hugh Street	2.81×10^3	<1	Cracking of the CTSB layer in the original design to occur within the initial year of operation
	4.09×10^6	12	Actual design life of the original post-cracked design
	2.22×10^8	140	As constructed pre-cracking of CTSB
	5.67×10^{10}	417	As constructed post-cracking of CTSB
Palmerston Street (Reconstructed)	2.41×10^3	<1	Cracking of the CTSB layer in the original design to occur within the initial year of operation
	2.08×10^6	33	Actual design life of the original post-cracked design
	9.9×10^8	525	As constructed pre-cracking of CTSB
Palmerston Street (Rehabilitated)	2.16×10^5	4	Actual design life of the original post-cracked design
	5.86×10^6	74	As constructed pre-cracking of CMB
	9.21×10^9	748	As constructed post-cracking of CMB

Although the above suggest that majority of the as constructed profiles will never fail in this life, other factors that can contribute to the structural deterioration of a pavement such as the following haven't been accounted for:

- Reflective cracking penetrating the surface and allowing the ingress of moisture into the pavement.
- Moisture fluctuations in the subgrade, particularly during the wet season.
- Fatigue of the wearing surface.
- General disintegration of materials over time.

Another interesting observation of the results in **Table 4-8** is the temperature and loading factored modulus of the FBS pavement yields a longer estimated design life than the un-factored modulus. This seems to suggests that the factored modulus is more flexible in nature, consequently developing less tensile strain and transferring more load to the subgrade. This is supported by the increase in strain observed in the subgrade layers of the factor FBS modulus when compared with the un-factored FBS modulus. Therefore it could be stated that providing the FBS layer is the critical failure layer, a lower FBS modulus will provide better long term performance.

4.4.2 Structural Number (SN)

The SN and SNSG values were calculated using Rhode's, Jameson's and Paterson's methods as describe in Section 2.3.2. As previously mentioned, the FWD results were normalised to load of 50kN and additional adjustments to these results were required in order to assess the SN via Rhode's method. Rhode's requires a deflection results based on a 40kN load, therefore the results from the 50kN loading were normalised to 40kN loads by assuming a linear relationship, i.e the 50kN results were multiplied by a factor of 4/5. Similarly, where the methods required a deflection value that varied from the offsets that results were obtained at, deflection was estimated via linear interpolation.

Due to time restrictions, a detailed evaluation of the pavements via the use of the SN value was note completed, however **Figure 4-9** provide a comparison plot of the values calculated.

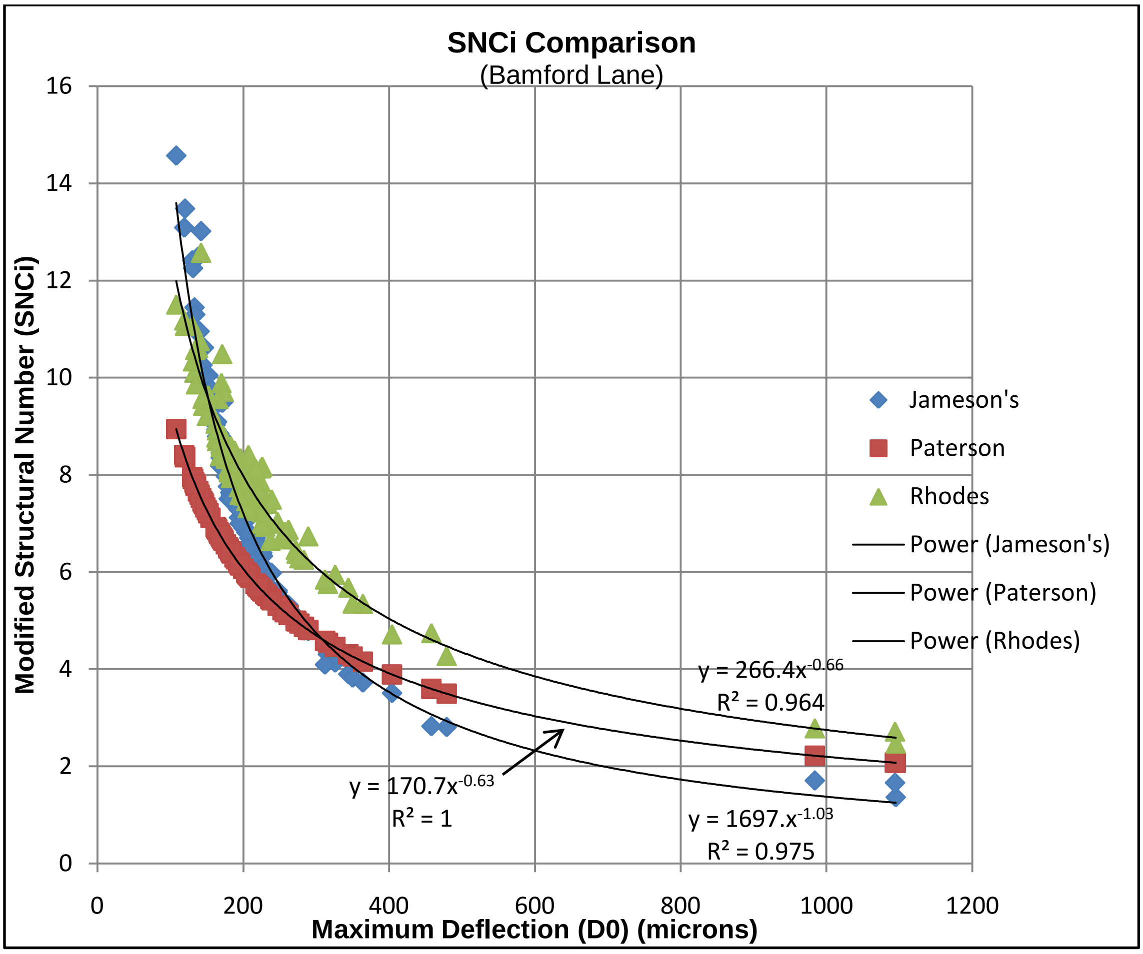

Figure 4-9 Modified Structural Number (SNC) method comparison

4.5 Cost-benefit assessment

Table 4-9 details the overall design and constructions associated with each site as well as a calculated unit rate in terms of $/m and $m^2. The spilt of costs associated with the reconstructed and rehabilitation portions of Palmerston Street were unable to be extracted from the cost data obtained and have subsequently been prorated based on the proportionate areas. From **Table 4-9** it is evident that in-situ stabilisation is a more cost-effective treatment than reconstruction. This is assumed to be attributed to the significantly shorter construction duration. However there appears to be a significant difference between the costs associated with in-situ cement and foam bitumen stabilisation without any significant benefit in terms of as constructed pavement life. However it is anticipated that these cost may begin to even out through ongoing maintenance as it is anticipated that cracking in the wearing surface will be observed at each site where the as constructed CMB layer appears to be behaving more like a CTB without the recommended cover to prevent reflective cracking.

Table 4-9 Overall design and construction costs

Road	**Year Constructed**	**Overall Cost**	**Length (m)**	**$/m**	**Area (m^2)**	**$/m**
Bamford Lane	2010	$ 1,511,080	650	$ 2,325	5,200	$ 291
Hugh Street	2012	$ 1,218,940	400	$ 3,047	3,000	$ 406
Woodlands Service Road	2009	$ 195,600	300	$ 652	1,500	$ 130
Palmerston Street (Reconstructed)	2012	$ 1,079,360	360	$ 1,597	4,445	$ 63
Palmerston Street (Reconstructed)	2012	$ 1,079,360	500	$ 781	6,135	$ 130

CHAPTER 5 – CONCLUSIONS

5.0 Introduction

This chapter will summarise the findings of the project and provide recommendation based on these findings. In addition it will outline potential future research originating from other points of interested that were identified during this project but were beyond the scope of works.

5.1 Conclusions and Recommendations

Whilst the concept of being able to accurately determine a cost effective profile that could be blindly adopted within the local region appears to be useful, the complexities behind pavement design, evaluation, construction and general overall variability of materials result in an extremely complicated procedure.

Notwithstanding this project has indicated that where applicable in-situ stabilising of the exiting pavement is the most cost effective treatment. Further investigation should be undertaken into FBS as it would appear that the performance of this type of pavement is just as effective as cement stabilisation although a little more expensive. This investigation may wish to look at the recyclability of each stabilisation method as it is anticipated that FBS would be more recycle friendly than cement stabilised materials.

Depending of available funding, periodic monitoring aging roads would provide Council with the invaluable information in relation pavement performance and greatly assist with the refinement of maintenance and rehabilitation programs. Additionally periodic modelling would also assist in refining specific pavement design parameters, tailored purposely for Townsville. Periodic monitoring should also include new developments where new and different approaches to pavement design a being undertaken. This would also provide insight into the effect that traffic loading has on increasing the CBR value of the subgrade as the back-analysed FWD results at these sites indicated subgrade CBR values above 20% were being achieved. This strength CBR is nearly unheard of in current greenfield sites that are being developed. Subsequently, these high CBR values could simply be a lack of accurate as constructed recording where workings platforms are placed in thicker layers than designed as a result of unforseen subgrade issues experienced during construction.

It is recommend that when designs are completed and construction is not commenced within two (2) years, the pavement designer is re-engaged to confirm the suitability of original design loading estimate and subsequently the overall design of the pavement. This recommendation is on the basis that traffic volume may have substantially increased during this time and/or the in-service conditions that formed the foundation of the design may have significantly changed.

5.2 Further Research

Below are suggested areas of future research associated with this project and other topics of interest that were identified during the research and analysis phases.

1. Follow up with regular future FWD testing of the sites in order to build a database of information that will allow a more accurate assessment of structural deterioration of the pavements at each site.
2. Investigate the maintenance requirements associated with each site a predict the associated cost to gain a better understanding of the long term cost implications of each pavement profile.

3. As discussed in Section 2.1.2 further research is required into the suspected improved nature of modified materials. As this was a topic of interest an assessment of the effect of the CDF at subgrade level between a modified and unbound pavement profile was conducted with the aid of CIRCLY. The scope of this assessment was limited to substantially increasing the vertical modulus of the modified material and comparing the layer thickness with all other parameters remaining unchanged, i.e. vertical to horizontal modulus ratio, traffic loading, Poisson's ratio, subgrade CBR (5%) and CDF=1. A 3.6% decrease in pavement thickness was observed when the vertical modulus of the modified layer was increase to 1000 MPa (greatly above the recommendations of Austroads). This decrease in pavement thickness is not considered to be representative of the improved nature of a modified material, subsequently attention was given to modification of the vertical to horizontal modulus ratio.

   Whilst no comprehensive research or testing was undertaken to support the succeeding statement, the characteristics of a modified material is expected to fall between an anisotropic and isotropic material as the addition of a cementitious binder is expected to improve the material's ability to develop tensile strain. This would result in a vertical to horizontal modulus ratio within the range of 2:1 to 1:1. To assess the influence this statement had on the CDF, a ratio of 1.5:1 was adopted for a modified material with all parameters previously mentioned preserved. The exception to this was a decrease in the vertical modulus of the modified material to align with Austroads recommendations, i.e. E_v = 500 MPa. A 8.5% decrease in pavement thickness was observed which is substantially greater than that previously seen.

   From a cost perspective, should an improvement in modified materials (such as that described above) not be accounted for in the design model, there is limited benefit to their inclusion in a pavement profile. It is for this reason that further investigation should be focused in this area.

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APPENDIX A

Project Specification

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEY

ENG4111/4112 Research Project
PROJECT SPECIFICATION

FOR: **JOHN HENRY SINGLE**

TOPIC: COST-BENEFIT OF VARIOUS PAVEMENT RECONSTRUCTION PROFILES FOR THE TOWNSVILLE REGION

SUPERVISOR: Prof. Ron Ayers

SPONSERSHIP: Townsville City Council, Northern Consulting Engineers, Northern Pavement Consultants,

PROJECT AIM: To determine the most cost effective profile type for pavement reconstruction of a collector road within the Townsville City Councils jurisdiction.

PROGRAMME: (Version 1.2, 19 March 2014)

1. Undertake a literature review that considers pavement design parameters and associated testing of these parameters, current technical design methods, reconstruction (and/or rehabilitation) of road pavements under traffic, public perception associated with road works, theoretical pavement design life for various profiles, typical specifications and standards of pavement and cost-benefit issues associated with choice of pavement type, design methods and construction techniques relating to pavements within the Townsville Region. This research will need to be undertaken on a broader scale, i.e. Queensland/Australia and correlated appropriately to the Townsville Region.
2. Identify up to four (4) collector/substantial road sites within the Townsville Region that have been reconstructed under traffic within the past 1-10 years. Each site should have a varying pavement profile, be similar in traffic loads and ideally have had testing undertaken prior to construction/design.
3. Obtain and collate design testing data, pavement design, construction testing data, construction duration, number of complaints received during construction, construction methodology, design cost, construction cost and any other data consider relevant for undertaking a cost benefit analysis.
4. Obtain/undertake traffic count data/analysis to determine current traffic volumes and predicted traffic volumes.
5. Undertake non-destructive testing such as Falling Weight Deflectometer (FWD) to analyse the performance and expected constructed pavement life.
6. Evaluate constructed pavement profiles using computer software (CIRCLY) to establish current pavement life versus theoretical pavement life and predicted constructed pavement life.
7. Evaluate all data and undertake a cost-benefit analysis of pavement profile taking into consideration pavement design life, predicted pavement life, design and construction costs with the inclusion of public perception value associated with road works.
8. Compare findings with the specifications and standards of Townsville City Council's Pavement Design Manual (currently in draft, however due for release this year).
9. Present project findings in the required written and oral formats.

As time permits:

10. Design a typical reconstruction pavement profile suitable for collector roads that may also provide benefit for road construction within 'green' field sites.

AGREED ______________________ (Student) ______________________ (Supervisor)

Date: / / 2014 Date: / / 2014

______________________ (Examiner/Co-examiner)

Date: / / 2014

APPENDIX B

FWD Tabulated Deflection Results

Normalised to 50 kN Deflection Results

Client	Townsville City Council	**Start Date of Testing**	24-Jul-14	**Target Load (kN)**	50	
Road	Bamford Lane (Mill Drive to Dalrymple Road)	**Start Reference**	FWD 0 m = Start of kerb, Mill Drive			
Comments	1L = OWP towards Dalrymple Road, 1R = IWP towards Dalrymple Road, 2L = OWP towards Mill Drive, 2R = IWP towards Mill Drive					

FWD Chainage (m)	Lane	**Deflections (microns)** Geophone Radius (mm) D0	D200	D300	D400	D500	D600	D700	D800	D900	D1000	D1200	D1400	D1600	D1800	D2000	D2250	D2500	Air Temp. (oC)	Surf Temp. (oC)
0	1L	1095	830	646	496	378	300	238	198	166	145	113	97	84	75	65	57	39	20.7	20.5
25	1L	233	186	174	160	148	138	129	120	109	102	83	73	64	56	47	39	27	20.8	20.6
50	1L	155	129	119	111	103	97	91	85	79	75	65	58	51	45	39	32	22	20.9	20.7
75	1L	163	125	114	106	98	92	87	83	76	74	63	56	50	44	38	32	23	20.9	20.8
100	1L	204	147	118	109	102	97	90	85	77	74	63	56	49	43	37	30	21	20.9	20.8
125	1L	180	156	143	131	119	106	91	81	73	68	56	47	41	36	31	26	17	20.9	20.9
150	1L	230	186	163	145	130	119	107	96	84	77	63	54	46	41	33	28	19	21.1	21
175	1L	145	120	109	101	94	88	83	80	72	69	59	53	46	42	36	30	20	21.2	21.1
200	1L	219	184	167	153	139	127	116	108	97	90	75	66	57	51	43	36	24	21.1	21
226	1L	227	196	175	160	145	131	118	110	100	95	81	73	65	58	50	42	29	21.1	21
250	1L	166	143	135	127	119	114	108	104	94	91	78	70	62	54	46	39	27	21.2	21
275	1L	196	169	153	142	132	123	115	109	99	96	80	70	62	55	47	39	27	21.2	21.1
300	1L	283	224	192	170	150	135	123	112	100	93	76	66	56	49	42	35	23	21.3	21.1
326	1L	230	198	181	157	126	112	102	96	87	82	68	60	52	46	39	33	21	21.4	21.1
351	1L	190	160	147	135	123	114	105	99	89	85	71	62	54	48	41	35	23	21.5	21.2
376	1L	182	154	138	124	112	102	94	87	79	74	63	54	47	41	35	29	20	21.4	21.3
401	1L	217	168	149	135	121	112	102	96	85	79	66	57	48	41	35	28	19	21.4	21.4
425	1L	204	167	160	155	146	134	117	101	86	76	62	52	43	37	29	24	17	21.5	21.4
450	1L	254	208	182	162	145	132	121	113	101	94	77	64	54	46	38	30	19	21.5	21.4
475	1L	200	146	128	116	106	100	92	87	80	75	63	56	48	42	35	27	19	21.6	21.4
501	1L	144	117	109	101	95	89	84	81	74	70	59	53	47	41	34	29	19	21.5	21.4
525	1L	194	155	136	121	109	101	93	88	79	75	62	55	47	41	34	28	19	21.4	21.4
550	1L	193	158	141	131	119	109	103	97	88	84	69	61	53	45	37	31	21	21.4	21.4
575	1L	225	183	161	143	128	115	103	93	82	76	60	51	43	37	31	25	18	21.4	21.4
600	1L	169	132	120	111	103	97	90	86	77	74	63	56	48	43	36	30	20	21.4	21.4
626	1L	180	126	116	107	101	95	90	86	79	75	64	55	47	41	34	28	19	21.6	21.4
650	1L	237	173	145	124	108	98	87	82	73	68	54	47	41	35	30	27	18	21.7	21.3
13	1R	226	207	200	187	173	162	149	138	124	114	92	82	69	61	51	43	30	20.5	21.3
38	1R	146	124	106	100	95	91	86	84	77	75	65	59	53	47	39	33	23	20.6	21.3
62	1R	170	149	143	137	130	124	117	113	102	97	81	66	58	52	45	38	25	20.6	21.3
88	1R	257	197	171	154	139	128	117	109	98	92	76	64	54	45	38	32	24	20.6	21
112	1R	180	137	122	112	103	96	89	85	77	73	61	54	47	43	36	31	21	20.7	21
138	1R	179	154	135	122	112	105	97	91	79	76	63	54	46	40	34	27	19	20.8	21.1

Normalised to 50 kN Deflection Results

Client Townsville City Council | **Start Date of Testing** 24-Jul-14 | **Target Load (kN)** 50

Road Bamford Lane (Mill Drive to Dalrymple Road) | **Start Reference** FWD 0 m = Start of kerb, Mill Drive

Comments 1L = OWP towards Dalrymple Road, 1R = IWP towards Dalrymple Road, 2L = OWP towards Mill Drive, 2R = IWP towards Mill Drive

FWD Chainage (m)	Lane	Deflections (microns) Geophone Radius (mm) D0	D200	D300	D400	D500	D600	D700	D800	D900	D1000	D1200	D1400	D1600	D1800	D2000	D2250	D2500	Air Temp. (oC)	Surf Temp. (oC)
163	1R	316	241	194	160	137	122	109	100	88	82	66	56	47	42	35	29	20	20.7	21
188	1R	220	186	166	150	136	126	115	107	96	90	75	66	57	51	44	37	26	20.8	20.9
213	1R	219	183	165	150	136	127	117	110	100	94	79	68	58	52	42	36	25	20.8	21
237	1R	173	151	141	134	127	122	115	112	104	101	87	79	70	63	54	45	31	20.9	21
262	1R	224	194	179	166	153	143	133	126	115	108	90	76	65	58	50	42	29	20.9	21
289	1R	194	156	135	123	113	105	98	94	87	84	72	64	58	52	43	37	25	20.9	21
313	1R	200	167	153	142	130	122	114	108	98	94	79	72	64	58	50	42	28	20.9	21.1
339	1R	247	212	193	176	161	147	133	121	106	98	80	70	61	54	46	39	26	21	21.1
362	1R	220	187	169	154	141	131	121	113	103	97	82	72	62	55	47	40	27	21.1	21
388	1R	169	137	127	117	107	99	92	87	78	75	62	54	47	42	36	30	21	21.2	21.1
413	1R	162	134	124	116	107	101	95	91	82	79	65	58	51	45	39	34	22	21.2	21
438	1R	231	196	176	165	155	146	134	123	110	101	82	69	57	49	41	34	23	21.1	21.1
463	1R	344	292	257	230	204	184	164	149	131	120	97	84	70	60	49	40	25	21	21.1
488	1R	150	124	112	103	95	89	83	81	74	71	61	54	49	43	36	31	20	21.1	21.1
513	1R	224	196	184	173	160	151	141	133	122	116	96	82	71	61	51	43	27	21.2	21.1
539	1R	273	221	189	163	145	132	119	110	98	91	74	64	55	48	40	34	22	21.2	21.1
563	1R	120	105	99	93	86	82	78	75	70	68	58	53	48	43	37	31	21	21.2	21.1
589	1R	133	104	97	92	88	84	80	77	70	68	58	53	46	41	35	29	19	21.3	21.1
613	1R	167	141	131	121	112	105	98	94	85	80	65	61	54	49	42	36	23	21.4	21.1
637	1R	479	396	341	290	243	206	173	147	123	108	80	64	54	47	39	33	24	21.4	21.1
13	2L	1094	749	544	397	296	229	178	143	118	104	83	72	63	57	49	43	30	20.3	21.5
38	2L	172	148	135	124	114	107	100	94	87	83	71	63	55	50	43	38	26	20.3	21.5
62	2L	119	109	104	99	93	84	77	74	68	65	55	50	44	40	35	28	20	20.3	21.5
87	2L	135	121	112	101	91	85	79	76	68	66	56	50	44	39	33	28	20	20.3	21.5
113	2L	176	138	128	118	107	101	94	89	79	74	62	55	47	42	36	30	21	20.3	21.4
137	2L	226	184	162	146	132	122	111	104	93	88	73	63	54	47	39	32	22	20.3	21.3
162	2L	173	146	133	123	112	104	97	91	83	77	64	57	49	44	38	32	21	20.2	21.4
187	2L	108	89	85	81	75	72	69	67	61	60	51	46	41	37	31	26	18	20.2	21.4
212	2L	164	130	120	112	103	97	92	88	80	78	66	61	53	48	42	35	24	20.2	21.4
237	2L	184	148	132	120	109	100	92	86	78	74	61	53	46	40	34	29	20	20.2	21.4
262	2L	210	186	174	160	147	134	123	114	103	97	80	70	60	52	44	37	25	20.3	21.4
286	2L	277	222	190	165	144	129	116	107	95	89	72	61	52	45	37	32	22	20.2	21.3
312	2L	326	272	242	219	195	177	161	148	132	122	99	84	72	62	52	43	29	20.3	21.5

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Normalised to 50 kN Deflection Results

Client Townsville City Council | **Start Date of Testing** 24-Jul-14 | **Target Load (kN)** 50

Road Bamford Lane (Mill Drive to Dalrymple Road) | **Start Reference** FWD 0 m = Start of kerb, Mill Drive

Comments 1L = OWP towards Dalrymple Road, 1R = IWP towards Dalrymple Road, 2L = OWP towards Mill Drive, 2R = IWP towards Mill Drive

FWD Chainage (m)	Lane	Deflections (microns) Geophone Radius (mm)																	Air Temp. (oC)	Surf Temp. (oC)
		D0	D200	D300	D400	D500	D600	D700	D800	D900	D1000	D1200	D1400	D1600	D1800	D2000	D2250	D2500		
337	2L	184	153	143	133	123	112	103	99	91	86	72	62	53	47	40	33	22	20.3	21.4
363	2L	152	128	121	114	105	100	94	91	83	80	68	61	53	47	38	32	22	20.4	21.6
387	2L	131	106	99	94	88	84	81	78	73	71	61	57	51	46	40	34	23	20.4	21.6
412	2L	200	165	137	120	110	103	97	92	84	80	67	60	52	46	38	31	20	20.4	21.5
437	2L	140	126	124	116	107	101	95	91	85	82	70	61	47	40	35	28	20	20.4	21.6
462	2L	134	116	111	106	100	93	87	83	76	72	61	54	46	41	34	28	19	20.4	21.5
487	2L	193	173	164	150	129	118	109	103	92	87	71	62	53	46	38	30	20	20.4	21.5
512	2L	312	286	262	236	213	193	170	149	123	103	74	62	50	43	35	30	21	20.8	21.5
537	2L	257	212	189	166	148	136	125	117	107	102	84	73	61	52	44	36	25	20.5	21.4
562	2L	148	119	115	108	101	96	89	85	78	75	62	55	49	43	38	32	23	20.6	21.3
587	2L	221	180	167	153	140	131	122	114	105	101	85	75	65	56	46	38	25	21	21.4
612	2L	206	165	145	128	113	102	91	85	76	71	57	49	40	35	30	25	17	20.8	21.3
637	2L	404	326	275	223	180	147	120	100	81	71	53	42	35	31	26	22	15	20.8	21.1
3	2R	984	718	558	417	308	236	185	150	125	108	83	73	62	56	49	43	30	19.9	20.9
25	2R	202	208	212	211	184	156	132	115	97	88	69	60	52	48	41	34	25	19.8	20.9
50	2R	208	173	159	144	130	120	108	101	91	85	69	62	54	49	41	36	24	20	20.8
75	2R	130	117	111	105	98	94	89	86	77	73	63	57	52	47	41	35	24	20	20.8
100	2R	188	160	150	139	127	119	110	104	94	89	76	67	59	53	45	38	25	19.8	20.8
125	2R	364	296	246	207	176	154	137	123	109	100	81	69	59	52	44	37	26	19.7	20.8
149	2R	183	146	127	114	103	94	87	82	74	71	58	52	46	42	36	30	21	19.7	20.7
176	2R	164	135	123	111	101	94	87	84	76	73	61	55	49	44	37	31	21	19.8	20.8
200	2R	272	210	177	155	138	125	114	108	98	93	77	70	61	55	48	39	27	19.8	20.9
225	2R	205	158	144	139	131	125	119	116	108	103	91	82	72	65	55	46	30	19.7	20.9
250	2R	207	182	172	160	148	140	130	123	113	106	90	78	65	57	48	40	28	19.7	20.9
273	2R	184	156	141	130	121	114	108	103	92	88	74	65	56	49	41	34	23	19.8	21
300	2R	262	219	195	176	159	147	136	128	117	109	91	78	69	60	50	42	27	19.9	20.9
324	2R	458	384	338	297	264	236	211	191	168	153	123	101	86	72	58	47	31	19.9	20.9
351	2R	223	192	174	158	143	133	123	115	105	100	82	74	65	58	49	42	28	19.9	20.9
375	2R	217	193	183	170	158	147	136	127	115	108	88	78	67	57	47	37	25	19.8	20.9
400	2R	142	131	129	124	119	116	112	110	102	98	84	77	67	60	52	43	28	20	21
425	2R	138	115	109	103	98	94	90	89	83	81	72	67	60	55	48	41	28	20	21
450	2R	171	152	148	142	136	131	124	120	113	109	96	82	64	57	49	40	27	20	21
475	2R	247	201	173	158	144	135	125	119	108	102	84	73	62	55	46	38	24	20	21

Normalised to 50 kN Deflection Results

Client	Townsville City Council	**Start Date of Testing**	24-Jul-14
		Target Load (kN)	50
Road	Bamford Lane (Mill Drive to Dalrymple Road)	**Start Reference**	FWD 0 m = Start of kerb, Mill Drive
Comments	1L = OWP towards Dalrymple Road, 1R = IWP towards Dalrymple Road, 2L = OWP towards Mill Drive, 2R = IWP towards Mill Drive		

FWD Chainage (m)	Lane	Deflections (microns) Geophone Radius (mm)																	Air Temp. (oC)	Surf Temp. (oC)
		D0	D200	D300	D400	D500	D600	D700	D800	D900	D1000	D1200	D1400	D1600	D1800	D2000	D2250	D2500		
500	2R	183	165	148	134	123	116	106	101	92	87	72	63	54	48	40	33	21	20	20.9
526	2R	289	244	227	210	194	180	167	155	140	130	106	91	76	64	51	40	26	20.1	21
550	2R	239	198	186	172	159	148	137	129	118	111	93	81	69	60	48	39	26	20.1	20.9
575	2R	206	172	161	149	135	125	115	107	97	91	75	65	56	49	41	35	23	19.9	20.8
601	2R	350	283	240	204	174	151	132	117	102	92	71	59	49	44	36	31	22	20	20.6
622	2R	195	148	133	121	108	99	90	84	76	70	58	51	45	40	33	27	18	20	20.5
650	2R	168	142	124	110	97	90	84	80	73	69	57	50	41	36	29	23	14	20	20.4

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Normalised Deflection and Deflection Analysis Results

Client Townsville City Council | **Start Date of Testing** 24-Jul-14 | **Target Load (kN)** 50

Road Bamford Lane (Mill Drive to Dalrymple Road) | **Start Reference** FWD 0 m = Start of kerb, Mill Drive

Comments 1L = OWP towards Dalrymple Road, 1R = IWP towards Dalrymple Road, 2L = OWP towards Mill Drive, 2R = IWP towards Mill Drive

FWD Chainage (m)	Lane	Deflections (microns) Geophone Radius (mm) D0	D200	D300	D400	D500	D600	D700	D800	D900	D1000	D1200	D1400	D1600	D1800	D2000	D2250	D2500	Back Analysed Modulus (MPa) Combined Base (200 mm)	Subbase (250 mm)	Upper Subgrade (300 mm)	Lower Subgrade (Semi-infinite)
0	1L	1095	830	646	496	378	300	238	198	166	145	113	97	84	75	65	57	39	709	41	111	109
25	1L	233	186	174	160	148	138	129	120	109	102	83	73	64	56	47	39	27	1732	4192	131	159
50	1L	155	129	119	111	103	97	91	85	79	75	65	58	51	45	39	32	22	3434	4931	396	197
75	1L	163	125	114	106	98	92	87	83	76	74	63	56	50	44	38	32	23	1980	5310	1085	194
100	1L	204	147	118	109	102	97	90	85	77	74	63	56	49	43	37	30	21	935	10000	406	205
125	1L	180	156	143	131	119	106	91	81	73	68	56	47	41	36	31	26	17	4842	2011	59	297
150	1L	230	186	163	145	130	119	107	96	84	77	63	54	46	41	33	28	19	1777	2341	86	237
175	1L	145	120	109	101	94	88	83	80	72	69	59	53	46	42	36	30	20	3199	5410	525	214
200	1L	219	184	167	153	139	127	116	108	97	90	75	66	57	51	43	36	24	3527	1585	134	180
226	1L	227	196	175	160	145	131	118	110	100	95	81	73	65	58	50	42	29	4933	805	317	155
250	1L	166	143	135	127	119	114	108	104	94	91	78	70	62	54	46	39	27	3518	7583	244	161
275	1L	196	169	153	142	132	123	115	109	99	96	80	70	62	55	47	39	27	2511	4861	190	163
300	1L	283	224	192	170	150	135	123	112	100	93	76	66	56	49	42	35	23	1325	1413	148	178
326	1L	230	198	181	157	126	112	102	96	87	82	68	60	52	46	39	33	21	5000	403	402	183
351	1L	190	160	147	135	123	114	105	99	89	85	71	62	54	48	41	35	23	3157	2847	180	187
376	1L	182	154	138	124	112	102	94	87	79	74	63	54	47	41	35	29	20	3987	1598	266	209
401	1L	217	168	149	135	121	112	102	96	85	79	66	57	48	41	35	28	19	1448	3923	147	211
425	1L	204	167	160	155	146	134	117	101	86	76	62	52	43	37	29	24	17	2488	7799	20	480
450	1L	254	208	182	162	145	132	121	113	101	94	77	64	54	46	38	30	19	1595	2045	144	176
475	1L	200	146	128	116	106	100	92	87	80	75	63	56	48	42	35	27	19	1288	4631	455	203
501	1L	144	117	109	101	95	89	84	81	74	70	59	53	47	41	34	29	19	3189	6519	429	212
525	1L	194	155	136	121	109	101	93	88	79	75	62	55	47	41	34	28	19	1916	2756	323	208
550	1L	193	158	141	131	119	109	103	97	88	84	69	61	53	45	37	31	21	2000	4336	216	192
575	1L	225	183	161	143	128	115	103	93	82	76	60	51	43	37	31	25	18	2329	1550	101	238
600	1L	169	132	120	111	103	97	90	86	77	74	63	56	48	43	36	30	20	2057	5540	432	205
626	1L	180	126	116	107	101	95	90	86	79	75	64	55	47	41	34	28	19	1319	9525	469	201
650	1L	237	173	145	124	108	98	87	82	73	68	54	47	41	35	30	27	18	1243	1432	297	236
13	1R	226	207	200	187	173	162	149	138	124	114	92	82	69	61	51	43	30	5000	2356	20	234
38	1R	146	124	106	100	95	91	86	84	77	75	65	59	53	47	39	33	23	2328	10000	1243	184
62	1R	170	149	143	137	130	124	117	113	102	97	81	66	58	52	45	38	25	4352	10000	28	212
88	1R	257	197	171	154	139	128	117	109	98	92	76	64	54	45	38	32	24	1137	3241	142	183
112	1R	180	137	122	112	103	96	89	85	77	73	61	54	47	43	36	31	21	1744	4871	419	209
138	1R	179	154	135	122	112	105	97	91	79	76	63	54	46	40	34	27	19	2916	3316	168	215
163	1R	316	241	194	160	137	122	109	100	88	82	66	56	47	42	35	29	20	985	828	203	198
188	1R	220	186	166	150	136	126	115	107	96	90	75	66	57	51	44	37	26	3116	1576	170	177
213	1R	219	183	165	150	136	127	117	110	100	94	79	68	58	52	42	36	25	2086	3188	155	171
237	1R	173	151	141	134	127	122	115	112	104	101	87	79	70	63	54	45	31	3477	8724	291	141
262	1R	224	194	179	166	153	143	133	126	115	108	90	76	65	58	50	42	29	2446	3965	134	146

NPC NORTHERN PAVEMENT CONSULTANTS

Normalised Deflection and Deflection Analysis Results

Client	Townsville City Council	**Start Date of Testing**	24-Jul-14
		Target Load (kN)	50
Road	Bamford Lane (Mill Drive to Dalrymple Road)	**Start Reference**	FWD 0 m = Start of kerb, Mill Drive
Comments	1L = OWP towards Dalrymple Road, 1R = IWP towards Dalrymple Road, 2L = OWP towards Mill Drive, 2R = IWP towards Mill Drive		

FWD Chainage (m)	Lane	Deflections (microns) Geophone Radius (mm)																	Back Analysed Modulus (MPa)			
		D0	D200	D300	D400	D500	D600	D700	D800	D900	D1000	D1200	D1400	D1600	D1800	D2000	D2250	D2500	Combined Base (200 mm)	Subbase (250 mm)	Upper Subgrade (300 mm)	Lower Subgrade (Semi-infinite)
289	1R	194	156	135	123	113	105	98	94	87	84	72	64	58	52	43	37	25	1908	2061	1249	170
313	1R	200	167	153	142	130	122	114	108	98	94	79	72	64	58	50	42	28	2707	3094	327	158
339	1R	247	212	193	176	161	147	133	121	106	98	80	70	61	54	46	39	26	2851	1901	49	195
362	1R	220	187	169	154	141	131	121	113	103	97	82	72	62	55	47	40	27	3024	1958	180	161
388	1R	169	137	127	117	107	99	92	87	78	75	62	54	47	42	36	30	21	2505	5034	209	215
413	1R	162	134	124	116	107	101	95	91	82	79	65	58	51	45	39	34	22	2718	6512	241	199
438	1R	231	196	176	165	155	146	134	123	110	101	82	69	57	49	41	34	23	1851	7559	20	297
463	1R	344	292	257	230	204	184	164	149	131	120	97	84	70	60	49	40	25	2459	724	54	155
488	1R	150	124	112	103	95	89	83	81	74	71	61	54	49	43	36	31	20	3026	4197	830	203
513	1R	224	196	184	173	160	151	141	133	122	116	96	82	71	61	51	43	27	3955	2712	128	132
539	1R	273	221	189	163	145	132	119	110	98	91	74	64	55	48	40	34	22	1603	1171	166	179
563	1R	120	105	99	93	86	82	78	75	70	68	58	53	48	43	37	31	21	5000	9010	415	218
589	1R	133	104	97	92	88	84	80	77	70	68	58	53	46	41	35	29	19	2576	10000	1192	205
613	1R	167	141	131	121	112	105	98	94	85	80	65	61	54	49	42	36	23	3328	4640	220	193
637	1R	479	396	341	290	243	206	173	147	123	108	80	64	54	47	39	33	24	2677	158	55	177
13	2L	1094	749	544	397	296	229	178	143	118	104	83	72	63	57	49	43	30	398	62	78	153
38	2L	172	148	135	124	114	107	100	94	87	83	71	63	55	50	43	38	26	3690	3093	337	180
62	2L	119	109	104	99	93	84	77	74	68	65	55	50	44	40	35	28	20	5000	6752	234	236
87	2L	135	121	112	101	91	85	79	76	68	66	56	50	44	39	33	28	20	5000	4416	273	235
113	2L	176	138	128	118	107	101	94	89	79	74	62	55	47	42	36	30	21	2082	5549	182	219
137	2L	226	184	162	146	132	122	111	104	93	88	73	63	54	47	39	32	22	1885	2373	171	185
162	2L	173	146	133	123	112	104	97	91	83	77	64	57	49	44	38	32	21	3169	3505	202	204
187	2L	108	89	85	81	75	72	69	67	61	60	51	46	41	37	31	26	18	4497	9995	1468	228
212	2L	164	130	120	112	103	97	92	88	80	78	66	61	53	48	42	35	24	2424	4939	824	184
237	2L	184	148	132	120	109	100	92	86	78	74	61	53	46	40	34	29	20	2219	3233	245	217
262	2L	210	186	174	160	147	134	123	114	103	97	80	70	60	52	44	37	25	5000	1518	101	170
286	2L	277	222	190	165	144	129	116	107	95	89	72	61	52	45	37	32	22	1556	1059	166	186
312	2L	326	272	242	219	195	177	161	148	132	122	99	84	72	62	52	43	29	1817	1104	82	140
337	2L	184	153	143	133	123	112	103	99	91	86	72	62	53	47	40	33	22	2636	4535	200	183
363	2L	152	128	121	114	105	100	94	91	83	80	68	61	53	47	38	32	22	3649	6904	280	188
387	2L	131	106	99	94	88	84	81	78	73	71	61	57	51	46	40	34	23	3117	7970	1967	190
412	2L	200	165	137	120	110	103	97	92	84	80	67	60	52	46	38	31	20	1726	2440	646	187
437	2L	140	126	124	116	107	101	95	91	85	82	70	61	47	40	35	28	20	5000	5237	268	181
462	2L	134	116	111	106	100	93	87	83	76	72	61	54	46	41	34	28	19	5000	6872	178	215
487	2L	193	173	164	150	129	118	109	103	92	87	71	62	53	46	38	30	20	5000	1489	160	180
512	2L	312	286	262	236	213	193	170	149	123	103	74	62	50	43	35	30	21	5000	679	20	355
537	2L	257	212	189	166	148	136	125	117	107	102	84	73	61	52	44	36	25	1727	1804	196	157
562	2L	148	119	115	108	101	96	89	85	78	75	62	55	49	43	38	32	23	3174	8074	253	207

Normalised Deflection and Deflection Analysis Results

Client	Townsville City Council	**Start Date of Testing**	24-Jul-14
Target Load (kN)	50		
Road	Bamford Lane (Mill Drive to Dalrymple Road)	**Start Reference**	FWD 0 m = Start of kerb, Mill Drive
Comments	1L = OWP towards Dalrymple Road, 1R = IWP towards Dalrymple Road, 2L = OWP towards Mill Drive, 2R = IWP towards Mill Drive		

FWD Chainage (m)	Lane	Deflections (microns) Geophone Radius (mm)																	Back Analysed Modulus (MPa)			
		D0	D200	D300	D400	D500	D600	D700	D800	D900	D1000	D1200	D1400	D1600	D1800	D2000	D2250	D2500	Combined Base (200 mm)	Subbase (250 mm)	Upper Subgrade (300 mm)	Lower Subgrade (Semi-infinite)
587	2L	221	180	167	153	140	131	122	114	105	101	85	75	65	56	46	38	25	1929	3932	178	158
612	2L	206	165	145	128	113	102	91	85	76	71	57	49	40	35	30	25	17	1981	1996	179	237
637	2L	404	326	275	223	180	147	120	100	81	71	53	42	35	31	26	22	15	3023	116	104	257
3	2R	984	718	558	417	308	236	185	150	125	108	83	73	62	56	49	43	30	684	50	91	148
50	2R	208	173	159	144	130	120	108	101	91	85	69	62	54	49	41	36	24	3221	1815	147	191
75	2R	130	117	111	105	98	94	89	86	77	73	63	57	52	47	41	35	24	5000	8198	217	202
100	2R	188	160	150	139	127	119	110	104	94	89	76	67	59	53	45	38	25	3878	2877	173	174
125	2R	364	296	246	207	176	154	137	123	109	100	81	69	59	52	44	37	26	1766	377	147	162
149	2R	183	146	127	114	103	94	87	82	74	71	58	52	46	42	36	30	21	2045	2573	451	217
176	2R	164	135	123	111	101	94	87	84	76	73	61	55	49	44	37	31	21	3118	2730	532	204
200	2R	272	210	177	155	138	125	114	108	98	93	77	70	61	55	48	39	27	1313	977	536	162
225	2R	205	158	144	139	131	125	119	116	108	103	91	82	72	65	55	46	30	1412	10000	878	132
250	2R	207	182	172	160	148	140	130	123	113	106	90	78	65	57	48	40	28	5000	2361	136	144
273	2R	184	156	141	130	121	114	108	103	92	88	74	65	56	49	41	34	23	2425	5438	214	177
300	2R	262	219	195	176	159	147	136	128	117	109	91	78	69	60	50	42	27	2041	1639	187	144
324	2R	458	384	338	297	264	236	211	191	168	153	123	101	86	72	58	47	31	1531	565	46	119
351	2R	223	192	174	158	143	133	123	115	105	100	82	74	65	58	49	42	28	3002	1902	197	155
375	2R	217	193	183	170	158	147	136	127	115	108	88	78	67	57	47	37	25	5000	2354	39	182
400	2R	142	131	129	124	119	116	112	110	102	98	84	77	67	60	52	43	28	5000	10000	283	145
425	2R	138	115	109	103	98	94	90	89	83	81	72	67	60	55	48	41	28	3459	7797	2409	159
450	2R	171	152	148	142	136	131	124	120	113	109	96	82	64	57	49	40	27	5000	9316	229	131
475	2R	247	201	173	158	144	135	125	119	108	102	84	73	62	55	46	38	24	1325	3958	161	159
500	2R	183	165	148	134	123	116	106	101	92	87	72	63	54	48	40	33	21	5000	2144	190	177
526	2R	289	244	227	210	194	180	167	155	140	130	106	91	76	64	51	40	26	2449	2074	44	143
550	2R	239	198	186	172	159	148	137	129	118	111	93	81	69	60	48	39	26	2022	3628	135	143
575	2R	206	172	161	149	135	125	115	107	97	91	75	65	56	49	41	35	23	3424	2198	133	179
601	2R	350	283	240	204	174	151	132	117	102	92	71	59	49	44	36	31	22	1656	528	78	199
622	2R	195	148	133	121	108	99	90	84	76	70	58	51	45	40	33	27	18	2031	2153	305	224
650	2R	168	142	124	110	97	90	84	80	73	69	57	50	41	36	29	23	14	2452	3444	285	234

Normalised to 50 kN Deflection Results

Client	Townsville City Council	**Start Date of Testing**	24-Jul-14	**Target Load (kN)**	50
Road	Hugh Street (Attlee Street to Bayswater Road)	**Start Reference**	FWD 0 m = 29 m north of CL of Attlee Street		
Comments	1L = OWP outer lane towards Bayswater Road, 1R = IWP outer lane towards Bayswater Road, 3L = OWP inner lane towards Bayswater Road, 3R = IWP inner lane towards Bayswater				

FWD Chainage (m)	Lane	**Deflections (microns)** Geophone Radius (mm)															Air Temp. (oC)	Surf Temp. (oC)
		D0	D200	D300	D400	D500	D600	D700	D800	D900	D1000	D1200	D1400	D1600	D1800	D2000	D2250	D2500		
0	1L	201	175	160	148	134	123	113	105	93	87	68	54	46	41	33	28	20	18.8	19.3
25	1L	347	282	253	227	198	175	151	131	111	99	72	57	46	39	32	28	19	18.9	19.2
50	1L	195	183	170	154	139	129	119	112	102	95	78	68	57	49	39	31	21	19.1	19.2
75	1L	552	454	390	337	291	257	227	202	176	157	117	92	70	55	43	36	23	19.1	19.2
100	1L	399	336	292	255	219	191	166	146	125	111	81	62	49	43	36	32	24	19.2	19.1
126	1L	304	253	221	194	169	152	134	120	103	95	74	60	49	41	34	28	19	19.2	19
150	1L	323	287	259	232	206	184	161	143	123	110	82	62	49	40	33	28	20	19.3	18.9
176	1L	413	320	261	211	171	143	118	101	85	74	53	42	33	28	23	19	14	18.7	18.3
200	1L	313	228	201	173	149	131	116	103	91	84	66	56	47	41	33	27	19	18	17.5
226	1L	220	195	178	163	149	138	126	115	102	94	76	64	54	48	40	34	24	18.2	17.7
250	1L	275	223	197	178	162	151	138	129	116	109	90	79	67	59	49	41	28	18.5	17.8
275	1L	126	105	99	95	90	86	82	80	73	71	62	56	49	45	39	33	23	18.8	18
300	1L	142	113	101	93	84	80	75	72	65	63	51	48	42	39	34	28	20	18.9	18.1
325	1L	635	477	383	310	254	218	187	164	142	131	105	89	75	65	55	46	31	18.8	18.3
350	1L	357	304	272	247	223	206	187	172	153	142	114	97	79	68	57	46	32	18.7	18.3
375	1L	223	193	180	171	162	155	145	139	128	121	101	89	76	65	53	42	27	18.8	18.4
401	1L	202	183	175	164	153	144	135	127	116	109	89	75	63	51	41	31	20	18.7	18.4
12	1R	690	555	462	379	308	252	205	169	140	120	89	71	55	46	38	32	22	19.2	19.3
37	1R	220	193	180	167	151	137	124	114	101	94	76	63	53	45	38	31	21	19.1	19.2
62	1R	1009	779	625	495	385	305	242	197	161	135	99	79	66	60	52	48	36	19.2	19
87	1R	368	292	251	218	190	170	151	136	120	110	87	71	57	46	37	31	21	19.1	19
113	1R	144	127	120	118	113	109	104	101	93	89	75	65	54	45	36	28	19	19.1	18.9
137	1R	143	124	120	116	111	108	104	101	93	90	76	67	56	47	38	31	19	19.2	18.9
162	1R	247	216	201	187	173	160	146	131	115	106	81	65	51	42	33	28	20	19.1	18.9
187	1R	253	216	190	166	144	126	111	101	87	79	61	50	41	35	30	25	18	19.2	18.8
212	1R	238	176	152	135	121	109	98	90	79	74	58	51	43	39	33	28	20	19.1	18.7
239	1R	190	170	158	147	135	125	116	109	99	94	79	68	58	52	42	36	24	19.1	18.7
263	1R	195	186	160	122	97	90	85	82	75	71	60	53	45	41	35	29	21	18.9	18.6
287	1R	146	123	114	107	99	93	88	85	77	73	62	55	48	43	37	32	22	18.8	18.5
313	1R	656	526	441	361	289	235	187	151	118	97	63	54	46	42	35	32	25	18.5	18.5
339	1R	307	280	262	242	220	202	185	170	151	140	112	93	78	65	54	45	30	18.5	18.6
363	1R	221	198	185	174	161	150	139	132	120	113	92	79	67	57	47	38	25	18.6	18.7

Normalised to 50 kN Deflection Results

Client Townsville City Council | **Start Date of Testing** 24-Jul-14 | **Target Load (kN)** 50

Road Hugh Street (Attlee Street to Bayswater Road) | **Start Reference** FWD 0 m = 29 m north of CL of Attlee Street

Comments 1L = OWP outer lane towards Bayswater Road, 1R = IWP outer lane towards Bayswater Road, 3L = OWP inner lane towards Bayswater Road, 3R = IWP inner lane towards Bayswater

FWD Chainage (m)	Lane	Deflections (microns) Geophone Radius (mm)																	Air Temp. (oC)	Surf Temp. (oC)
		D0	D200	D300	D400	D500	D600	D700	D800	D900	D1000	D1200	D1400	D1600	D1800	D2000	D2250	D2500		
387	1R	240	227	217	206	193	183	171	162	149	141	120	107	93	81	68	55	35	18.3	18.7
0	3L	237	192	170	147	127	113	98	88	76	69	53	44	37	31	26	22	16	18.6	19.2
26	3L	621	544	482	422	359	308	260	222	188	164	118	89	70	57	46	40	28	18.6	19.1
51	3L	102	79	72	70	67	66	64	64	60	59	52	49	45	41	35	29	19	18.6	18.9
76	3L	74	60	58	57	55	54	53	53	49	49	44	41	38	35	31	27	17	18.7	18.9
100	3L	81	73	71	68	63	60	57	56	52	52	45	42	39	36	31	27	17	18.6	18.9
125	3L	110	99	97	96	93	92	90	89	82	78	64	53	43	36	27	23	16	18.5	18.8
150	3L	193	167	153	140	127	118	109	103	94	88	73	62	52	45	36	29	19	18.4	18.8
175	3L	159	132	122	113	104	98	92	86	77	72	60	53	45	38	30	24	16	18.5	18.7
201	3L	68	56	53	52	51	49	49	49	46	46	41	40	37	36	32	29	20	18.7	18.7
225	3L	153	133	124	116	107	101	95	90	81	78	64	57	48	43	37	31	21	18.6	18.5
251	3L	147	129	123	118	111	106	101	98	90	87	74	66	58	52	43	37	24	18.7	18.5
277	3L	210	181	160	144	131	121	112	105	94	89	72	63	55	48	40	33	22	18.8	18.5
300	3L	187	151	139	129	119	110	102	96	88	83	68	60	52	46	39	33	22	18.8	18.5
325	3L	329	291	257	226	198	178	161	146	130	119	94	80	70	62	53	45	31	18.9	18.5
351	3L	121	110	106	103	99	96	93	92	84	83	73	68	62	57	49	42	27	18.9	18.5
375	3L	205	184	171	160	149	138	129	122	111	105	88	77	66	58	48	39	26	19	18.5
400	3L	233	210	200	187	174	163	152	143	130	123	101	86	71	59	47	36	23	19	18.4
13	3R	492	403	341	283	235	198	165	141	118	102	72	57	45	40	33	29	22	19	19.7
37	3R	335	293	265	240	214	192	172	157	141	129	104	88	74	63	51	42	28	18.8	19.6
62	3R	103	90	87	84	81	79	76	76	71	70	63	59	54	50	43	37	25	18.8	19.5
88	3R	195	176	167	156	145	135	125	117	105	98	81	68	57	47	38	30	20	18.6	19.5
112	3R	195	181	173	165	155	148	139	133	122	115	95	80	63	49	39	32	22	18.5	19.5
139	3R	125	112	108	103	98	93	88	85	78	75	64	57	50	44	36	28	18	18.3	19.5
163	3R	307	261	233	210	186	167	148	134	119	109	86	69	56	46	37	30	21	18	19.4
188	3R	142	124	116	108	100	95	89	85	75	73	61	54	47	42	35	29	20	17.8	19.2
212	3R	179	157	144	132	120	111	101	95	85	80	67	58	49	43	36	30	21	17.8	19.2
237	3R	153	129	120	111	103	98	92	89	81	77	66	60	53	48	42	34	23	18.1	19.1
263	3R	159	141	132	123	112	105	98	94	85	82	71	64	56	51	43	36	26	17.9	19
287	3R	178	153	144	133	122	115	108	102	92	88	74	65	55	49	41	33	23	17.5	18.9
312	3R	684	531	436	352	280	231	185	156	128	110	78	60	48	42	34	28	19	17.3	18.9
338	3R	146	128	118	112	106	103	99	97	90	87	77	70	61	55	46	37	24	17.3	18.9

Normalised to 50 kN Deflection Results

Client	Townsville City Council	**Start Date of Testing**	24-Jul-14	**Target Load (kN)** 50
Road	Hugh Street (Attlee Street to Bayswater Road)	**Start Reference**	FWD 0 m = 29 m north of CL of Attlee Street	
Comments	1L = OWP outer lane towards Bayswater Road, 1R = IWP outer lane towards Bayswater Road, 3L = OWP inner lane towards Bayswater Road, 3R = IWP inner lane towards Bayswater			

FWD Chainage (m)	Lane	Deflections (microns) Geophone Radius (mm) D0	D200	D300	D400	D500	D600	D700	D800	D900	D1000	D1200	D1400	D1600	D1800	D2000	D2250	D2500	Air Temp. (oC)	Surf Temp. (oC)
363	3R	178	159	147	138	128	122	115	108	100	95	81	71	62	54	45	36	24	17.7	18.9
387	3R	218	201	191	180	167	157	147	138	126	118	99	85	72	62	51	42	30	17.6	18.9

Normalised Deflection and Deflection Analysis Results

Client Townsville City Council | **Start Date of Testing** 24-Jul-14 | **Target Load (kN)** 50

Road Hugh Street (Attlee Street to Bayswater Road) | **Start Reference** FWD 0 m = 29 m north of CL of Attlee Street

Comments 1L = OWP outer lane towards Bayswater Road, 1R = IWP outer lane towards Bayswater Road, 3L = OWP inner lane towards Bayswater Road, 3R = IWP inner lane towards Bayswater Road

FWD Chainage (m)	Lane	Deflections (microns) Geophone Radius (mm)																	Back Analysed Modulus (Mpa)			
		D0	D200	D300	D400	D500	D600	D700	D800	D900	D1000	D1200	D1400	D1600	D1800	D2000	D2250	D2500	Combined Base (180 mm)	Subbase (180 mm)	Upper Subgrade (300 mm)	Lower Subgrade (Semi-infinite)
0	1L	201	175	160	148	134	123	113	105	93	87	68	54	46	41	33	28	20	2541	6557	204	202
25	1L	347	282	253	227	198	175	151	131	111	99	72	57	46	39	32	28	19	1706	2035	31	255
50	1L	195	183	170	154	139	129	119	112	102	95	78	68	57	49	39	31	21	5000	3311	250	163
75	1L	552	454	390	337	291	257	227	202	176	157	117	92	70	55	43	36	23	794	1050	69	107
100	1L	399	336	292	255	219	191	166	146	125	111	81	62	49	43	36	32	24	2160	756	58	166
126	1L	304	253	221	194	169	152	134	120	103	95	74	60	49	41	34	28	19	1752	1856	112	179
150	1L	323	287	259	232	206	184	161	143	123	110	82	62	49	40	33	28	20	5000	1126	27	241
176	1L	413	320	261	211	171	143	118	101	85	74	53	42	33	28	23	19	14	922	749	79	240
200	1L	313	228	201	173	149	131	116	103	91	84	66	56	47	41	33	27	19	982	1980	183	201
226	1L	220	195	178	163	149	138	126	115	102	94	76	64	54	48	40	34	24	4477	3707	85	186
250	1L	275	223	197	178	162	151	138	129	116	109	90	79	67	59	49	41	28	1312	5090	308	145
275	1L	126	105	99	95	90	86	82	80	73	71	62	56	49	45	39	33	23	4240	10000	3087	202
300	1L	142	113	101	93	84	80	75	72	65	63	51	48	42	39	34	28	20	2361	9972	1550	243
325	1L	635	477	383	310	254	218	187	164	142	131	105	89	75	65	55	46	31	750	243	115	123
350	1L	357	304	272	247	223	206	187	172	153	142	114	97	79	68	57	46	32	1357	3456	113	117
375	1L	223	193	180	171	162	155	145	139	128	121	101	89	76	65	53	42	27	2598	10000	278	132
401	1L	202	183	175	164	153	144	135	127	116	109	89	75	63	51	41	31	20	4884	7811	222	144
12	1R	690	555	462	379	308	252	205	169	140	120	89	71	55	46	38	32	22	1711	153	38	157
37	1R	220	193	180	167	151	137	124	114	101	94	76	63	53	45	38	31	21	5000	2616	102	184
62	1R	1009	779	625	495	385	305	242	197	161	135	99	79	66	60	52	48	36	773	107	32	130
87	1R	368	292	251	218	190	170	151	136	120	110	87	71	57	46	37	31	21	911	2522	118	156
113	1R	144	127	120	118	113	109	104	101	93	89	75	65	54	45	36	28	19	5000	10000	778	175
137	1R	143	124	120	116	111	108	104	101	93	90	76	67	56	47	38	31	19	5000	10000	1563	161
162	1R	247	216	201	187	173	160	146	131	115	106	81	65	51	42	33	28	20	2788	9400	20	308
187	1R	253	216	190	166	144	126	111	101	87	79	61	50	41	35	30	25	18	2688	1534	151	208
212	1R	238	176	152	135	121	109	98	90	79	74	58	51	43	39	33	28	20	1112	5256	272	225
239	1R	190	170	158	147	135	125	116	109	99	94	79	68	58	52	42	36	24	4282	6444	271	167
263	1R	195	186	160	122	97	90	85	82	75	71	60	53	45	41	35	29	21	5000	344	2784	204
287	1R	146	123	114	107	99	93	88	85	77	73	62	55	48	43	37	32	22	3498	10000	1192	205
313	1R	656	526	441	361	289	235	187	151	118	97	63	54	46	42	35	32	25	1863	169	29	225
339	1R	307	280	262	242	220	202	185	170	151	140	112	93	78	65	54	45	30	5000	1558	81	117
363	1R	221	198	185	174	161	150	139	132	120	113	92	79	67	57	47	38	25	3546	6963	223	141
387	1R	240	227	217	206	193	183	171	162	149	141	120	107	93	81	68	55	35	5000	6233	157	105
0	3L	237	192	170	147	127	113	98	88	76	69	53	44	37	31	26	22	16	2113	2170	149	246

Normalised Deflection and Deflection Analysis Results

Client	Townsville City Council	**Start Date of Testing**	24-Jul-14	**Target Load (kN)** 50
Road	Hugh Street (Attlee Street to Bayswater Road)	**Start Reference**	FWD 0 m = 29 m north of CL of Attlee Street	
Comments	1L = OWP outer lane towards Bayswater Road, 1R = IWP outer lane towards Bayswater Road, 3L = OWP inner lane towards Bayswater Road, 3R = IWP inner lane towards Bayswater Road			

FWD Chainage (m)	Lane	Deflections (microns) Geophone Radius (mm) D0	D200	D300	D400	D500	D600	D700	D800	D900	D1000	D1200	D1400	D1600	D1800	D2000	D2250	D2500	Back Analysed Modulus (Mpa) Combined Base (180 mm)	Subbase (180 mm)	Upper Subgrade (300 mm)	Lower Subgrade (Semi-infinite)
26	3L	621	544	482	422	359	308	260	222	188	164	118	89	70	57	46	40	28	4871	91	29	134
51	3L	102	79	72	70	67	66	64	64	60	59	52	49	45	41	35	29	19	3146	10000	5000	240
76	3L	74	60	58	57	55	54	53	53	49	49	44	41	38	35	31	27	17	5000	10000	5000	312
100	3L	81	73	71	68	63	60	57	56	52	52	45	42	39	36	31	27	17	5000	10000	5000	285
125	3L	110	99	97	96	93	92	90	89	82	78	64	53	43	36	27	23	16	5000	10000	3976	188
150	3L	193	167	153	140	127	118	109	103	94	88	73	62	52	45	36	29	19	2899	6669	295	187
175	3L	159	132	122	113	104	98	92	86	77	72	60	53	45	38	30	24	16	2983	10000	467	216
201	3L	68	56	53	52	51	49	49	49	46	46	41	40	37	36	32	29	20	5000	10000	5000	337
225	3L	153	133	124	116	107	101	95	90	81	78	64	57	48	43	37	31	21	4249	9991	535	198
251	3L	147	129	123	118	111	106	101	98	90	87	74	66	58	52	43	37	24	5000	10000	1617	162
277	3L	210	181	160	144	131	121	112	105	94	89	72	63	55	48	40	33	22	2344	5330	339	179
300	3L	187	151	139	129	119	110	102	96	88	83	68	60	52	46	39	33	22	2087	9635	523	188
325	3L	329	291	257	226	198	178	161	146	130	119	94	80	70	62	53	45	31	3151	931	145	134
351	3L	121	110	106	103	99	96	93	92	84	83	73	68	62	57	49	42	27	5000	10000	5000	150
375	3L	205	184	171	160	149	138	129	122	111	105	88	77	66	58	48	39	26	3900	6984	302	145
400	3L	233	210	200	187	174	163	152	143	130	123	101	86	71	59	47	36	23	4008	6528	181	130
13	3R	492	403	341	283	235	198	165	141	118	102	72	57	45	40	33	29	22	1545	461	44	195
37	3R	335	293	265	240	214	192	172	157	141	129	104	88	74	63	51	42	28	3043	1337	95	130
62	3R	103	90	87	84	81	79	76	76	71	70	63	59	54	50	43	37	25	5000	10000	5000	190
88	3R	195	176	167	156	145	135	125	117	105	98	81	68	57	47	38	30	20	4745	7068	201	160
112	3R	195	181	173	165	155	148	139	133	122	115	95	80	63	49	39	32	22	5000	9830	257	131
139	3R	125	112	108	103	98	93	88	85	78	75	64	57	50	44	36	28	18	5000	10000	1882	187
163	3R	307	261	233	210	186	167	148	134	119	109	86	69	56	46	37	30	21	2480	1636	92	161
188	3R	142	124	116	108	100	95	89	85	75	73	61	54	47	42	35	29	20	4975	10000	627	207
212	3R	179	157	144	132	120	111	101	95	85	80	67	58	49	43	36	30	21	3818	6155	269	198
237	3R	153	129	120	111	103	98	92	89	81	77	66	60	53	48	42	34	23	3311	9999	1287	189
263	3R	159	141	132	123	112	105	98	94	85	82	71	64	56	51	43	36	26	5000	5398	861	178
287	3R	178	153	144	133	122	115	108	102	92	88	74	65	55	49	41	33	23	3692	7915	413	177
312	3R	684	531	436	352	280	231	185	156	128	110	78	60	48	42	34	28	19	724	341	36	178
338	3R	146	128	118	112	106	103	99	97	90	87	77	70	61	55	46	37	24	3567	9024	5000	146
363	3R	178	159	147	138	128	122	115	108	100	95	81	71	62	54	45	36	24	4031	9945	481	158
387	3R	218	201	191	180	167	157	147	138	126	118	99	85	72	62	51	42	30	5000	5276	201	126

Normalised to 50 kN Deflection Results

Client	Townsville City Council	**Start Date of Testing**	24-Jul-14	**Target Load (kN)**	50
Road	Palmerston Street (Hugh Street to Kings Road)	**Start Reference**	FWD 0 m = Start of Kerb, Hugh Street RHS		
Comments	1L = OWP towards Kings Road, 1R = IWP towards Kings Road, 2L = OWP towards Hugh Street, 2R = IWP towards Hugh Street				

FWD Chainage (m)	Lane	**Deflections (microns)** Geophone Radius (mm) D0	D200	D300	D400	D500	D600	D700	D800	D900	D1000	D1200	D1400	D1600	D1800	D2000	D2250	D2500	Air Temp. (oC)	Surf Temp. (oC)
0	1L	1809	1144	911	714	554	439	342	273	223	190	152	130	116	104	94	82	59	18.7	19
25	1L	535	428	373	321	271	234	201	174	149	133	104	86	72	65	56	49	34	19	19.2
51	1L	593	472	394	333	280	240	206	180	153	137	103	87	74	65	57	50	34	18.9	19.2
75	1L	371	315	282	250	218	194	169	150	130	118	93	78	66	59	52	46	32	18.9	19.2
100	1L	649	500	406	335	281	244	211	186	161	145	116	96	83	72	62	53	38	19	19.4
126	1L	630	489	408	339	282	241	207	180	157	139	109	93	79	71	61	54	38	19	19.4
150	1L	758	565	456	360	283	231	190	163	141	125	99	84	73	65	56	49	35	19.1	19.5
175	1L	404	342	305	265	230	202	176	156	136	123	99	85	73	65	58	50	34	19.1	19.6
200	1L	344	301	270	239	209	185	163	146	128	116	92	77	66	58	50	42	30	19	19.6
225	1L	358	309	278	247	210	185	161	143	124	110	83	66	55	48	41	36	25	18.9	19.5
251	1L	591	462	384	320	261	216	177	150	126	109	84	71	61	55	47	41	28	19	19.5
276	1L	108	90	86	82	78	76	73	72	68	66	59	54	47	43	37	31	20	19	19.6
300	1L	151	130	121	112	104	96	89	84	76	73	61	53	46	41	34	27	17	19.1	19.6
325	1L	160	136	125	117	107	100	92	86	78	73	60	51	43	37	30	24	15	19.2	19.6
350	1L	152	132	123	114	105	97	90	85	77	72	57	49	42	36	29	25	17	19.1	19.6
375	1L	199	173	161	148	136	126	118	110	100	94	78	67	57	50	42	36	23	19.1	19.6
400	1L	150	123	112	106	100	96	92	89	83	81	69	63	56	50	41	35	22	19.2	19.6
426	1L	195	159	146	133	122	114	105	99	90	85	72	63	54	46	38	30	19	19.1	19.5
451	1L	165	144	135	126	116	109	102	96	88	85	71	63	56	48	40	33	21	19.3	19.6
475	1L	333	279	258	235	210	192	176	162	143	130	102	86	71	58	47	37	24	19.3	19.7
500	1L	310	271	252	234	215	200	182	167	151	139	111	92	76	62	50	38	25	19.3	19.7
525	1L	275	230	213	199	183	170	157	145	132	123	100	84	71	59	48	38	25	19.3	19.6
550	1L	310	286	267	245	222	197	177	162	144	133	105	87	71	58	47	38	25	19.4	19.8
576	1L	320	292	272	251	227	209	184	167	148	137	109	91	74	60	47	37	25	19.5	19.9
600	1L	355	294	255	229	206	186	167	153	137	126	102	85	70	60	49	41	28	19.5	20
625	1L	387	316	278	250	225	205	184	166	148	136	110	91	77	64	52	42	27	19.4	19.9
651	1L	425	332	283	249	220	199	178	161	142	131	102	85	70	59	49	41	27	19.3	20.1
676	1L	408	361	329	296	262	232	206	183	157	144	113	91	77	65	55	47	31	19.5	20.2
701	1L	400	338	306	278	253	229	206	186	167	154	124	104	87	72	60	49	33	19.3	20
726	1L	1033	798	651	528	431	363	306	261	221	193	145	117	94	82	69	60	41	19.3	20
750	1L	223	174	156	144	135	128	121	116	107	104	90	81	71	63	54	45	31	19.3	20.1
776	1L	221	190	174	161	149	140	132	126	116	111	97	88	77	65	54	44	28	19.3	20.1
802	1L	208	182	166	153	141	133	124	117	104	98	80	69	60	52	44	36	24	19.3	20.1

Normalised to 50 kN Deflection Results

Client	Townsville City Council	**Start Date of Testing**	24-Jul-14	**Target Load (kN)**	50
Road	Palmerston Street (Hugh Street to Kings Road)	**Start Reference**	FWD 0 m = Start of Kerb, Hugh Street RHS		
Comments	1L = OWP towards Kings Road, 1R = IWP towards Kings Road, 2L = OWP towards Hugh Street, 2R = IWP towards Hugh Street				

FWD Chainage (m)	Lane	**Deflections (microns)** Geophone Radius (mm)																	Air Temp. (oC)	Surf Temp. (oC)
		D0	D200	D300	D400	D500	D600	D700	D800	D900	D1000	D1200	D1400	D1600	D1800	D2000	D2250	D2500		
826	1L	123	109	103	98	92	88	84	81	74	72	61	53	47	42	36	30	20	19.4	20.2
850	1L	338	272	224	181	144	117	95	86	77	76	64	59	52	48	41	36	24	19.7	20.2
12	1R	1136	821	643	495	377	298	237	196	165	145	113	95	81	71	61	55	39	18.7	18.9
37	1R	744	597	484	395	311	254	206	175	149	132	105	91	77	69	61	55	39	18.3	19
62	1R	556	455	387	329	275	236	201	173	149	133	103	86	73	65	57	50	35	18.1	18.8
88	1R	130	115	111	106	101	97	95	92	87	85	75	70	64	60	54	48	31	18.1	18.9
113	1R	315	266	244	222	201	184	167	152	136	125	101	85	71	62	52	44	31	18.2	18.9
138	1R	400	344	305	269	235	207	183	162	143	129	100	82	68	58	49	42	30	18.2	18.9
163	1R	528	422	361	309	257	221	189	165	140	126	94	80	68	59	50	43	30	18.2	19
187	1R	975	689	519	388	293	233	188	158	134	118	93	78	67	59	50	44	30	18.2	19
214	1R	422	358	321	282	240	211	183	161	137	123	92	74	60	54	46	38	27	18.4	19
238	1R	635	504	420	343	276	228	185	154	127	108	80	65	55	50	43	38	28	18.3	19
263	1R	175	145	130	120	111	105	100	96	88	86	74	67	58	50	42	36	24	18.2	19
288	1R	141	123	114	104	95	89	82	78	70	67	55	50	44	38	32	26	18	18.2	19
312	1R	150	128	122	114	107	101	94	89	81	77	64	55	47	39	32	26	17	18.4	19.1
338	1R	180	158	148	137	125	116	106	99	89	84	67	57	48	42	34	30	20	18.3	19.2
363	1R	189	162	147	135	124	115	106	99	89	84	69	60	52	45	38	32	21	18.6	19.3
388	1R	181	160	150	140	129	121	113	108	98	92	76	67	58	50	42	36	24	18.8	19.3
413	1R	158	142	135	127	118	112	104	99	90	86	73	62	56	48	41	33	23	18.8	19.3
438	1R	254	222	207	191	175	161	148	137	123	115	95	80	66	53	44	35	24	18.8	19.2
463	1R	711	564	460	377	309	262	220	190	160	139	101	80	65	53	43	37	26	18.7	19.2
487	1R	321	283	262	238	216	197	177	162	144	132	105	85	69	58	47	37	24	18.8	19.2
513	1R	337	275	250	225	200	181	162	148	131	120	95	78	64	54	44	36	24	18.8	19.2
538	1R	263	248	229	207	187	172	155	143	126	117	91	76	63	53	43	34	23	18.9	19.2
564	1R	315	271	249	229	207	191	172	158	141	129	102	84	68	56	45	37	24	18.9	19.2
587	1R	279	245	227	208	187	171	154	142	125	115	90	73	61	51	42	35	24	18.9	19.3
613	1R	301	253	231	207	183	165	148	134	118	108	85	70	57	49	40	33	23	18.9	19.3
637	1R	275	243	224	205	184	169	151	138	122	111	88	75	61	52	43	36	24	19	19.3
663	1R	275	241	221	203	182	168	152	140	126	116	93	79	67	57	48	40	27	19	19.5
689	1R	1036	828	673	542	437	357	295	247	207	180	136	110	89	77	65	57	39	19.1	19.5
713	1R	291	262	243	224	205	188	170	156	138	127	102	85	71	60	50	42	29	19.3	19.7
738	1R	426	340	297	263	231	205	175	154	133	125	103	89	74	63	52	43	29	19.4	19.7
764	1R	180	152	141	132	122	115	107	102	92	88	73	65	58	51	43	35	23	19	19.7

NPC NORTHERN PAVEMENT CONSULTANTS

Normalised to 50 kN Deflection Results

Client	Townsville City Council	**Start Date of Testing**	24-Jul-14
Target Load (kN)	50		
Road	Palmerston Street (Hugh Street to Kings Road)	**Start Reference**	FWD 0 m = Start of Kerb, Hugh Street RHS
Comments	1L = OWP towards Kings Road, 1R = IWP towards Kings Road, 2L = OWP towards Hugh Street, 2R = IWP towards Hugh Street		

FWD Chainage (m)	Lane	Deflections (microns) Geophone Radius (mm) D0	D200	D300	D400	D500	D600	D700	D800	D900	D1000	D1200	D1400	D1600	D1800	D2000	D2250	D2500	Air Temp. (oC)	Surf Temp. (oC)
787	1R	165	145	133	125	116	109	103	99	91	87	73	65	56	49	41	35	23	19	19.7
813	1R	247	221	200	180	164	154	141	131	118	110	88	73	60	51	42	35	25	19.1	19.8
838	1R	170	147	132	122	111	103	95	88	80	74	59	51	43	38	31	26	19	19.4	19.8
862	1R	140	119	109	102	96	92	88	86	80	78	68	62	56	51	44	37	25	19.4	19.6
12	2L	163	148	127	118	112	108	103	100	92	89	78	70	61	55	46	37	25	19.1	18.3
37	2L	549	442	381	322	276	241	206	180	155	139	107	89	75	65	56	48	33	18.9	18.3
62	2L	755	553	438	352	286	240	203	175	150	132	102	86	73	65	56	49	35	18.8	18.3
88	2L	104	91	88	86	82	80	79	78	73	73	65	59	53	49	43	38	25	18.7	18.4
110	2L	379	301	267	242	220	201	181	166	149	137	108	91	76	64	54	46	31	18.8	18.5
137	2L	433	344	304	269	236	211	188	167	145	125	102	85	71	62	52	47	31	18.8	18.4
162	2L	390	329	274	236	211	191	171	154	137	124	99	83	68	60	50	44	30	18.7	18.3
186	2L	634	509	432	361	299	250	211	181	153	134	102	86	72	64	55	47	33	18.7	18.2
212	2L	581	477	420	366	319	283	247	218	190	170	130	101	79	65	53	44	30	18.9	18.5
237	2L	332	291	269	245	221	200	181	161	142	129	98	80	64	51	41	33	23	19.1	18.7
262	2L	158	144	137	135	136	136	136	133	121	110	77	57	46	41	35	30	22	19.3	18.9
288	2L	120	99	91	86	81	76	73	70	65	62	53	48	41	37	31	26	18	19.2	18.9
312	2L	203	171	158	146	134	123	110	102	92	86	70	60	50	44	35	28	19	19.3	19
338	2L	198	175	161	147	134	124	113	106	96	89	73	61	51	44	37	31	21	19.4	19
363	2L	166	132	122	114	106	100	94	89	81	79	66	59	51	45	38	32	22	19.3	18.9
387	2L	221	197	183	168	153	142	130	121	111	103	83	70	58	50	41	35	24	19.1	18.9
412	2L	143	123	115	108	102	98	93	91	83	81	70	61	54	48	40	32	21	19	19
437	2L	188	158	147	135	123	116	108	102	93	88	73	64	55	47	39	32	21	19.1	19
462	2L	773	607	507	417	335	277	227	188	158	136	97	75	54	39	31	26	20	19.2	19
487	2L	407	338	304	273	242	219	195	176	153	138	105	85	67	54	43	35	23	19.2	19
512	2L	294	253	233	214	196	181	165	152	137	126	100	84	68	56	44	35	24	19.2	19
538	2L	349	298	274	248	223	204	182	166	147	133	105	85	68	56	44	36	23	19.2	18.9
563	2L	380	333	305	278	250	227	204	183	162	145	112	90	71	57	45	35	23	19.1	18.9
587	2L	333	287	264	236	212	193	175	158	140	129	100	81	64	53	43	34	23	19.5	19
613	2L	233	208	197	181	166	154	142	131	116	107	85	71	60	50	41	32	22	19.6	19
637	2L	316	272	250	227	205	185	167	153	135	125	99	82	68	57	46	37	26	19.6	19.1
661	2L	359	316	293	270	239	216	193	176	156	143	113	92	75	62	51	42	28	19.1	19
688	2L	459	386	342	303	265	236	210	189	167	152	119	98	81	68	56	47	32	19.2	18.9
713	2L	375	330	301	267	236	216	196	180	163	149	117	97	79	65	53	41	29	19	18.9

Normalised to 50 kN Deflection Results

Client	Townsville City Council	**Start Date of Testing**	24-Jul-14	**Target Load (kN)**	50
Road	Palmerston Street (Hugh Street to Kings Road)	**Start Reference**	FWD 0 m = Start of Kerb, Hugh Street RHS		
Comments	1L = OWP towards Kings Road, 1R = IWP towards Kings Road, 2L = OWP towards Hugh Street, 2R = IWP towards Hugh Street				

FWD Chainage (m)	Lane	Deflections (microns) Geophone Radius (mm) D0	D200	D300	D400	D500	D600	D700	D800	D900	D1000	D1200	D1400	D1600	D1800	D2000	D2250	D2500	Air Temp. (oC)	Surf Temp. (oC)
737	2L	368	317	282	254	226	203	180	160	138	123	91	72	56	49	41	35	26	19	18.9
763	2L	131	117	112	106	100	96	91	88	82	79	69	63	57	50	43	37	24	18.9	18.8
787	2L	145	129	124	118	111	107	101	98	90	86	73	65	58	51	44	36	24	18.9	18.8
813	2L	110	98	95	91	85	83	80	78	72	70	60	55	49	44	38	32	21	19.5	18.8
838	2L	122	107	101	96	90	87	83	80	74	71	57	50	44	39	33	28	19	19.2	18.6
862	2L	94	87	85	83	80	78	77	77	72	72	64	61	56	52	46	40	26	19.2	18.4
0	2R	972	700	546	419	323	263	215	181	151	132	103	90	80	76	69	64	43	18.7	19.3
25	2R	119	105	102	100	96	93	90	89	83	81	72	67	60	53	46	39	26	18.7	19.4
49	2R	493	409	357	313	267	233	203	178	155	139	107	90	75	66	57	49	34	18.7	19.4
74	2R	96	81	78	76	73	71	70	69	64	64	56	53	49	44	39	33	23	18.7	19.6
100	2R	404	340	306	273	241	216	192	173	151	138	108	90	75	67	57	49	34	18.7	19.7
125	2R	288	258	241	224	206	189	172	159	143	133	106	90	75	65	55	47	32	18.7	19.8
149	2R	301	268	242	218	195	176	158	142	124	115	90	75	62	53	45	38	28	18.6	19.8
175	2R	264	235	218	197	178	162	146	133	116	106	82	69	57	50	42	35	24	18.6	19.8
200	2R	350	294	262	232	201	172	150	133	113	103	78	64	53	47	40	34	24	18.5	19.7
225	2R	271	237	218	197	176	159	142	128	110	102	78	65	54	46	39	34	24	18.6	19.7
249	2R	491	402	355	312	271	237	206	181	156	137	102	80	64	53	44	37	26	18.6	19.7
272	2R	125	100	90	82	75	71	66	64	57	56	47	42	37	34	28	24	17	18.5	19.6
300	2R	268	219	192	168	149	134	121	110	97	90	73	62	52	45	37	31	21	18.5	19.5
325	2R	576	457	376	311	256	216	183	159	132	116	86	69	54	46	37	32	22	18.5	19.5
349	2R	189	168	156	143	131	120	109	100	89	82	66	55	44	38	31	26	18	18.6	19.6
375	2R	252	224	203	186	170	157	143	130	116	107	85	72	59	51	43	36	25	18.7	19.6
400	2R	211	185	169	156	143	133	123	115	104	97	80	69	57	49	40	33	22	19	20.1
426	2R	162	144	137	128	120	114	106	100	91	85	71	62	53	45	36	29	19	19.2	20.2
449	2R	118	101	98	92	87	82	80	77	71	69	61	54	49	43	36	29	20	19.2	20.2
475	2R	475	379	336	296	255	226	197	174	149	133	101	79	62	52	41	34	24	19.2	20.1
500	2R	397	346	316	281	249	222	197	176	153	137	105	84	67	55	44	36	24	19.1	20.1
525	2R	348	307	281	254	226	204	183	165	145	132	102	84	67	57	46	37	26	19.1	20.1
550	2R	444	414	377	340	306	276	246	214	185	166	125	99	79	64	51	42	28	19.2	20.2
575	2R	411	359	325	292	259	235	209	188	164	148	113	89	71	58	46	37	25	19.2	20.2
598	2R	380	313	281	249	219	195	172	152	132	118	93	74	61	52	44	38	26	19.1	20.2
625	2R	385	333	298	264	232	207	182	162	140	126	97	79	66	56	47	39	26	19.3	20.1
650	2R	490	405	361	317	276	243	211	187	162	144	110	88	71	60	49	41	27	19.2	20

Normalised to 50 kN Deflection Results

Client	Townsville City Council
Start Date of Testing	24-Jul-14
Target Load (kN)	50
Road	Palmerston Street (Hugh Street to Kings Road)
Start Reference	FWD 0 m = Start of Kerb, Hugh Street RHS
Comments	1L = OWP towards Kings Road, 1R = IWP towards Kings Road, 2L = OWP towards Hugh Street, 2R = IWP towards Hugh Street

FWD Chainage (m)	Lane	**Deflections (microns)** Geophone Radius (mm)																	Air Temp. (oC)	Surf Temp. (oC)
		D0	D200	D300	D400	D500	D600	D700	D800	D900	D1000	D1200	D1400	D1600	D1800	D2000	D2250	D2500		
675	2R	332	293	261	236	208	187	167	151	132	121	95	79	63	57	48	41	28	19.1	19.8
700	2R	523	431	384	336	290	254	221	193	167	149	114	93	78	67	56	48	32	19.1	19.8
725	2R	1085	796	616	470	360	292	239	203	172	152	118	98	82	70	61	53	37	19	19.7
750	2R	296	260	236	215	196	180	166	155	141	132	107	92	79	68	58	49	33	18.8	19.6
775	2R	252	222	206	190	174	160	147	138	125	118	98	87	75	66	56	46	31	18.8	19.5
799	2R	169	156	149	142	134	128	120	114	103	98	81	70	60	53	44	38	25	18.7	19.4
825	2R	201	177	164	153	143	137	128	122	113	108	92	81	70	60	51	41	27	18.6	19.2
850	2R	125	112	108	103	97	93	89	87	80	77	67	59	52	46	40	33	21	18.5	19

Normalised Deflection and Deflection Analysis Results

Client Townsville City Council | **Start Date of Testing** 24-Jul-14 | **Target Load (kN)** 50

Road Palmerston Street (Hugh Street to Kings Road) | **Start Reference** FWD 0 m = Start of Kerb, Hugh Street RHS

Comments 1L = OWP towards Kings Road, 1R = IWP towards Kings Road, 2L = OWP towards Hugh Street, 2R = IWP towards Hugh Street

FWD Chainage (m)	Lane	Deflections (microns) Geophone Radius (mm) D0	D200	D300	D400	D500	D600	D700	D800	D900	D1000	D1200	D1400	D1600	D1800	D2000	D2250	D2500	Back Analysed Modulus (Mpa) Combined Base (170 mm)	Combined Base (300 mm)	Subbase (200 mm)	Subgrade 1 (300 mm)	Subgrade 2 (500 mm)	Subgrade 3 (Semi-infinite)
0	1L	1809	1144	911	714	554	439	342	273	223	190	152	130	116	104	94	82	59		184		27	71	80
25	1L	535	428	373	321	271	234	201	174	149	133	104	86	72	65	56	49	34		1243		84	100	130
51	1L	593	472	394	333	280	240	206	180	153	137	103	87	74	65	57	50	34		970		85	91	129
75	1L	371	315	282	250	218	194	169	150	130	118	93	78	66	59	52	46	32		2494		115	107	150
100	1L	649	500	406	335	281	244	211	186	161	145	116	96	83	72	62	53	38		648		136	85	114
126	1L	630	489	408	339	282	241	207	180	157	139	109	93	79	71	61	54	38		788		101	90	121
150	1L	758	565	456	360	283	231	190	163	141	125	99	84	73	65	56	49	35		580		51	209	123
175	1L	404	342	305	265	230	202	176	156	136	123	99	85	73	65	58	50	34		2199		73	187	134
200	1L	344	301	270	239	209	185	163	146	128	116	92	77	66	58	50	42	30		3259		50	429	149
225	1L	358	309	278	247	210	185	161	143	124	110	83	66	55	48	41	36	25		3247		28	4708	186
251	1L	591	462	384	320	261	216	177	150	126	109	84	71	61	55	47	41	28	1455		275	34	1075	155
276	1L	108	90	86	82	78	76	73	72	68	66	59	54	47	43	37	31	20	4766		10000	5000	430	181
300	1L	151	130	121	112	104	96	89	84	76	73	61	53	46	41	34	27	17	4380		6185	785	135	229
325	1L	160	136	125	117	107	100	92	86	78	73	60	51	43	37	30	24	15	3519		7073	714	95	265
350	1L	152	132	123	114	105	97	90	85	77	72	57	49	42	36	29	25	17	4566		7067	493	112	262
375	1L	199	173	161	148	136	126	118	110	100	94	78	67	57	50	42	36	23	3591		4676	347	130	175
400	1L	150	123	112	106	100	96	92	89	83	81	69	63	56	50	41	35	22	2318		10000	2548	242	167
426	1L	195	159	146	133	122	114	105	99	90	85	72	63	54	46	38	30	19	3696		1636	1413	80	208
451	1L	165	144	135	126	116	109	102	96	88	85	71	63	56	48	40	33	21		5000		2045	92	203
475	1L	333	279	258	235	210	192	176	162	143	130	102	86	71	58	47	37	24		2582		510	37	185
500	1L	310	271	252	234	215	200	182	167	151	139	111	92	76	62	50	38	25		3358		794	20	285
525	1L	275	230	213	199	183	170	157	145	132	123	100	84	71	59	48	38	25		2542		1388	26	248
550	1L	310	286	267	245	222	197	177	162	144	133	105	87	71	58	47	38	25		5000		89	72	153
576	1L	320	292	272	251	227	209	184	167	148	137	109	91	74	60	47	37	25		5000		80	74	147
600	1L	355	294	255	229	206	186	167	153	137	126	102	85	70	60	49	41	28		1529		609	57	157
625	1L	387	316	278	250	225	205	184	166	148	136	110	91	77	64	52	42	27		1476		522	54	144
651	1L	425	332	283	249	220	199	178	161	142	131	102	85	70	59	49	41	27		1026		520	53	158
676	1L	408	361	329	296	262	232	206	183	157	144	113	91	77	65	55	47	31		3355		24	1679	138
701	1L	400	338	306	278	253	229	206	186	167	154	124	104	87	72	60	49	33		2059		374	47	128
726	1L	1033	798	651	528	431	363	306	261	221	193	145	117	94	82	69	60	41		428		73	42	99
750	1L	223	174	156	144	135	128	121	116	107	104	90	81	71	63	54	45	31	1473		1998	3350	85	149
776	1L	221	190	174	161	149	140	132	126	116	111	97	88	77	65	54	44	28	2346		5258	605	207	123
802	1L	208	182	166	153	141	133	124	117	104	98	80	69	60	52	44	36	24	2847		6774	308	99	180
826	1L	123	109	103	98	92	88	84	81	74	72	61	53	47	42	36	30	20	5000		4618	5000	20	955
850	1L	338	272	224	181	144	117	95	86	77	76	64	59	52	48	41	36	24	3082		274	103	5000	164
12	1R	1136	821	643	495	377	298	237	196	165	145	113	95	81	71	61	55	39		338		37	116	109
37	1R	744	597	484	395	311	254	206	175	149	132	105	91	77	69	61	55	39		795		26	3212	113
62	1R	556	455	387	329	275	236	201	173	149	133	103	86	73	65	57	50	35		1235		51	199	125
88	1R	130	115	111	106	101	97	95	92	87	85	75	70	64	60	54	48	31		5000		5000	439	143
113	1R	315	266	244	222	201	184	167	152	136	125	101	85	71	62	52	44	31		2645		561	48	169
138	1R	400	344	305	269	235	207	183	162	143	129	100	82	68	58	49	42	30		2338		106	91	143
163	1R	528	422	361	309	257	221	189	165	140	126	94	80	68	59	50	43	30		1185		87	97	144

Normalised Deflection and Deflection Analysis Results

Client Townsville City Council | **Start Date of Testing** 24-Jul-14 | **Target Load (kN)** 50

Road Palmerston Street (Hugh Street to Kings Road) | **Start Reference** FWD 0 m = Start of Kerb, Hugh Street RHS

Comments 1L = OWP towards Kings Road, 1R = IWP towards Kings Road, 2L = OWP towards Hugh Street, 2R = IWP towards Hugh Street

FWD Chainage (m)	Lane	Deflections (microns) Geophone Radius (mm)																	Back Analysed Modulus (Mpa)					
		D0	D200	D300	D400	D500	D600	D700	D800	D900	D1000	D1200	D1400	D1600	D1800	D2000	D2250	D2500	Combined Base (170 mm)	Combined Base (300 mm)	Subbase (200 mm)	Subgrade 1 (300 mm)	Subgrade 2 (500 mm)	Subgrade 3 (Semi-infinite)
187	1R	975	689	519	388	293	233	188	158	134	118	93	78	67	59	50	44	30		337		54	136	132
214	1R	422	358	321	282	240	211	183	161	137	123	92	74	60	54	46	38	27		2248		88	76	167
238	1R	635	504	420	343	276	228	185	154	127	108	80	65	55	50	43	38	28		954		34	392	162
263	1R	175	145	130	120	111	105	100	96	88	86	74	67	58	50	42	36	24	4106		1307	5000	20	503
288	1R	141	123	114	104	95	89	82	78	70	67	55	50	44	38	32	26	18	5000		4111	1263	106	269
312	1R	150	128	122	114	107	101	94	89	81	77	64	55	47	39	32	26	17	5000		3382	2760	20	1194
338	1R	180	158	148	137	125	116	106	99	89	84	67	57	48	42	34	30	20	5000		4877	209	103	233
363	1R	189	162	147	135	124	115	106	99	89	84	69	60	52	45	38	32	21	2887		4927	643	98	214
388	1R	181	160	150	140	129	121	113	108	98	92	76	67	58	50	42	36	24	4411		6180	528	99	184
413	1R	158	142	135	127	118	112	104	99	90	86	73	62	56	48	41	33	23	5000		9282	301	164	183
438	1R	254	222	207	191	175	161	148	137	123	115	95	80	66	53	44	35	24	5000		1150	841	20	386
463	1R	711	564	460	377	309	262	220	190	160	139	101	80	65	53	43	37	26		689		100	53	146
487	1R	321	283	262	238	216	197	177	162	144	132	105	85	69	58	47	37	24		3708		371	36	194
513	1R	337	275	250	225	200	181	162	148	131	120	95	78	64	54	44	36	24		1973		552	46	190
538	1R	263	248	229	207	187	172	155	143	126	117	91	76	63	53	43	34	23		5000		294	49	198
564	1R	315	271	249	229	207	191	172	158	141	129	102	84	68	56	45	37	24		2898		676	25	262
587	1R	279	245	227	208	187	171	154	142	125	115	90	73	61	51	42	35	24		4758		250	58	187
613	1R	301	253	231	207	183	165	148	134	118	108	85	70	57	49	40	33	23		2777		435	54	210
637	1R	275	243	224	205	184	169	151	138	122	111	88	75	61	52	43	36	24		4828		239	70	178
663	1R	275	241	221	203	182	168	152	140	126	116	93	79	67	57	48	40	27		4366		312	76	160
689	1R	1036	828	673	542	437	357	295	247	207	180	136	110	89	77	65	57	39		501		39	69	97
713	1R	291	262	243	224	205	188	170	156	138	127	102	85	71	60	50	42	29		5000		209	58	158
738	1R	426	340	297	263	231	205	175	154	133	125	103	89	74	63	52	43	29		1614		117	164	124
764	1R	180	152	141	132	122	115	107	102	92	88	73	65	58	51	43	35	23	2598		8542	1040	81	203
787	1R	165	145	133	125	116	109	103	99	91	87	73	65	56	49	41	35	23	3591		9056	766	150	177
813	1R	247	221	200	180	164	154	141	131	118	110	88	73	60	51	42	35	25	5000		1098	925	20	470
838	1R	170	147	132	122	111	103	95	88	80	74	59	51	43	38	31	26	19	3112		7879	307	116	263
862	1R	140	119	109	102	96	92	88	86	80	78	68	62	56	51	44	37	25	3253		4200	5000	125	178
12	2L	163	148	127	118	112	108	103	100	92	89	78	70	61	55	46	37	25		4859		2060	294	149
37	2L	549	442	381	322	276	241	206	180	155	139	107	89	75	65	56	48	33		1116		105	83	127
62	2L	755	553	438	352	286	240	203	175	150	132	102	86	73	65	56	49	35		496		102	83	128
88	2L	104	91	88	86	82	80	79	78	73	73	65	59	53	49	43	38	25		5000		4171	710	173
110	2L	379	301	267	242	220	201	181	166	149	137	108	91	76	64	54	46	31		1311		778	37	170
137	2L	433	344	304	269	236	211	188	167	145	125	102	85	71	62	52	47	31		1458		250	63	146
162	2L	390	329	274	236	211	191	171	154	137	124	99	83	68	60	50	44	30		1215		510	60	157
186	2L	634	509	432	361	299	250	211	181	153	134	102	86	72	64	55	47	33		1010		47	138	129
212	2L	581	477	420	366	319	283	247	218	190	170	130	101	79	65	53	44	30		1108		205	33	139
237	2L	332	291	269	245	221	200	181	161	142	129	98	80	64	51	41	33	23		4011		193	43	194
262	2L	158	144	137	135	136	136	136	133	121	110	77	57	46	41	35	30	22	4736		10000	1433	105	199
288	2L	120	99	91	86	81	76	73	70	65	62	53	48	41	37	31	26	18	3564		10000	2111	261	233
312	2L	203	171	158	146	134	123	110	102	92	86	70	60	50	44	35	28	19	2716		6172	141	155	212
338	2L	198	175	161	147	134	124	113	106	96	89	73	61	51	44	37	31	21	4692		3420	342	85	214

Normalised Deflection and Deflection Analysis Results

Client Townsville City Council | **Start Date of Testing** 24-Jul-14 | **Target Load (kN)** 50

Road Palmerston Street (Hugh Street to Kings Road) | **Start Reference** FWD 0 m = Start of Kerb, Hugh Street RHS

Comments 1L = OWP towards Kings Road, 1R = IWP towards Kings Road, 2L = OWP towards Hugh Street, 2R = IWP towards Hugh Street

FWD Chainage (m)	Lane	Deflections (microns) Geophone Radius (mm)																	Back Analysed Modulus (Mpa)					
		D0	D200	D300	D400	D500	D600	D700	D800	D900	D1000	D1200	D1400	D1600	D1800	D2000	D2250	D2500	Combined Base (170 mm)	Combined Base (300 mm)	Subbase (200 mm)	Subgrade 1 (300 mm)	Subgrade 2 (500 mm)	Subgrade 3 (Semi-infinite)
363	2L	166	132	122	114	106	100	94	89	81	79	66	59	51	45	38	32	22	1955		9730	1442	149	198
387	2L	221	197	183	168	153	142	130	121	111	103	83	70	58	50	41	35	24	5000		2837	254	61	208
412	2L	143	123	115	108	102	98	93	91	83	81	70	61	54	48	40	32	21	4595		3901	5000	20	527
437	2L	188	158	147	135	123	116	108	102	93	88	73	64	55	47	39	32	21	2750		5911	583	141	183
462	2L	773	607	507	417	335	277	227	188	158	136	97	75	54	39	31	26	20		734		47	78	144
487	2L	407	338	304	273	242	219	195	176	153	138	105	85	67	54	43	35	23		1789		388	30	205
512	2L	294	253	233	214	196	181	165	152	137	126	100	84	68	56	44	35	24		2744		1019	20	371
538	2L	349	298	274	248	223	204	182	166	147	133	105	85	68	56	44	36	23		2578		478	30	215
563	2L	380	333	305	278	250	227	204	183	162	145	112	90	71	57	45	35	23		3322		184	36	175
587	2L	333	287	264	236	212	193	175	158	140	129	100	81	64	53	43	34	23		2574		580	25	289
613	2L	233	208	197	181	166	154	142	131	116	107	85	71	60	50	41	32	22		5000		1013	20	597
637	2L	316	272	250	227	205	185	167	153	135	125	99	82	68	57	46	37	26		3356		315	56	165
661	2L	359	316	293	270	239	216	193	176	156	143	113	92	75	62	51	42	28		4130		91	65	142
688	2L	459	386	342	303	265	236	210	189	167	152	119	98	81	68	56	47	32		1657		211	55	127
713	2L	375	330	301	267	236	216	196	180	163	149	117	97	79	65	53	41	29		2465		394	36	157
737	2L	368	317	282	254	226	203	180	160	138	123	91	72	56	49	41	35	26		2608		251	34	245
763	2L	131	117	112	106	100	96	91	88	82	79	69	63	57	50	43	37	24	5000		9485	2307	178	170
787	2L	145	129	124	118	111	107	101	98	90	86	73	65	58	51	44	36	24	5000		10000	1396	109	177
813	2L	110	98	95	91	85	83	80	78	72	70	60	55	49	44	38	32	21	5000		10000	5000	147	197
838	2L	122	107	101	96	90	87	83	80	74	71	57	50	44	39	33	28	19	5000		6085	5000	20	1114
862	2L	94	87	85	83	80	78	77	77	72	72	64	61	56	52	46	40	26	5000		10000	5000	375	178
0	2R	972	700	546	419	323	263	215	181	151	132	103	90	80	76	69	64	43		368		56	97	121
25	2R	119	105	102	100	96	93	90	89	83	81	72	67	60	53	46	39	26		5000		4999	394	156
49	2R	493	409	357	313	267	233	203	178	155	139	107	90	75	66	57	49	34		1558		90	94	127
74	2R	96	81	78	76	73	71	70	69	64	64	56	53	49	44	39	33	23		5000		5000	581	208
100	2R	404	340	306	273	241	216	192	173	151	138	108	90	75	67	57	49	34		2232		147	82	130
125	2R	288	258	241	224	206	189	172	159	143	133	106	90	75	65	55	47	32		5000		467	31	204
149	2R	301	268	242	218	195	176	158	142	124	115	90	75	62	53	45	38	28		4000		160	85	166
175	2R	264	235	218	197	178	162	146	133	116	106	82	69	57	50	42	35	24		5000		206	74	190
200	2R	350	294	262	232	201	172	150	133	113	103	78	64	53	47	40	34	24		2518		114	107	185
225	2R	271	237	218	197	176	159	142	128	110	102	78	65	54	46	39	34	24		4582		183	81	199
249	2R	491	402	355	312	271	237	206	181	156	137	102	80	64	53	44	37	26		1560		133	50	160
272	2R	125	100	90	82	75	71	66	64	57	56	47	42	37	34	28	24	17	2627		8207	2026	270	267
300	2R	268	219	192	168	149	134	121	110	97	90	73	62	52	45	37	31	21	2813		823	550	79	213
325	2R	576	457	376	311	256	216	183	159	132	116	86	69	54	46	37	32	22	1325		251	124	56	189
349	2R	189	168	156	143	131	120	109	100	89	82	66	55	44	38	31	26	18	5000		4229	124	83	289
375	2R	252	224	203	186	170	157	143	130	116	107	85	72	59	51	43	36	25	3127		4016	84	78	206
400	2R	211	185	169	156	143	133	123	115	104	97	80	69	57	49	40	33	22	3429		4530	344	86	189
426	2R	162	144	137	128	120	114	106	100	91	85	71	62	53	45	36	29	19	5000		10000	223	139	195
449	2R	118	101	98	92	87	82	80	77	71	69	61	54	49	43	36	29	20	5000		9703	2064	334	192
475	2R	475	379	336	296	255	226	197	174	149	133	101	79	62	52	41	34	24		1326		245	40	185
500	2R	397	346	316	281	249	222	197	176	153	137	105	84	67	55	44	36	24		2848		130	50	164

Normalised Deflection and Deflection Analysis Results

Client Townsville City Council | **Start Date of Testing** 24-Jul-14 | **Target Load (kN)** 50

Road Palmerston Street (Hugh Street to Kings Road) | **Start Reference** FWD 0 m = Start of Kerb, Hugh Street RHS

Comments 1L = OWP towards Kings Road, 1R = IWP towards Kings Road, 2L = OWP towards Hugh Street, 2R = IWP towards Hugh Street

FWD Chainage (m)	Lane	Deflections (microns) Geophone Radius (mm) D0	D200	D300	D400	D500	D600	D700	D800	D900	D1000	D1200	D1400	D1600	D1800	D2000	D2250	D2500	Back Analysed Modulus (Mpa) Combined Base (170 mm)	Combined Base (300 mm)	Subbase (200 mm)	Subgrade 1 (300 mm)	Subgrade 2 (500 mm)	Subgrade 3 (Semi-infinite)
525	2R	348	307	281	254	226	204	183	165	145	132	102	84	67	57	46	37	26		3667		140	57	164
550	2R	444	414	377	340	306	276	246	214	185	166	125	99	79	64	51	42	28		3900		42	31	189
575	2R	411	359	325	292	259	235	209	188	164	148	113	89	71	58	46	37	25		2517		236	31	189
598	2R	380	313	281	249	219	195	172	152	132	118	93	74	61	52	44	38	26		1973		281	53	185
625	2R	385	333	298	264	232	207	182	162	140	126	97	79	66	56	47	39	26		2640		118	76	155
650	2R	490	405	361	317	276	243	211	187	162	144	110	88	71	60	49	41	27		1598		144	52	143
675	2R	332	293	261	236	208	187	167	151	132	121	95	79	63	57	48	41	28		3196		236	55	177
700	2R	523	431	384	336	290	254	221	193	167	149	114	93	78	67	56	48	32		1557		84	78	123
725	2R	1085	796	616	470	360	292	239	203	172	152	118	98	82	70	61	53	37		348		47	96	106
750	2R	296	260	236	215	196	180	166	155	141	132	107	92	79	68	58	49	33	3138		1578	390	58	140
775	2R	252	222	206	190	174	160	147	138	125	118	98	87	75	66	56	46	31	4979		1896	323	75	148
799	2R	169	156	149	142	134	128	120	114	103	98	81	70	60	53	44	38	25	5000		10000	1303	20	447
825	2R	201	177	164	153	143	137	128	122	113	108	92	81	70	60	51	41	27	2920		9559	430	145	137
850	2R	125	112	108	103	97	93	89	87	80	77	67	59	52	46	40	33	21	5000		4854	5000	20	611

Normalised to 50 kN Deflection Results

Client	Townsville City Council	**Start Date of Testing**	24-Jul-14	**Target Load (kN)**	50
Road	Woodlands Service Road	**Start Reference**	FWD 0 m = property boundary of service station on southern access		
Comments	1L = OWP towards Bruce Highway North, 1R = IWP towards Bruce Highway North				

FWD Chainage (m)	Lane	**Deflections (microns)** Geophone Radius (mm) D0	D200	D300	D400	D500	D600	D700	D800	D900	D1000	D1200	D1400	D1600	D1800	D2000	D2250	D2500	Air Temp. (oC)	Surf Temp. (oC)
0	1L	179	154	144	132	122	112	103	95	84	76	61	50	41	34	27	22	14	19.4	19.3
26	1L	183	163	154	142	131	121	110	102	91	84	66	54	42	34	26	19	13	19.4	19.5
50	1L	211	175	164	152	141	130	119	110	99	91	73	60	49	40	31	25	17	19.5	19.6
75	1L	201	176	165	151	137	126	114	106	94	87	69	59	49	42	35	29	19	19.4	19.5
100	1L	188	165	155	144	133	123	112	105	95	88	72	60	49	41	33	26	17	19.4	19.6
125	1L	183	155	144	131	118	108	97	89	78	73	57	47	38	32	25	19	13	19.5	19.5
151	1L	186	146	129	114	98	88	77	70	61	56	42	35	28	24	19	15	11	19.6	19.6
176	1L	195	162	148	135	122	111	100	92	80	74	57	46	37	31	25	20	13	19.6	19.7
200	1L	162	137	127	115	104	95	86	79	69	64	50	41	33	27	21	16	11	19.6	19.7
226	1L	127	111	103	95	84	78	71	65	56	52	40	32	25	21	16	12	8	19.7	19.6
250	1L	170	138	129	118	107	98	89	82	72	66	50	41	32	26	19	15	10	19.7	19.6
275	1L	179	151	140	129	118	107	98	91	80	74	58	48	39	33	26	20	14	19.7	19.6
300	1L	223	197	185	171	157	144	131	121	107	98	76	62	50	40	31	24	17	19.7	19.6
13	1R	198	174	163	151	137	126	114	105	93	85	67	54	44	36	28	21	14	20	20.1
38	1R	215	192	179	165	151	139	125	115	102	93	72	58	44	35	26	20	14	20	20.1
62	1R	166	141	130	117	104	93	82	75	64	58	44	36	29	25	20	17	12	20	19.8
88	1R	230	204	190	173	156	142	128	118	104	95	75	62	51	43	35	28	19	19.9	19.8
112	1R	243	213	198	180	161	145	130	118	104	93	71	56	44	36	28	22	16	19.8	19.8
137	1R	162	135	127	118	108	100	92	85	76	71	57	47	39	32	25	19	13	19.9	19.6
163	1R	159	139	131	123	114	105	98	92	83	77	63	54	44	38	31	25	17	20.1	19.7
188	1R	203	180	169	156	141	130	118	108	96	88	68	55	44	36	28	22	14	20.1	19.8
212	1R	177	148	135	122	110	102	93	85	76	70	56	45	37	31	24	17	12	20.1	19.8
238	1R	165	140	130	119	107	97	87	80	69	63	46	36	27	21	15	11	8	20.1	19.8
263	1R	179	149	138	126	114	104	94	87	77	70	54	44	36	30	24	18	12	20.1	19.8
289	1R	189	162	152	140	127	117	107	99	88	81	63	53	42	35	27	21	14	20.2	19.7

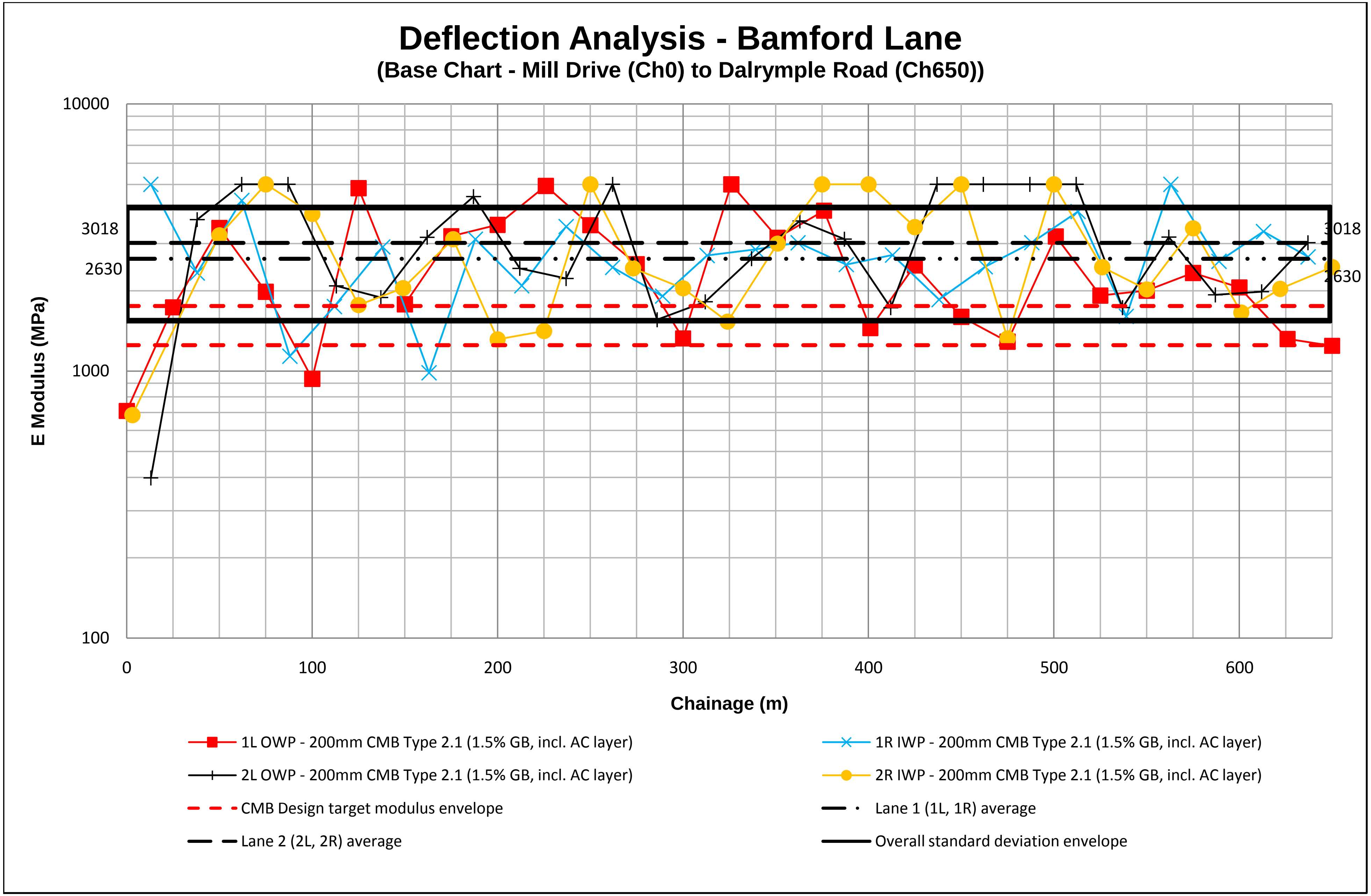
Normalised Deflection and Deflection Analysis Results

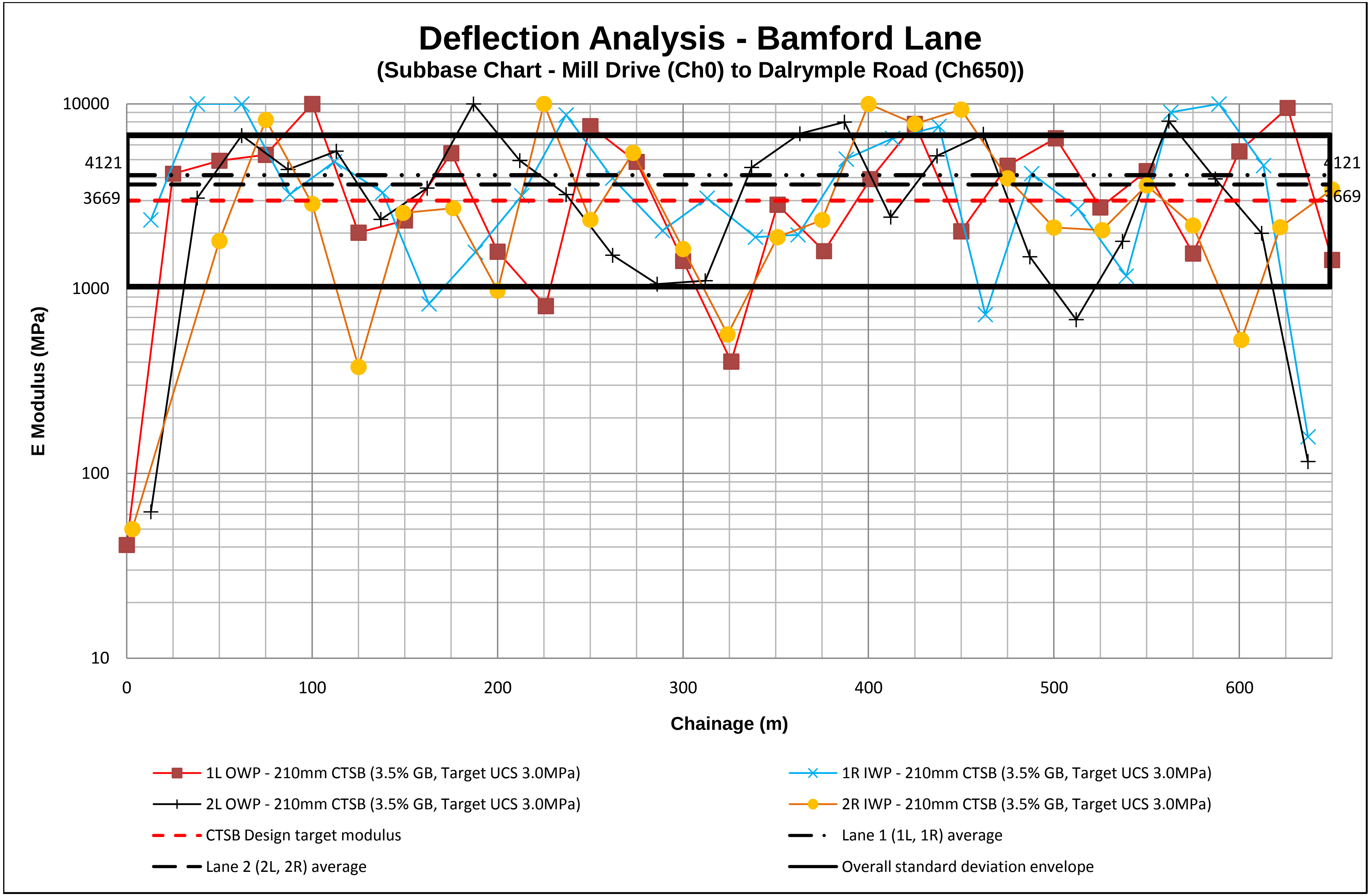
Client	Townsville City Council	**Start Date of Testing**	24-Jul-14	**Target Load (kN)**	50
Road	Woodlands Service Road	**Start Reference**	FWD 0 m = property boundary of service station on southern access		
Comments	1L = OWP towards Bruce Highway North, 1R = IWP towards Bruce Highway North				

FWD Chainage (m)	Lane	Deflections (microns) Geophone Radius (mm)																	Back Analysed Modulus (Mpa)		
		D0	D200	D300	D400	D500	D600	D700	D800	D900	D1000	D1200	D1400	D1600	D1800	D2000	D2250	D2500	Combined Base (280 mm)	Upper Subgrade (300 mm)	Lower Subgrade (Semi-infinite)
0	1L	179	154	144	132	122	112	103	95	84	76	61	50	41	34	27	22	14	6124	341	221
26	1L	183	163	154	142	131	121	110	102	91	84	66	54	42	34	26	19	13	7039	317	206
50	1L	211	175	164	152	141	130	119	110	99	91	73	60	49	40	31	25	17	5512	400	174
75	1L	201	176	165	151	137	126	114	106	94	87	69	59	49	42	35	29	19	6837	326	182
100	1L	188	165	155	144	133	123	112	105	95	88	72	60	49	41	33	26	17	7939	401	180
125	1L	183	155	144	131	118	108	97	89	78	73	57	47	38	32	25	19	13	5385	306	236
151	1L	186	146	129	114	98	88	77	70	61	56	42	35	28	24	19	15	11	3932	297	298
176	1L	195	162	148	135	122	111	100	92	80	74	57	46	37	31	25	20	13	4705	296	229
200	1L	162	137	127	115	104	95	86	79	69	64	50	41	33	27	21	16	11	6107	359	265
226	1L	127	111	103	95	84	78	71	65	56	52	40	32	25	21	16	12	8	8818	425	325
250	1L	170	138	129	118	107	98	89	82	72	66	50	41	32	26	19	15	10	5439	357	256
275	1L	179	151	140	129	118	107	98	91	80	74	58	48	39	33	26	20	14	5673	339	230
300	1L	223	197	185	171	157	144	131	121	107	98	76	62	50	40	31	24	17	5514	254	174
13	1R	198	174	163	151	137	126	114	105	93	85	67	54	44	36	28	21	14	5984	281	200
38	1R	215	192	179	165	151	139	125	115	102	93	72	58	44	35	26	20	14	5625	259	182
62	1R	166	141	130	117	104	93	82	75	64	58	44	36	29	25	20	17	12	5773	311	278
88	1R	230	204	190	173	156	142	128	118	104	95	75	62	51	43	35	28	19	5000	234	178
112	1R	243	213	198	180	161	145	130	118	104	93	71	56	44	36	28	22	16	4533	208	177
137	1R	162	135	127	118	108	100	92	85	76	71	57	47	39	32	25	19	13	7468	493	227
163	1R	159	139	131	123	114	105	98	92	83	77	63	54	44	38	31	25	17	9630	525	205
188	1R	203	180	169	156	141	130	118	108	96	88	68	55	44	36	28	22	14	6056	267	194
212	1R	177	148	135	122	110	102	93	85	76	70	56	45	37	31	24	17	12	5752	436	229
238	1R	165	140	130	119	107	97	87	80	69	63	46	36	27	21	15	11	8	6258	326	263
263	1R	179	149	138	126	114	104	94	87	77	70	54	44	36	30	24	18	12	5342	330	241
289	1R	189	162	152	140	127	117	107	99	88	81	63	53	42	35	27	21	14	5731	318	211

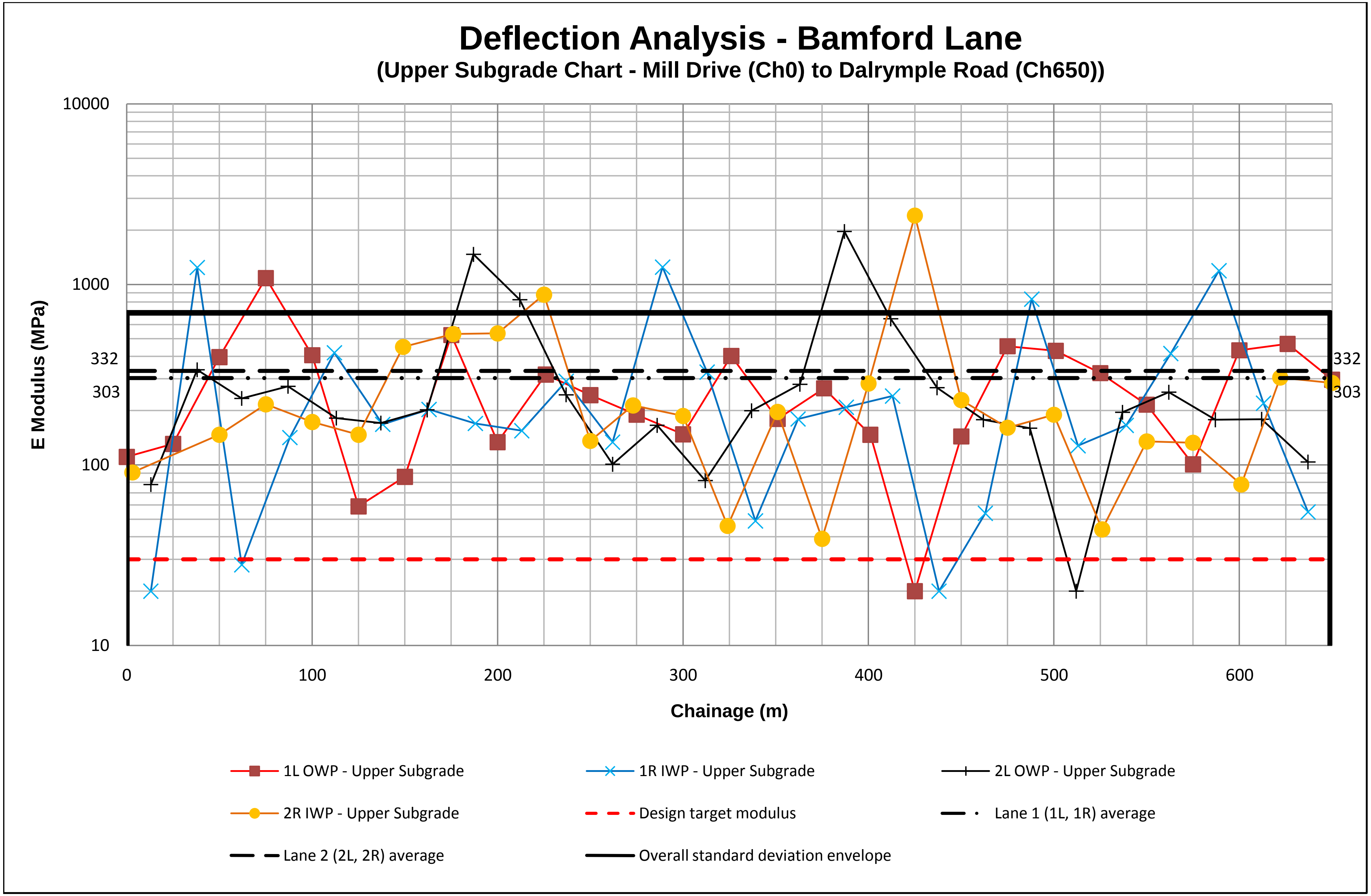
APPENDIX C

Back-analysis Layer Modulus Plots

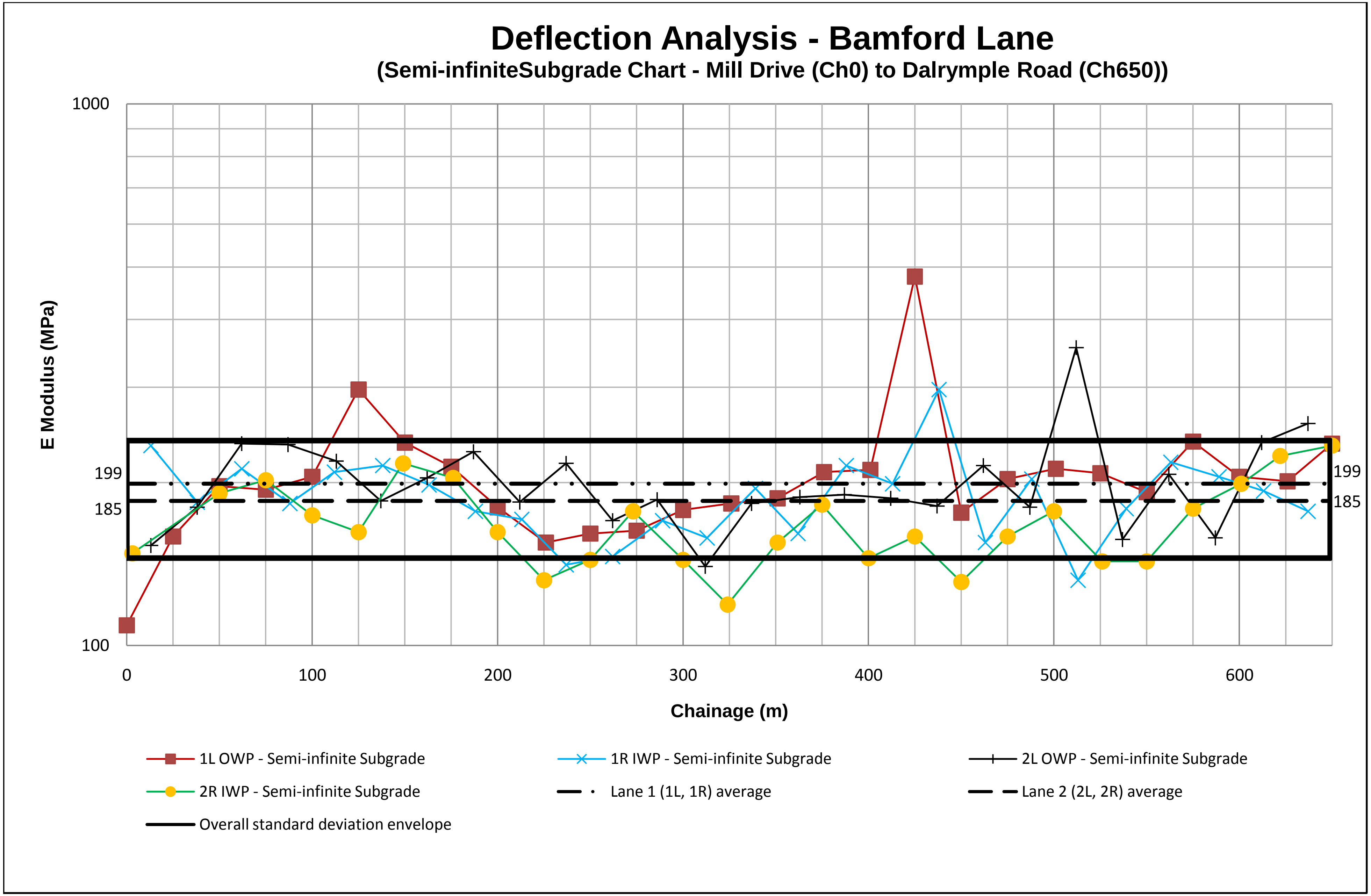

Deflection Analysis - Bamford Lane
(Base Chart - Mill Drive (Ch0) to Dalrymple Road (Ch650))
10000
3018
2630
1000
100
3018
2630
0
100
200
300
400
500
600
Chainage (m)
E Modulus (MPa)
1L OWP - 200mm CMB Type 2.1 (1.5% GB, incl. AC layer)
1R IWP - 200mm CMB Type 2.1 (1.5% GB, incl. AC layer)
2L OWP - 200mm CMB Type 2.1 (1.5% GB, incl. AC layer)
2R IWP - 200mm CMB Type 2.1 (1.5% GB, incl. AC layer)
CMB Design target modulus envelope
Lane 1 (1L, 1R) average
Lane 2 (2L, 2R) average
Overall standard deviation envelope



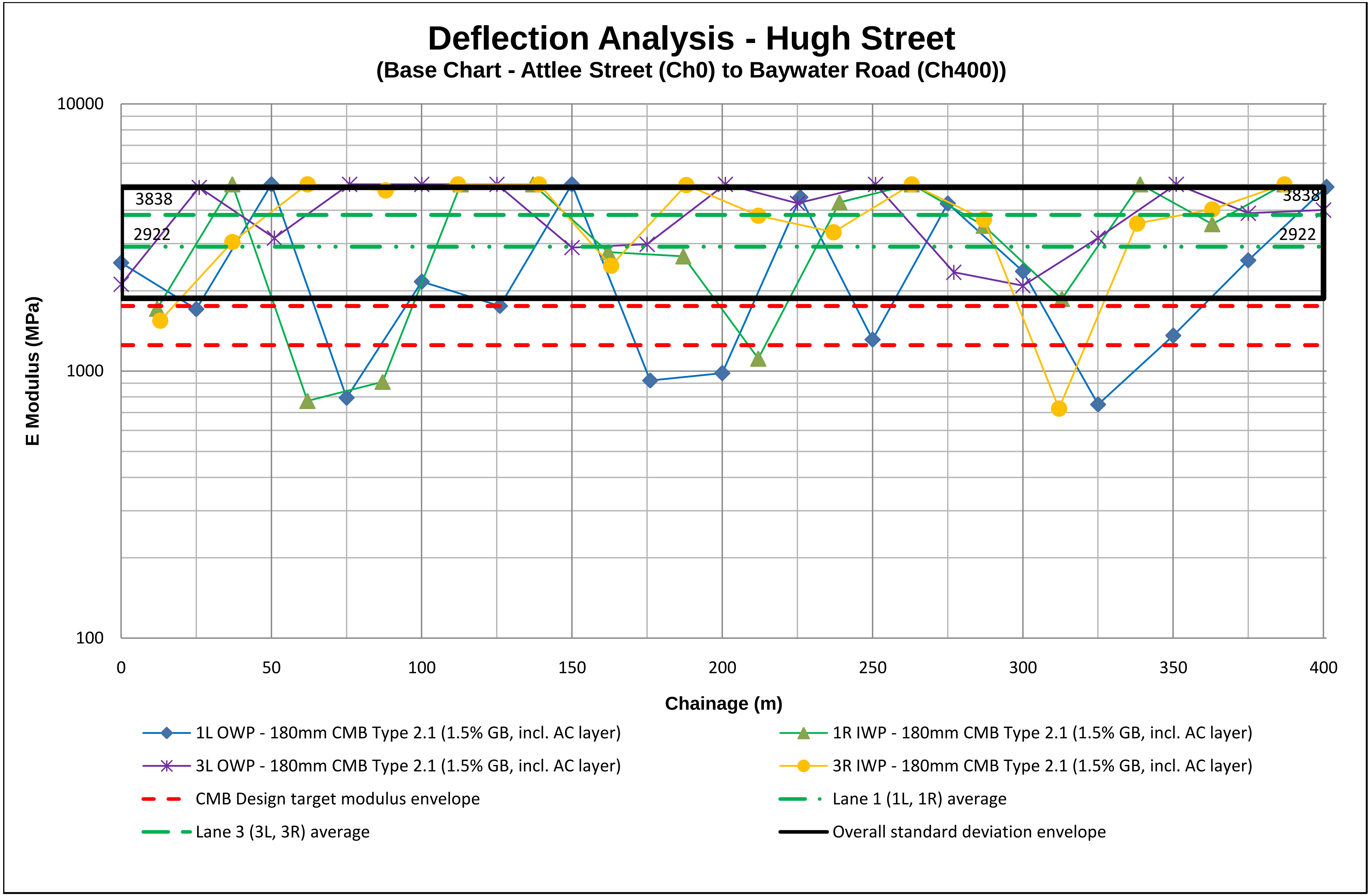
Deflection Analysis - Bamford Lane
(Subbase Chart - Mill Drive (Ch0) to Dalrymple Road (Ch650))
E Modulus (MPa)
10000
4121
3669
1000
100
10
4121
3669
0
100
200
300
400
500
600
Chainage (m)
1L OWP - 210mm CTSB (3.5% GB, Target UCS 3.0MPa)
1R IWP - 210mm CTSB (3.5% GB, Target UCS 3.0MPa)
2L OWP - 210mm CTSB (3.5% GB, Target UCS 3.0MPa)
2R IWP - 210mm CTSB (3.5% GB, Target UCS 3.0MPa)
CTSB Design target modulus
Lane 1 (1L, 1R) average
Lane 2 (2L, 2R) average
Overall standard deviation envelope

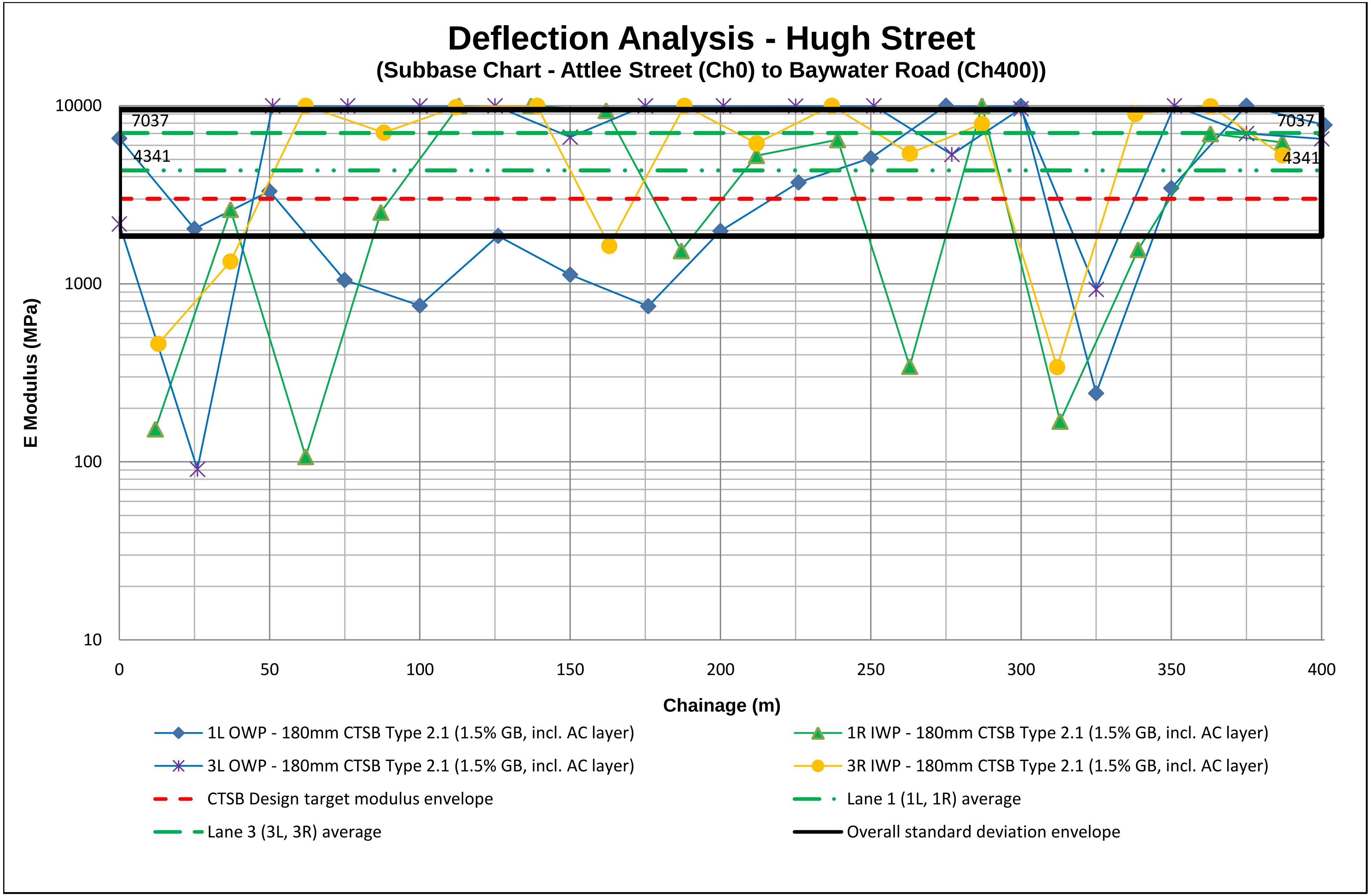


Deflection Analysis - Bamford Lane
(Upper Subgrade Chart - Mill Drive (Ch0) to Dalrymple Road (Ch650))
E Modulus (MPa)
10000
1000
332
303
100
10
0
100
200
300
400
500
600
Chainage (m)
1L OWP - Upper Subgrade
1R IWP - Upper Subgrade
2L OWP - Upper Subgrade
2R IWP - Upper Subgrade
Design target modulus
Lane 1 (1L, 1R) average
Lane 2 (2L, 2R) average
Overall standard deviation envelope

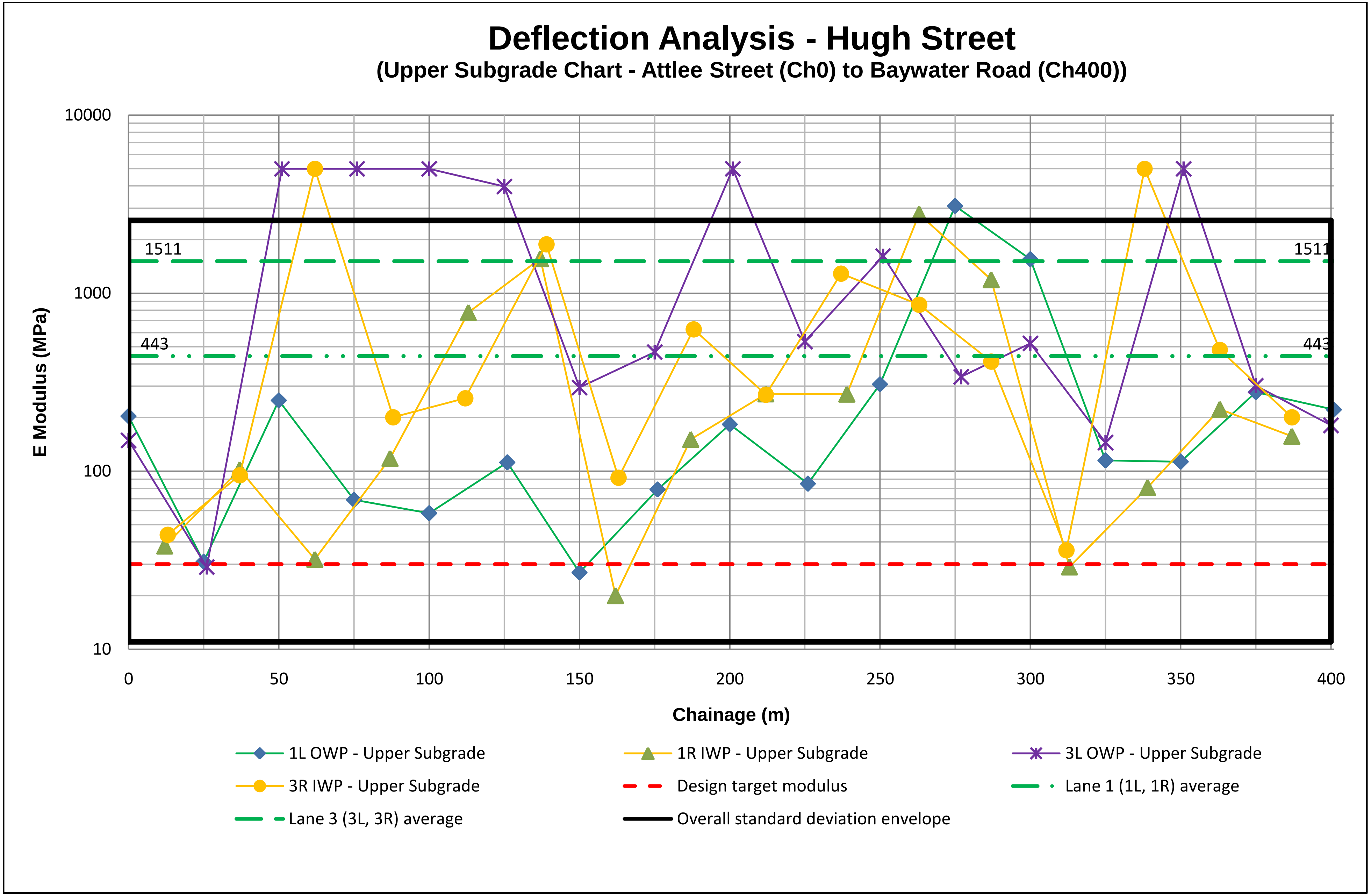


Deflection Analysis - Bamford Lane
(Semi-infiniteSubgrade Chart - Mill Drive (Ch0) to Dalrymple Road (Ch650))
E Modulus (MPa)
1000
199
185
100
199
185
0
100
200
300
400
500
600
Chainage (m)
1L OWP - Semi-infinite Subgrade
1R IWP - Semi-infinite Subgrade
2L OWP - Semi-infinite Subgrade
2R IWP - Semi-infinite Subgrade
Lane 1 (1L, 1R) average
Lane 2 (2L, 2R) average
Overall standard deviation envelope

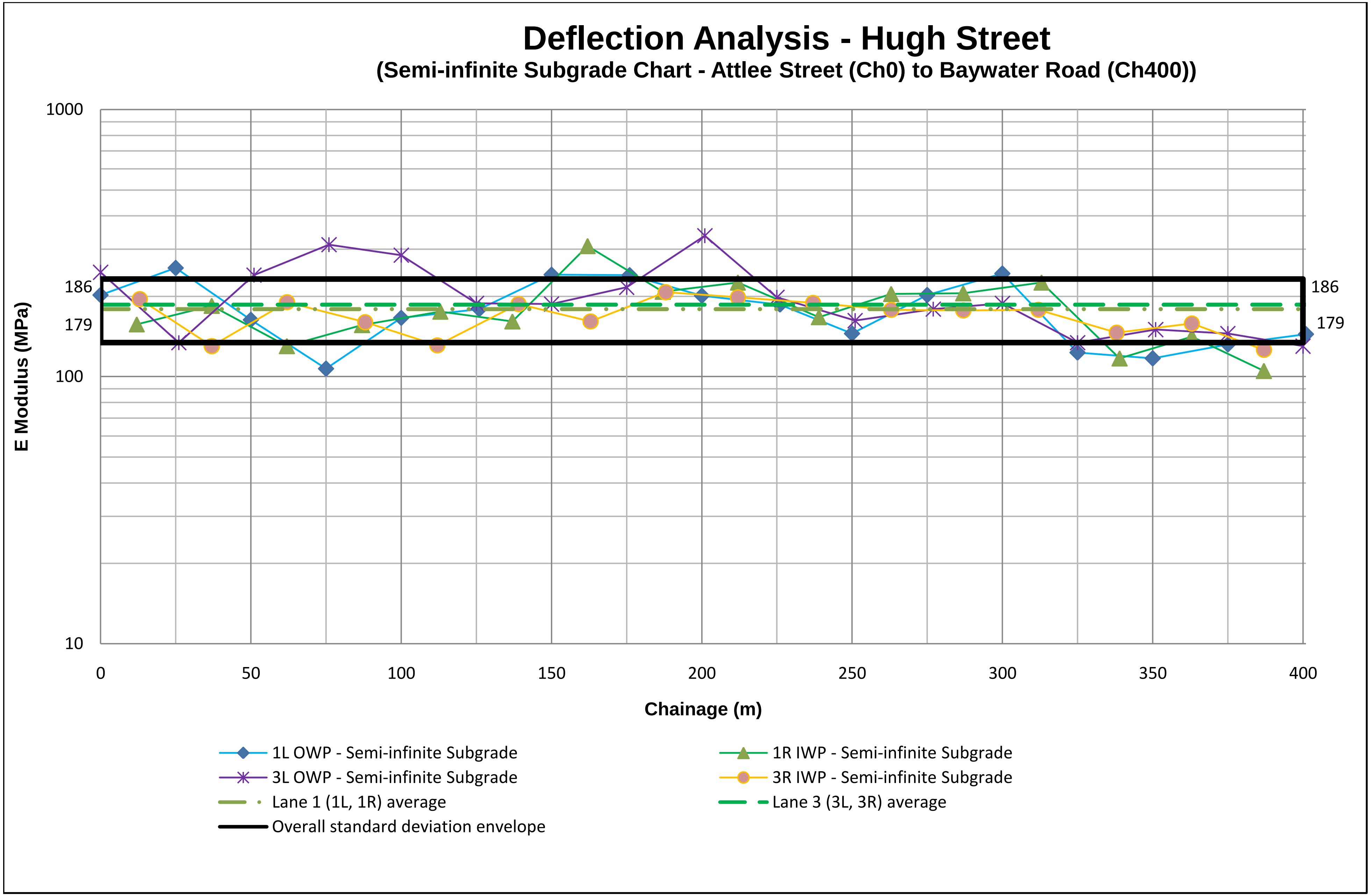

Deflection Analysis - Hugh Street
(Base Chart - Attlee Street (Ch0) to Baywater Road (Ch400))
E Modulus (MPa)
10000
1000
100
3838
2922
0
50
100
150
200
250
300
350
400
Chainage (m)
1L OWP - 180mm CMB Type 2.1 (1.5% GB, incl. AC layer)
1R IWP - 180mm CMB Type 2.1 (1.5% GB, incl. AC layer)
3L OWP - 180mm CMB Type 2.1 (1.5% GB, incl. AC layer)
3R IWP - 180mm CMB Type 2.1 (1.5% GB, incl. AC layer)
CMB Design target modulus envelope
Lane 1 (1L, 1R) average
Lane 3 (3L, 3R) average
Overall standard deviation envelope



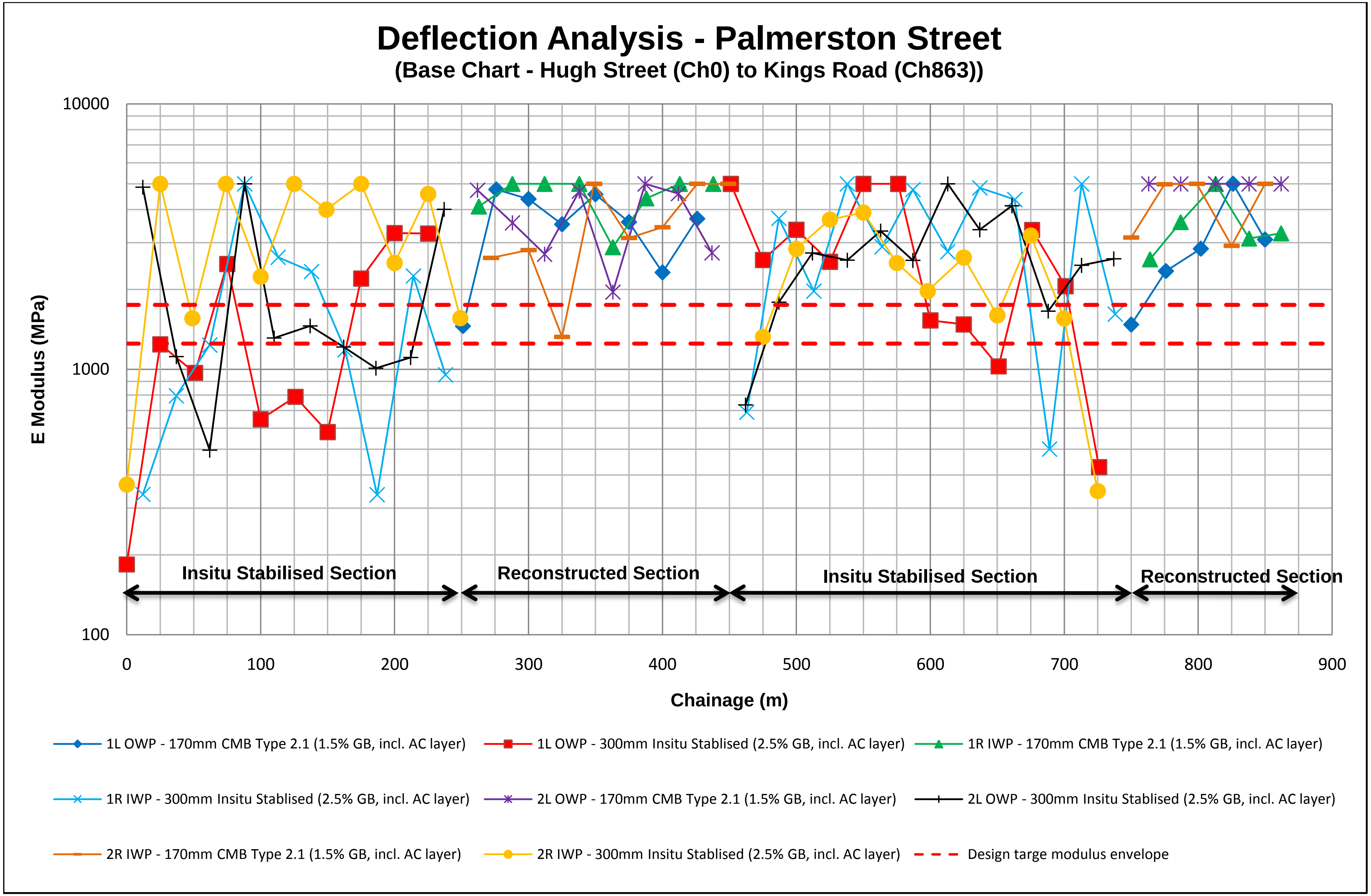
Deflection Analysis - Hugh Street
(Subbase Chart - Attlee Street (Ch0) to Baywater Road (Ch400))
E Modulus (MPa)
10000
1000
100
10
7037
4341
7037
4341
0
50
100
150
200
250
300
350
400
Chainage (m)
1L OWP - 180mm CTSB Type 2.1 (1.5% GB, incl. AC layer)
1R IWP - 180mm CTSB Type 2.1 (1.5% GB, incl. AC layer)
3L OWP - 180mm CTSB Type 2.1 (1.5% GB, incl. AC layer)
3R IWP - 180mm CTSB Type 2.1 (1.5% GB, incl. AC layer)
CTSB Design target modulus envelope
Lane 1 (1L, 1R) average
Lane 3 (3L, 3R) average
Overall standard deviation envelope



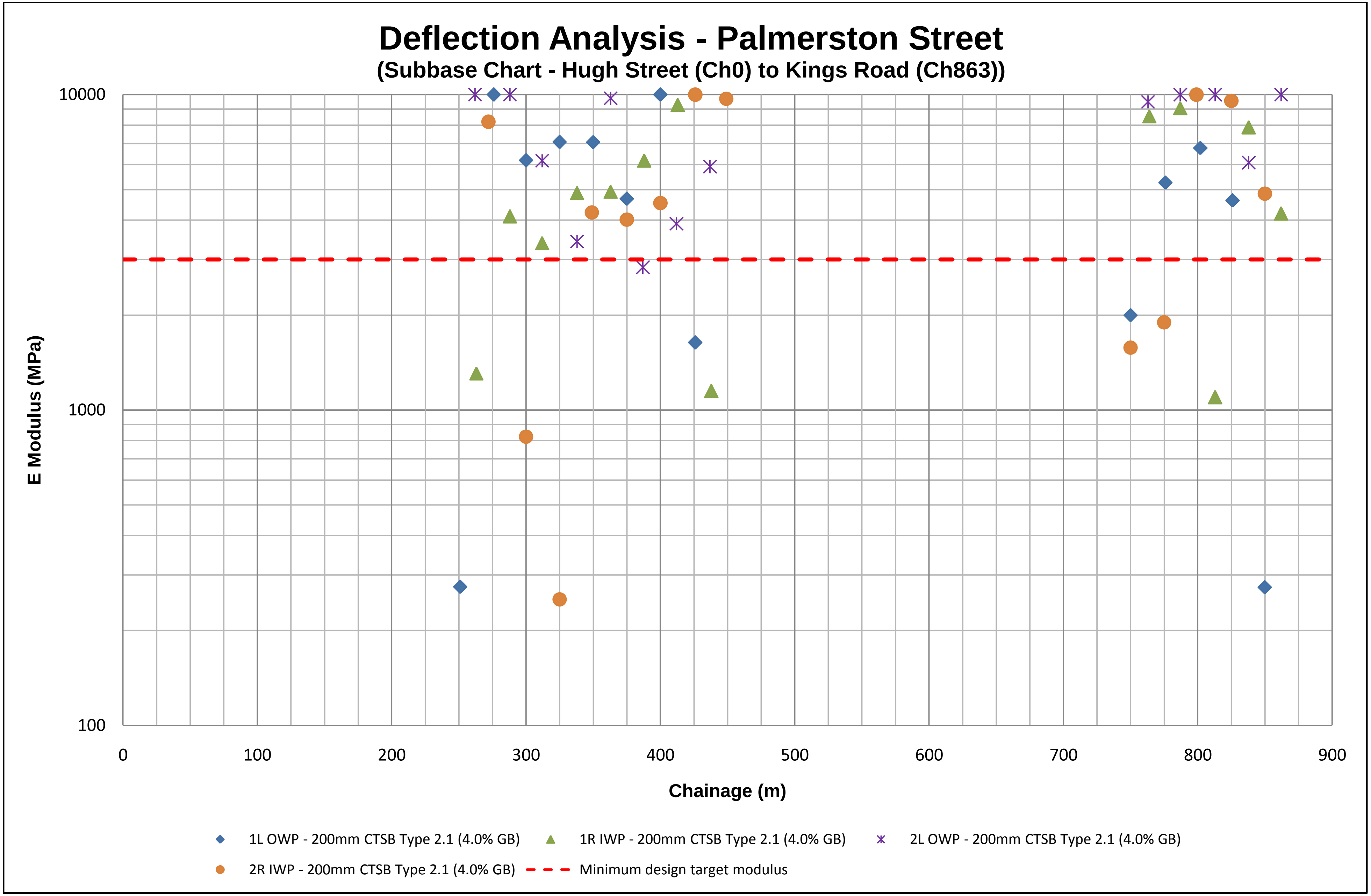
Deflection Analysis - Hugh Street
(Upper Subgrade Chart - Attlee Street (Ch0) to Baywater Road (Ch400))
E Modulus (MPa)
10000
1000
100
10
1511
443
0
50
100
150
200
250
300
350
400
Chainage (m)
1L OWP - Upper Subgrade
1R IWP - Upper Subgrade
3L OWP - Upper Subgrade
3R IWP - Upper Subgrade
Design target modulus
Lane 1 (1L, 1R) average
Lane 3 (3L, 3R) average
Overall standard deviation envelope



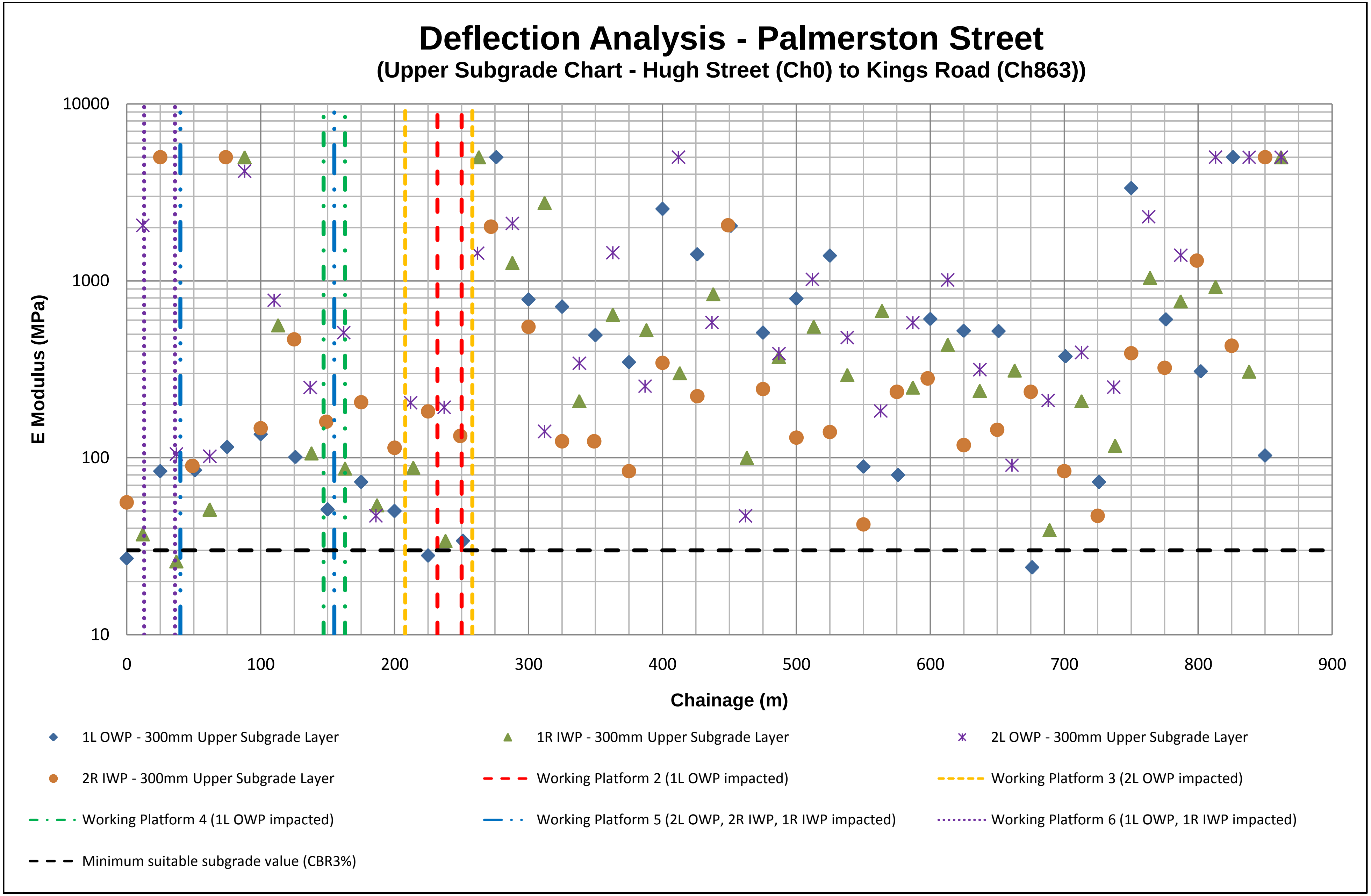
Deflection Analysis - Hugh Street
(Semi-infinite Subgrade Chart - Attlee Street (Ch0) to Baywater Road (Ch400))
E Modulus (MPa)
1000
186
179
100
10
186
179
0
50
100
150
200
250
300
350
400
Chainage (m)
1L OWP - Semi-infinite Subgrade
1R IWP - Semi-infinite Subgrade
3L OWP - Semi-infinite Subgrade
3R IWP - Semi-infinite Subgrade
Lane 1 (1L, 1R) average
Lane 3 (3L, 3R) average
Overall standard deviation envelope



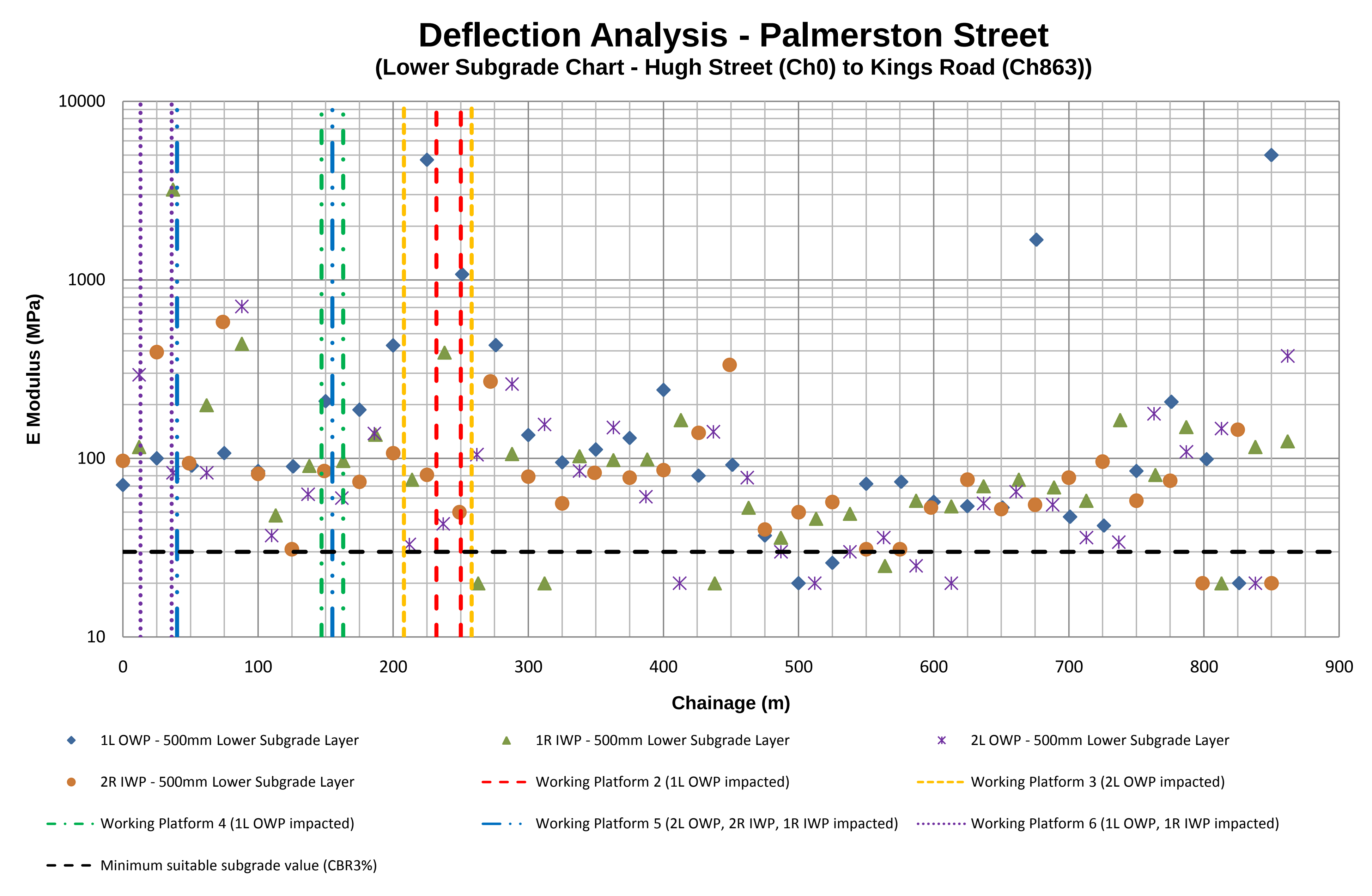
Deflection Analysis - Palmerston Street
(Base Chart - Hugh Street (Ch0) to Kings Road (Ch863))
10000
1000
100
E Modulus (MPa)
0
100
200
300
400
500
600
700
800
900
Chainage (m)
Insitu Stabilised Section
Reconstructed Section
Insitu Stabilised Section
Reconstructed Section
1L OWP - 170mm CMB Type 2.1 (1.5% GB, incl. AC layer)
1L OWP - 300mm Insitu Stablised (2.5% GB, incl. AC layer)
1R IWP - 170mm CMB Type 2.1 (1.5% GB, incl. AC layer)
1R IWP - 300mm Insitu Stablised (2.5% GB, incl. AC layer)
2L OWP - 170mm CMB Type 2.1 (1.5% GB, incl. AC layer)
2L OWP - 300mm Insitu Stablised (2.5% GB, incl. AC layer)
2R IWP - 170mm CMB Type 2.1 (1.5% GB, incl. AC layer)
2R IWP - 300mm Insitu Stablised (2.5% GB, incl. AC layer)
Design targe modulus envelope



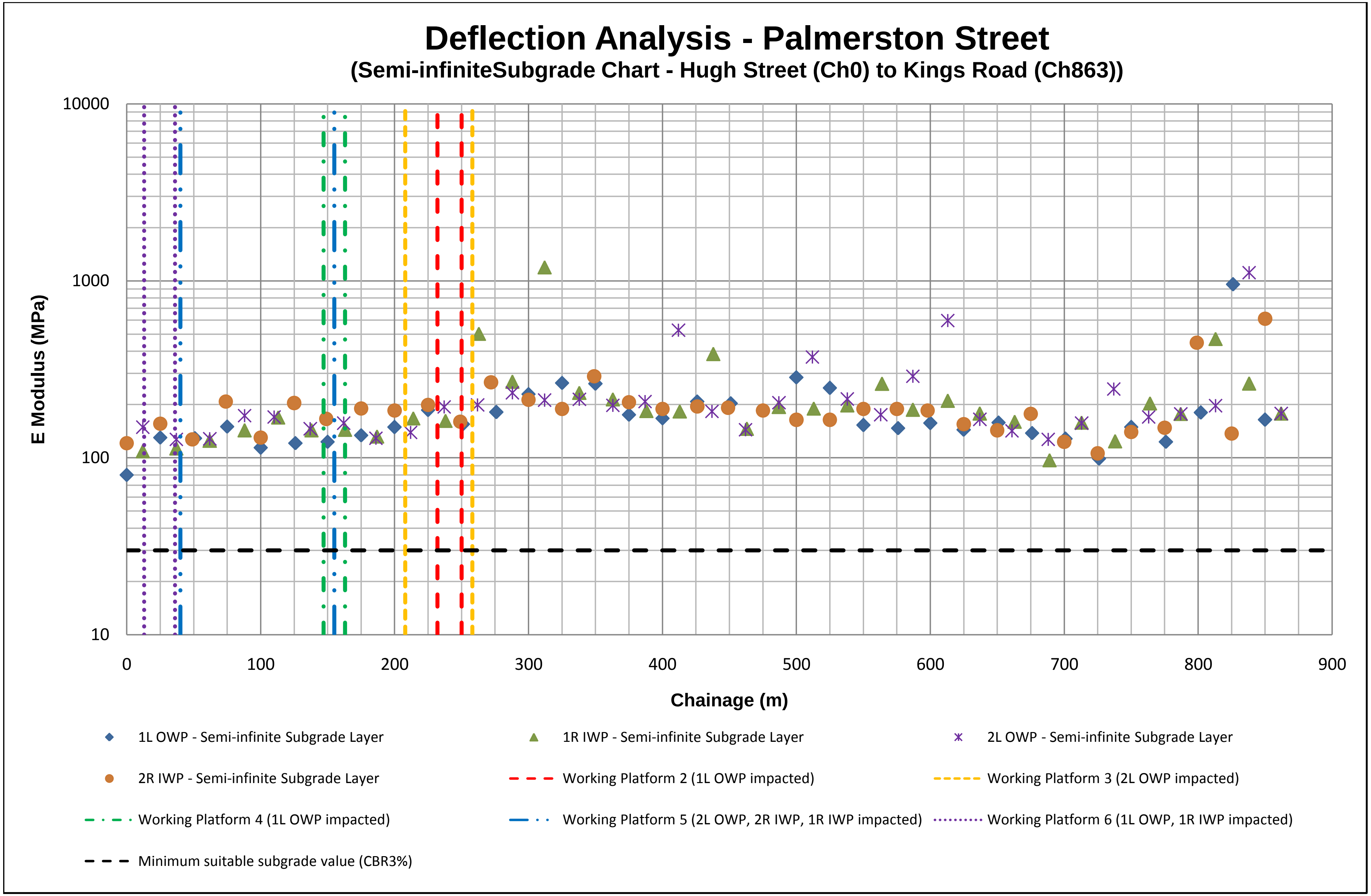
Deflection Analysis - Palmerston Street
(Subbase Chart - Hugh Street (Ch0) to Kings Road (Ch863))
10000
1000
100
E Modulus (MPa)
0
100
200
300
400
500
600
700
800
900
Chainage (m)
1L OWP - 200mm CTSB Type 2.1 (4.0% GB)
1R IWP - 200mm CTSB Type 2.1 (4.0% GB)
2L OWP - 200mm CTSB Type 2.1 (4.0% GB)
2R IWP - 200mm CTSB Type 2.1 (4.0% GB)
Minimum design target modulus

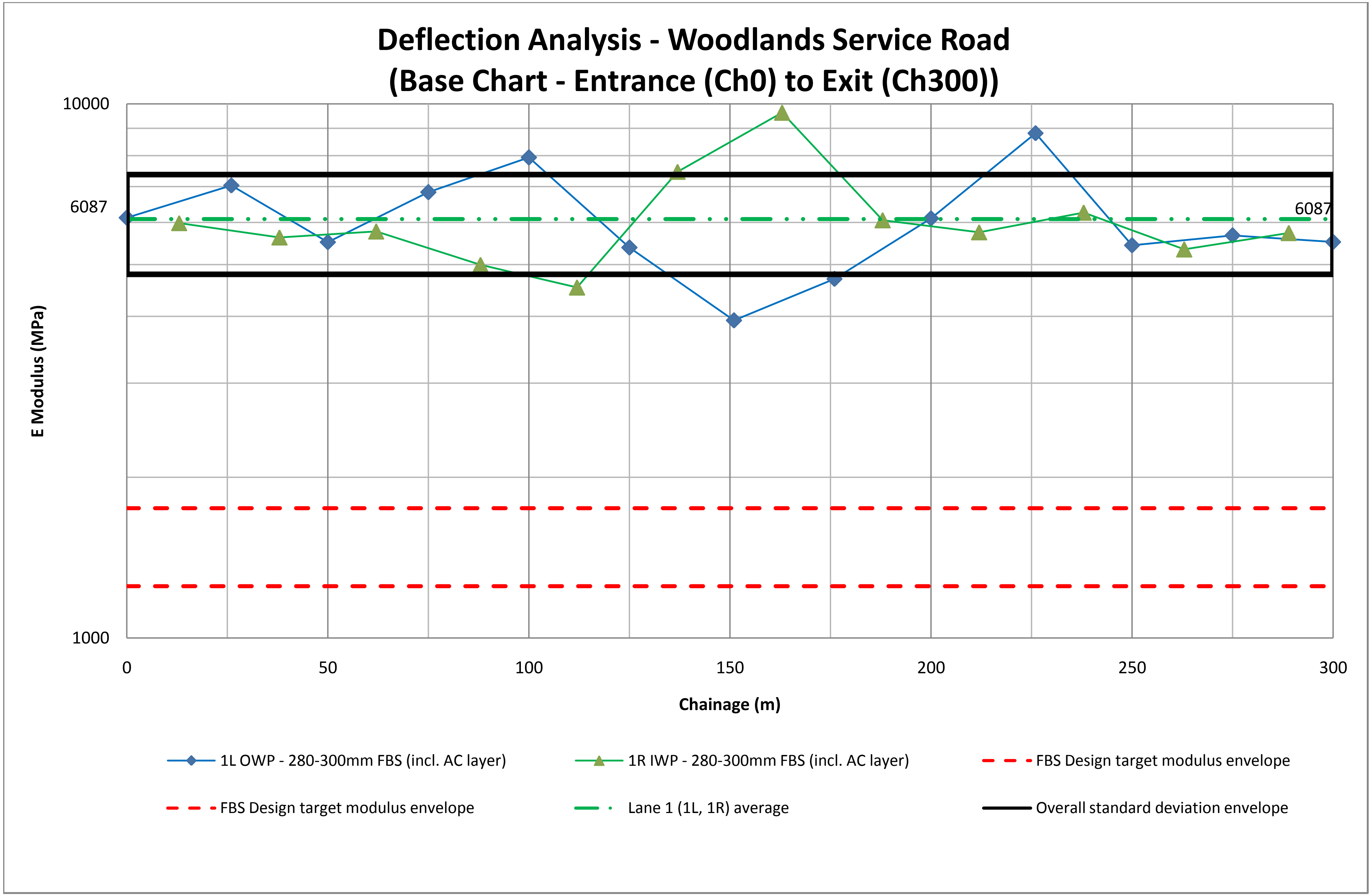


Deflection Analysis - Palmerston Street
(Upper Subgrade Chart - Hugh Street (Ch0) to Kings Road (Ch863))
E Modulus (MPa)
10000
1000
100
10
0
100
200
300
400
500
600
700
800
900
Chainage (m)
1L OWP - 300mm Upper Subgrade Layer
1R IWP - 300mm Upper Subgrade Layer
2L OWP - 300mm Upper Subgrade Layer
2R IWP - 300mm Upper Subgrade Layer
Working Platform 2 (1L OWP impacted)
Working Platform 3 (2L OWP impacted)
Working Platform 4 (1L OWP impacted)
Working Platform 5 (2L OWP, 2R IWP, 1R IWP impacted)
Working Platform 6 (1L OWP, 1R IWP impacted)
Minimum suitable subgrade value (CBR3%)

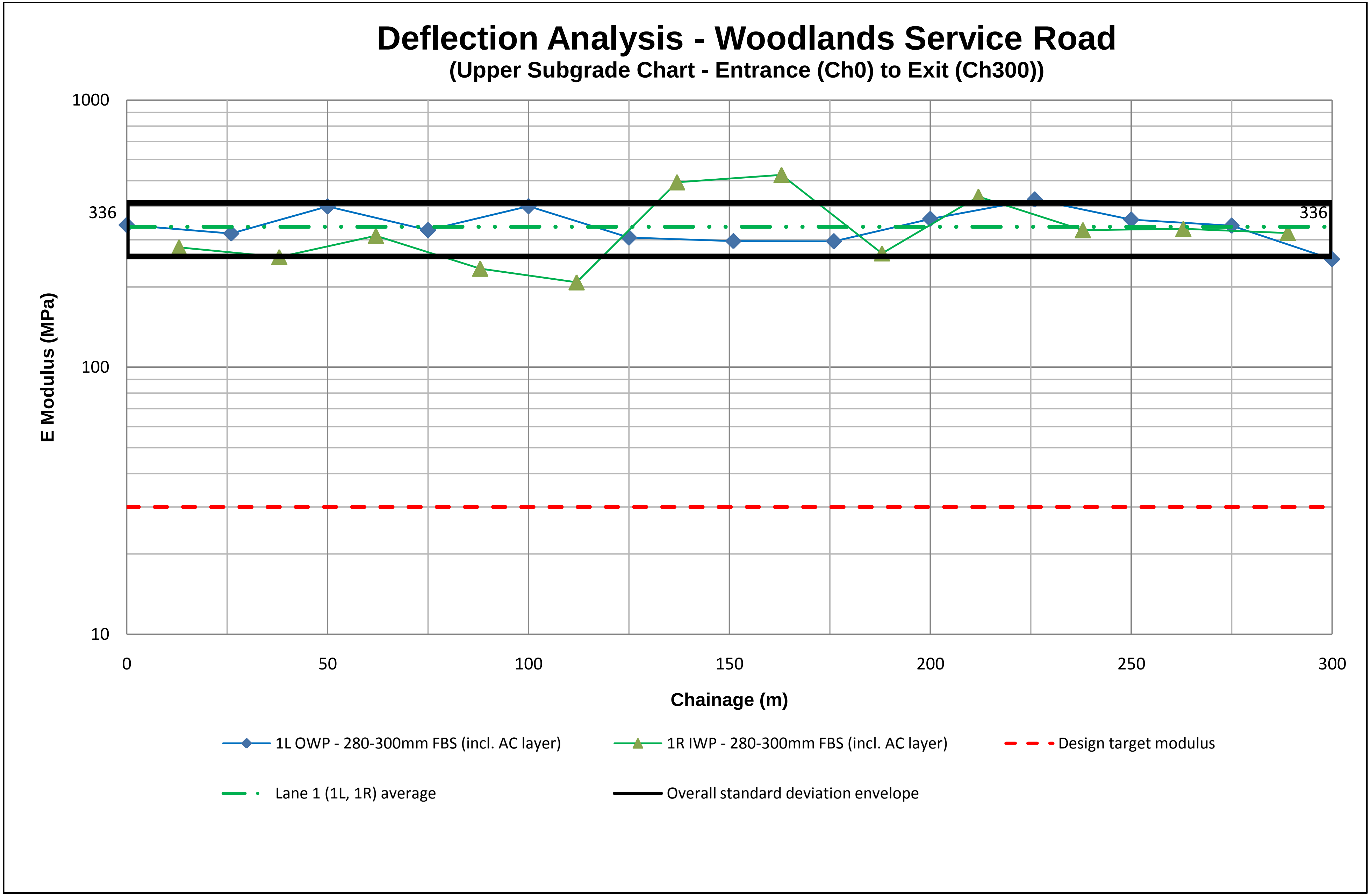


Deflection Analysis - Palmerston Street
(Lower Subgrade Chart - Hugh Street (Ch0) to Kings Road (Ch863))
E Modulus (MPa)
10000
1000
100
10
0
100
200
300
400
500
600
700
800
900
Chainage (m)
1L OWP - 500mm Lower Subgrade Layer
1R IWP - 500mm Lower Subgrade Layer
2L OWP - 500mm Lower Subgrade Layer
2R IWP - 500mm Lower Subgrade Layer
Working Platform 2 (1L OWP impacted)
Working Platform 3 (2L OWP impacted)
Working Platform 4 (1L OWP impacted)
Working Platform 5 (2L OWP, 2R IWP, 1R IWP impacted)
Working Platform 6 (1L OWP, 1R IWP impacted)
Minimum suitable subgrade value (CBR3%)

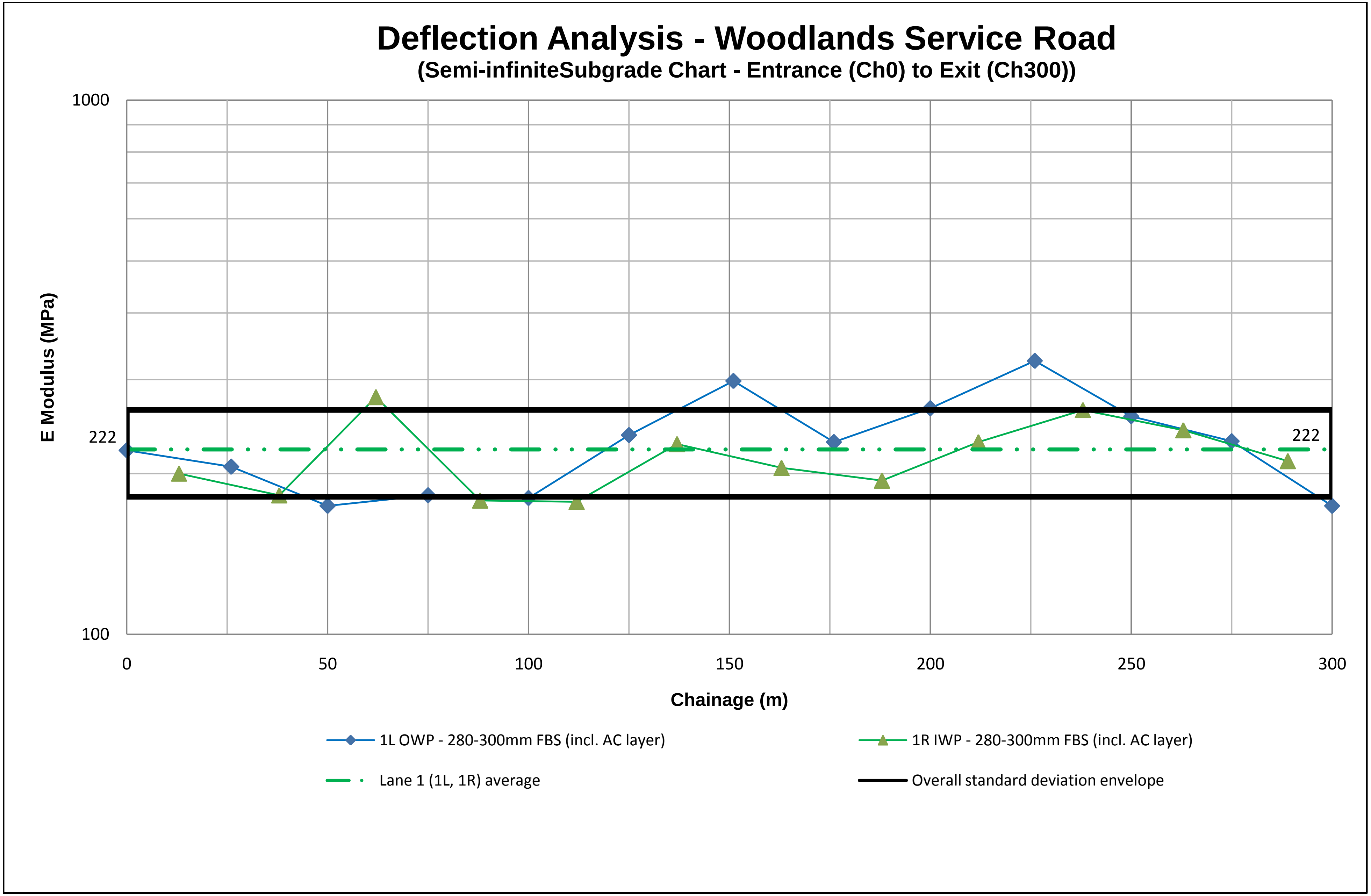

Deflection Analysis - Palmerston Street
(Semi-infiniteSubgrade Chart - Hugh Street (Ch0) to Kings Road (Ch863))
E Modulus (MPa)
10000
1000
100
10
0
100
200
300
400
500
600
700
800
900
Chainage (m)
1L OWP - Semi-infinite Subgrade Layer
1R IWP - Semi-infinite Subgrade Layer
2L OWP - Semi-infinite Subgrade Layer
2R IWP - Semi-infinite Subgrade Layer
Working Platform 2 (1L OWP impacted)
Working Platform 3 (2L OWP impacted)
Working Platform 4 (1L OWP impacted)
Working Platform 5 (2L OWP, 2R IWP, 1R IWP impacted)
Working Platform 6 (1L OWP, 1R IWP impacted)
Minimum suitable subgrade value (CBR3%)



Deflection Analysis - Woodlands Service Road
(Base Chart - Entrance (Ch0) to Exit (Ch300))
10000
6087
6087
1000
E Modulus (MPa)
0
50
100
150
200
250
300
Chainage (m)
1L OWP - 280-300mm FBS (incl. AC layer)
1R IWP - 280-300mm FBS (incl. AC layer)
FBS Design target modulus envelope
FBS Design target modulus envelope
Lane 1 (1L, 1R) average
Overall standard deviation envelope



Deflection Analysis - Woodlands Service Road
(Upper Subgrade Chart - Entrance (Ch0) to Exit (Ch300))
1000
336
100
10
336
E Modulus (MPa)
0
50
100
150
200
250
300
Chainage (m)
1L OWP - 280-300mm FBS (incl. AC layer)
1R IWP - 280-300mm FBS (incl. AC layer)
Design target modulus
Lane 1 (1L, 1R) average
Overall standard deviation envelope


Deflection Analysis - Woodlands Service Road
(Semi-infiniteSubgrade Chart - Entrance (Ch0) to Exit (Ch300))
E Modulus (MPa)
1000
222
100
0
50
100
150
200
250
300
Chainage (m)
1L OWP - 280-300mm FBS (incl. AC layer)
1R IWP - 280-300mm FBS (incl. AC layer)
Lane 1 (1L, 1R) average
Overall standard deviation envelope