University of the Sunshine Coast

School of Science and Engineering

Further Investigations into the Efficacy of a Soil Stabilisation Product for use within Australian Pavement Design

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Degree of Bachelor (Honours) of Engineering

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DECLARATION

I declare that the Bachelor of Engineering (Civil) thesis entitled "Further Investigation into the efficacy of a soil stabilisation Product for use within Australian Pavement design" is no more than 17,000 words exclusive of tables, figures, references, and appendices. This thesis is the result of my individual work and any contributions of others involved are specifically indicated throughout. I also certify that the material in this report has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

Shaun Callanan   26/10/2018

PURPOSE OF THE PROJECT AND CONTRIBUTION TO THE FIELD OF PRACTICE

Soil stabilisation is the future of pavement design, as an increased need to use readily available products is heightened by exhaustion of materials and enlarged construction costs. The purpose of this project was to investigate and test the long-term performance of a non-traditional soil stabilisation product to be used in pavement design. Built upon previous studies, this project will provide the basis for future research into stabilisation with this product. Additionally, testing will be performed and analysed to assist this product in gaining recognition within Australian pavement design guidelines. This research is beneficial to the Australian pavement industry with the use of natural resources and environmentally friendly construction set to intensify throughout the future.

ACKNOWLEDGEMENTS

This thesis is the culmination of my Bachelor of Engineering (civil) degree and was only possible through the support of several individuals and organisations. Also, this provides an opportunity to thank those that have provided support throughout the duration of my degree. Firstly, I must thank my academic advisor Adrian McCallum. You provided the guidance, knowledge and support to assist me in reaching my target and I greatly appreciate all the help you have offered me. I would like to acknowledge Mike Farrar from Austrablend Australia. You supplied any information and test results I asked for. And of course, thank you for allowing me to represent your product.

I must thank the Bracalba Quarry management for providing access for testing and inspections whenever requested. I would also like to thank Pavement Management Services for providing their time and equipment used for testing. Trent McDonald offered me guidance of the software used for data compilation and an overall understanding of the pavement concepts used in this investigation. The results gained would not have been possible without yourself and Pavement Management Services.

Finally, I would like to thank my family for the backing and continuous encouragement throughout this project and my entire degree. The reason that I have made it to this point of my studies is because of the constant backing and true inspiration given from the start by my biggest supporter – mum. Also, thanks to dad, who has always been there when I have needed throughout the duration of my studies. I must also thank my partner Sally, who has encouraged me through this project and has always been there to provide unquestionable support when I needed it the most.

ABSTRACT

The use of in-situ materials in road construction is becoming ever more important due to the forever increasing demands for environmentally and cost-effective construction practices, and to prevent the exhaustion of traditional pavement construction materials. Often however, this in-situ material will not provide the acceptable support to function under loading demands and perform in environmental conditions. Stabilisation has been used for decades to alter the properties of a soil for use in pavement design, however these traditional methods are not without their limitations, thus the research continues into providing more practical and effective techniques.

This investigation builds upon the work done by Hayden Curran in 2016 where a new, non-traditional stabilisation product was shown to improve the structural properties of pavement materials under substantial loading conditions. Modulus testing was performed on a section of haul road at Bracalba Quarry treated with the Consolid stabilisation system using a Falling Weight Deflectometer. Additional supporting tests included moisture sensor assessment, laboratory CBR testing, and visual inspections. Both qualitative and quantitative analysis of the test data was undertaken. Analysis of results revealed that the resilient modulus of the treated material has increased since treatment/construction, thus supporting the relevant theory and Hayden's work that material strength will increase over time after treatment. Laboratory CBR tests showed an increase in bearing capacity after treatment however clay must be present within the parent material. A slight increase in moisture content was shown after significant rainfall. Existing technology was applied throughout this work and used efficiently to show the benefits of Consolid as a soil stabilisation product and provide the basis for future work and its inclusion into Australian pavement design guidelines.

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1.0 INTRODUCTION

The reduced availability of suitable pavement materials, in addition to an ever-increasing demand for environmentally friendly and cost-effective construction practices, leads to a rise in the use of "in-situ" materials within the design of roads. The performance of a pavement structure is heavily reliant on its underlying material's strength, stability, and long-term suitability. Through engineering design, each layer in the pavement structure must contain the minimum level of specified structural quality to ensure loads are supported and distributed throughout its lifespan. If these layers are structurally weak and cannot resist permanent deformation, the overlying asphaltic layer will experience cracking and excessive damage.

The in-situ earth material present when constructing a pavement is widely used due to its availably and low cost however does not always meet the structural requirements of a suitable pavement sub layer. As an alternative to in-situ soil replacement, improvements to these materials may be performed to transform their engineering properties from available and inexpensive soils into quality construction resources. This can be accomplished by the process of stabilisation, where either chemically or physically, these unsuitable soils are modified to enhance the pavements structural properties. Products most commonly used for soil stabilisation include chemical altering additives such as cement, lime and bitumen. Quality granular materials can be added to improve a material through particle friction, known most commonly as physical stabilisation. Although soil stabilisation appears simple, the engineering properties of both in-situ and imported pavement materials vary widely due to the soil's particle size, composition, and interaction with water and air. Therefore, signifying the importance of material specific stabilisation treatment processes.

The process of soil stabilisation has been used within road construction throughout Australia since the 1940s on both sealed and unsealed pavements, thus providing a cost-effective solution in a world with increasing social and environmental pressures on material usage. Furthermore, soil stabilisation was later incorporated into Australian pavement design guidelines, providing standards on the methods and their subsequent application procedure. Soil stabilisation within the Australian road industry reduces the demand for quarry products, in turn limiting the expenditure within the construction industry of sourcing and producing unnecessary materials. Soil stabilisation is continuously evolving, and new, non-traditional methods are being tested for effectiveness and suitability on pavement materials in Australia. Now more than ever, soil stabilisation methods must not only improve the structural properties of a pavement material but continue to develop road design to the most social and environmentally friendly way possible. This report will investigate the efficiency and long-term effectiveness of a new stabilisation process for use in pavement design.

1.1 BACKGROUND & SCOPE

The Consolid System is a stabilisation method designed to inhibit the water intake and improve the bearing capacity of an undesirable soil. It consists of two parts, Solidry and C444, which are added to a natural material to reduce moisture, allow for greater compaction, and improve the strength over time. Furthermore, this product targets to increase the natural process in which cohesive soil is solidified over time, thus changing the physical behaviour (Consolid Australia 2018). Consolid is intended to treat an in-situ soil, thus reducing the cost of exporting and importing pavement materials.

An investigation was conducted by Hayden Curran in 2016 to help provide merit for the Consolid stabilisation system. This included the stabilisation using Consolid to a section of unsealed haul road at Bracalba quarry. Observations and testing found an improvement in pavement strength when stabilised with this technique, where field and laboratory testing supported the use of Consolid in road design. The complete methodology and results from this pilot study can be found in Curran (2016).

The Consolid system has been incorporated into pavement design throughout Europe for the past 40 years, however until Hayden's investigation, never in Australia. As a result, Austrablend Australia approached the University of the Sunshine Coast to provide further investigation into the efficiency of Consolid and examine the long-term performance of the stabilised quarry road. If successful, the results discovered throughout this investigation will support the previous study and aim for this product to be incorporated within the Australian pavement industry.

The trial site used for the initial experiment by Hayden Curran, and testing continued for this project, was conducted at Bracalba quarry which can be seen in figure 1.1 below. It was previously stated within Hayden Curran's work, and later determined from myself, that this site was suitable for such research. This is due to the road being exposed to large traffic loads, providing more than two million tonnes of quarry products to the construction industry annually which can be seen in figure 1.2 below.

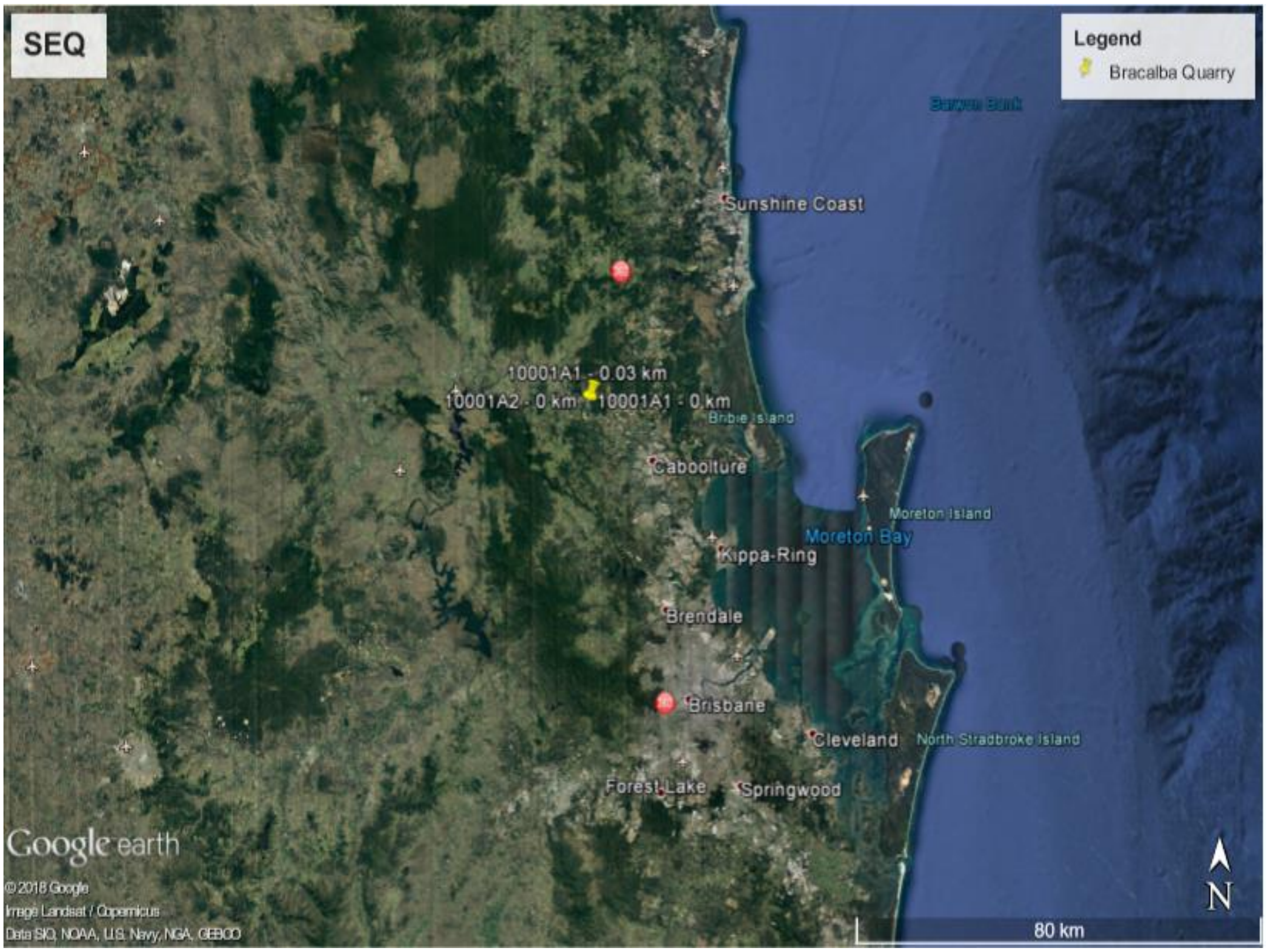

Figure 1. 1: Bracaba Quarry trial site

Figure 1. 2: Truck and dog on trial road at Braclba Quarry – typical load

Moisture sensors were installed for prior research and remain on site and will be accessed for this project. The resilient modulus measures pavement stiffness and is considered a fundamental property in a pavement structure. Consequently, the Falling Weight Deflectometer test, a method in which a stiffness of a pavement is determined, will be used in this investigation. This method of determining the strength of a pavement is supported by Rahim & George (2003) and Curran (2016). Furthermore, these results will be compared with previous results from Hayden's work in revealing the long-term stabilised material quality. Soil Engineering Services (SES) were engaged to provide laboratory testing to help assist in verifying the results obtained through this project and the original hypothesis that Consolid increases the load bearing properties of a soil.

To assist in addressing the aim of this project throughout, support was provided by Mike Farrar from Australblend Australia and the management from Bracalba quarry. Additionally, support was provided from Trent McDonald from Pavement Management Services, where comprehensive field testing was arranged, and assistance was sought after regarding the results. It is this field testing, along with moisture sensor data that provides the basis for material presented throughout this report.

1.2 PROJECT OBJECTIVE

The Australian pavement engineering sector is continuously aiming at improving construction methods to produce a more cost effective and longer lasting road structure. The ideology behind this investigation is that the sub layers with a pavement must provide the adequate structural support. The objective of this research is to further investigate the efficacy of the Consolid System in improving the intrinsic shear strength of a material over time under substantial traffic levels. The methodology within this investigation will build upon Hayden’s work and provide a base for future research. Furthermore, whether Consolid will reduce water intake within the structure over a long-term period will be observed. Overall, these objectives will help provide and support the inclusion of the Consolid System being integrated into Australian pavement design guidelines and specifications.

1.3 PROJECT STRUCTURE

This project firstly presents the general context of the problem followed by the specific methodology used to generate a comprehensive results section that follows. Results are then analysed and discussed to address the abovementioned aims of this investigation. This report will proceed as follows: Section 2 will provide information on pavement design, materials, testing, and stabilisation. Section 3 will present the methodology used for testing, and a summary of the original construction and treatment of the trial site from Hayden’s thesis. Section 4 will present the results through table and graph format acquired from each method. Section 5 will provide an interpretation of the results and assumptions of why. Section 6 will conclude this project and provide recommendations on future work and other possible uses of the Consoilid system. An appendices section will follow and provide; a project program, project logbook, raw data from testing, project poster.

2 LITERATURE REVIEW

The following section provides an in-depth review of the current knowledge and theoretical contributions for soil stabilisation within pavement design. This review will examine the nature of pavement structures, pavement design parameters, and the undesirable effect of moisture content within a pavement structure. Methodology of determining the strength, water content, stiffness, compaction, and overall construction feasibility of a pavement material will be briefly examined before specific soil stabilisation techniques will be discussed. Stabilisation methods will be examined in detail and in conjunction with the relevant standards and overall significance to the study being presented. Further discussion on the Consolid System is presented in this section and where appropriate throughout this report.

2.1 PAVEMENT DESIGN

Pavement design has been a subject of engineering research throughout time and is continuously evolving to ensure a quality structure. Mallick & El-Korch (2017) states that a pavement structure must limit the permeability through its layers whilst providing enough traction, low noise generation, and a long working life. When designing a pavement, the natural earth must be thoroughly investigated, as poor sublayers will eventuate in problems for the overlying pavements. There are numerous ways, both mechanistic and empirical, that are used to analyse a pavement structure and its sublayers. These methods will be discussed in detail further within this section. If the existing soil is deemed unsuitable for use in the pavement structure, it must be either treated, or a new material must be imported.

2.1.1 Soil Exploration

Before designing a pavement structure, soil exploration must be carried out to provide information and conditions of the underlaying structure that will determine its performance. This includes obtaining soil samples for testing methods and classification needed for pavement structure design. Subsurface pavement material investigation must be performed by experienced geotechnical engineers.

Geological research at a certain location determines the different earth materials present, thus identifying problems zones, imperative for road pavement construction as they can be built on these materials. As soil profiles are layered into horizons, reactivity of the soil with specific stabilisers as a function of depth can be identified (Little & Nair 2009). Furthermore, any compounds or materials present within the soil that may negatively affect stabilisation can be determined.

2.1.2 Subgrade/Subbase

A subgrade is a vital parameter within a pavement structures performance and it is essential that its bearing capacity is known before design. Soils are classified into subgrade and subbase materials created on fractions passing No. 200 sieve (Little & Nair 2009). The soil is classified a subgrade when 25% or more passes through the sieve whereas if under 25% the soil is classed as a subbase. These layers can be either bonded or unbonded to the overlaying pavement sealing. The purpose of the sub layers is to provide the following roles;

- Consistent and uniform support
- Stable construction platform
- Resist permanent deformation
- Provide drainage and frost protection

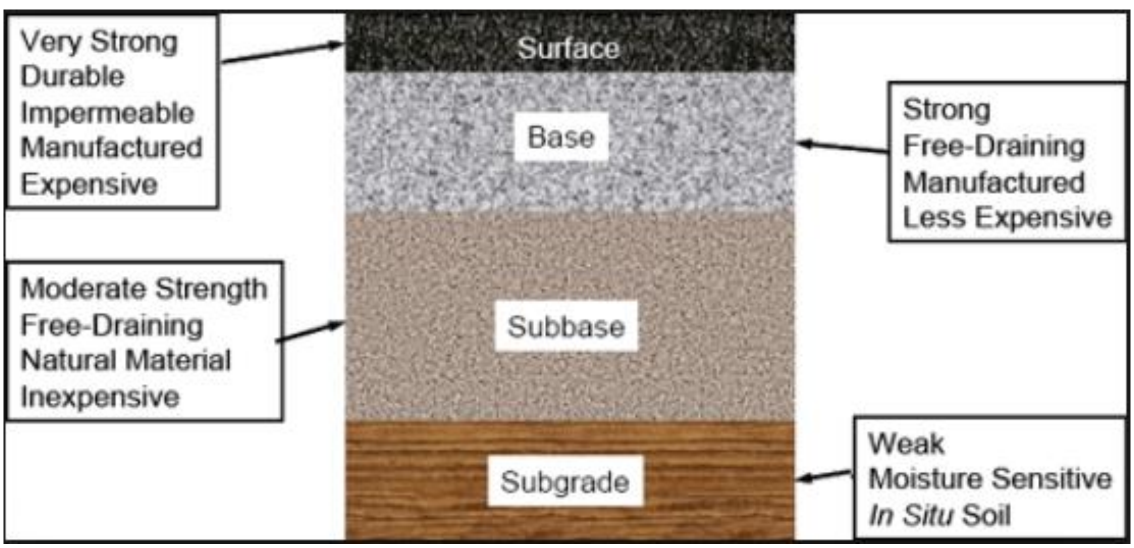

Figure 2. 1:Typical pavement structure layers (FHWA 2017)

Figure 2.1 above shows a basic road box and its layers. The determination of the bearing capacity of a subgrade is critical during the construction process. Regularly within Australian road construction, the subgrade quality is deemed insufficient for pavement design, thus requiring replacement. Permanent deformation of a subgrade is heavily influenced by moisture. It is how this moisture penetrates and reacts with the subgrade material that will affect stiffness. Moreover, the stiffness can be measured using various techniques, some of which will be discussed briefly within this section.

2.1.3 Unbound Pavement Materials

The subbase and replacement subgrade layers within pavement design are constructed with unbound granular materials. These unbound materials provide structural support for any overlaying layers such as asphalt and protect the underlaying material from extreme deformation (Salour & Erlingson 2017). Unbound pavement materials used for pavement design are categorised into four types; type 1, type 2, type 3, type 4. Type 2 is the predominant unbound material used within Australian pavement design.

2.1.4 Moisture in Pavement Structures

When working with unbound granular materials, moisture is considered the most influential factor determining pavement performance. Once constructed, moisture content within a pavement structure will fluctuate continuously over time and is dependent on material properties, environmental conditions, surface layers, and groundwater levels. This fluctuation makes moisture content within a pavement structure a difficult variable to account for (Abu-Farsakh et al 2015). The flow of moisture through a soil is called permeability and will significantly impact the strength of the material through pore pressure and/or seepage flow. It is essential to account for the moisture within the pavement sublayers as its variation will affect the resilient modulus. Ingles & Metcalf (1972) states that the flows of water throughout the soil, in addition to the water table at construction, must be understood. This is vital when limiting moisture flow through correct stabilisation, quality compaction, and drainage.

2.1.5 Permanent Deformation in Pavement Structures

As unbound granular materials used in road construction are not completely elastic, permanent deformation will accumulate through a result of continuous loads. As a result, rutting and cracking will occur. Deformation of pavement sublayers during cyclic loading is derived from friction between material aggregates and particle interlocking (Erlingson 2017). Movements between the particles caused by stress pulses can result in material crushing or migration to the extent of being unrecoverable. As moisture content within the subgrade increases, the build-up of permanent deformation increases. This is due to excessive moisture providing local pore pressure, which in turn will decrease the friction between particles therefore promoting their movement (Coronado et al 2016). Figure 2.2 below shows both rutting and cracking as result of permanent deformation of the pavement underlayers.

Figure 2. 2: Rutting and cracking of a pavement surface layer due to permanent deformation (Pavement Interactive 2018)

2.1.6 Resilient Modulus

The resilient modulus (MR) is a measure of a materials stiffness and is considered one of the fundamental properties of pavement design. It is defined as the ratio of stress to strain and indicates the stiffness of a pavement material under loading conditions (Han & Vanapalli 2016). It can be simply defined by the equation;

$$M_R = \frac{\Delta \sigma}{\Delta \varepsilon_a}$$

Where:

M_R = Resilient Modulus
$\Delta \sigma$ = Stress
$\Delta \varepsilon_a$ = Strain

The resilient modulus is used to quantify the support of sub layers. Abu-Farsakh (2015) states that the resilient modulus value is a measurement of elastic behaviour of soils under cyclic loading, comparable to vehicle loading over a pavement layer. As shown below in Figure 2.2, the resilient modulus is a direct measure of stiffness for unbound granular materials, where the ratio of applied cyclic stress to recoverable strain is obtained after cycles of repeated loading (FHWA 2017). In Australian pavement guidelines, the resilient modulus is the recommended practice for determining structural layer coefficients and characterising subgrade support for flexible pavements. Furthermore, it is a vital input into mechanistic pavement response models for unbound materials to compute strains, stresses, and deformation induced within the structure from constant loading (FHWA 2017). The resilient modulus is most commonly calculated within the laboratory using several methods, however in-situ modulus values can be determined through FWD results and back calculation. These will be discussed in further detail shortly.

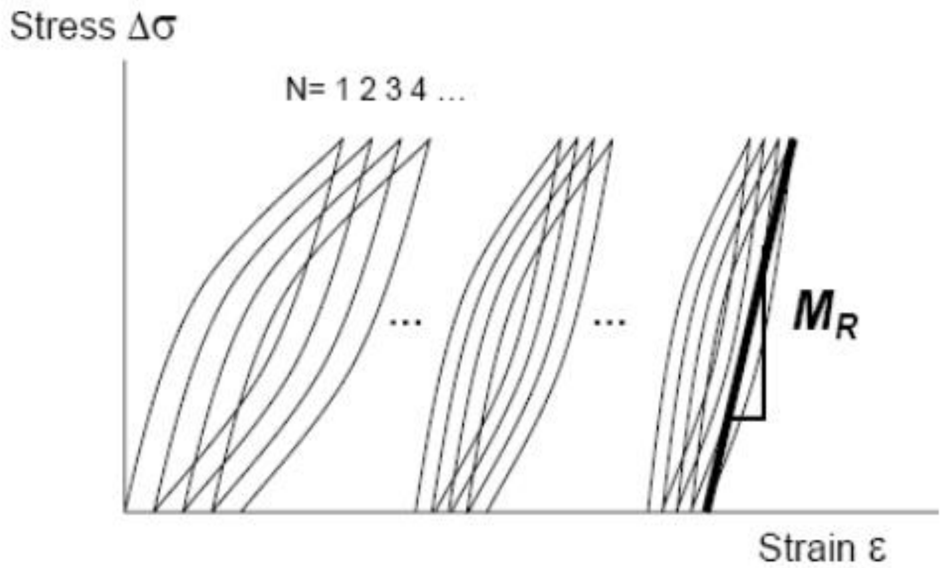

Figure 2. 3: Resilient modulus under cyclic loading (FHWA 2017)

Figure 2.3 above shows the resilient modulus under cyclic loading. The resilient modulus of a pavement sublayer can be dependent on several factors including; Stress state, density, soil type, number of load cycles, and moisture content. It is well known that moisture content can significantly affect the resilient modulus of unbound granular materials used in pavement design. Increased moisture in materials with a high fines content, such as those used for a subbase or subgrade, will result in a decrease in the soil matric suction (Salour 2015). Tests conducted by Salour (2015) and Abu-Farsakh et al (2015) clearly indicate that increased moisture content can have unfavourable effects on a subgrade through resilient modulus deformation and a decrease in matric suction. It is essential to account for the effect of moisture variation on the resilient modulus of subgrade soils, however can prove difficult due to fluctuating water content due to various seasons and conditions. Table 2.1 below shows the typical resilient modulus values of an unbound granular material based on Obrzud & Truty (2012).

Table 2. 1: Typical values for resilient modulus of unbound granular materials

Material Description	Loose (MPa)	Compacted (MPa)
Well graded sand/gravels	30-80	160-320
Uniform sand	10-30	50-80
Silty sand/gravel	7-12	20-30

2.2 PAVEMENT DESIGN TESTING METHODS

There are several methods that can be used to determine the strength and other properties of a pavement material or in-situ subgrade. These can be either laboratory or field tests, the latter considered the most appropriate as it replicates the pavement (Austroads 2009). Laboratory testing is most commonly performed on materials before placement to determine suitability, whereas in-situ testing can establish its current conditions. The following will discuss the testing methods with most significance to this study.

2.2.1 California Bearing Ratio (CBR)

When designing a pavement, it is critical to identify the bearing capacity of the subgrade. The California Bearing Ratio (CBR) is a common and widely applied parameter used to gauge a pavement soil strength. It is a simple penetration test where soil strength is based on resistance to penetration by pistons and can be performed either in-situ or laboratory. The CBR value is influenced by the material’s dry density, water content, and soil texture (Ampadu 2007). Typical values for different types of soil can be seen in Table 2.1 below.

Table 2. 2 - CBR values for materials

Type of Soil	**CBR range**
Clay	1-3
Sandy Clay	4-7
Well graded sand	15-40
Well graded sandy gravel	20-60

A subgrades design CBR has a significant effect on the required pavement layer thickness. This is due to the requirement of subgrade protection by the above pavement layer against loading deformation. Essentially meaning the weaker the subgrade, the thicker the pavement required. The FHWA (2017) states that the CBR test is a mostly inexpensive and straightforward test to perform and can be used as a direct input into pavement design methods. Moreover, the CBR test correlates with other engineering properties of pavement materials such as resilient modulus.

Table 2. 3: CBR values specified by TMR for type 2.1 road base materials

Property	**Limit**	**Subtype**				
		2.1	2.2	2.3	2.4	2.5
CBR soaked	Minimum	80	60	45	35	15

Table 2.2 above shows the California Bearing Ratio's for type 2 material as specified by Queensland department of transport and main roads. The soaked CBR test principally assesses the strength of a type 2 material and is used when designing a pavement structure. It must be noted however that the CBR test is a preliminary material assessment, therefore to comply with all required strength specifications, other testing methods may apply.

2.2.2 FWD

The falling weight deflectometer test (FWD) is the world's leading dynamic plate bearing test analysing the structural capacity of a pavement and its layers. The FWD assesses the load carrying capacity of an existing pavement structure, thus providing a quick and reliable method of characterising the properties of pavement layers (Pierce et al 2017). The FWD can be used on highways, local roads, car parks, unsealed roads, and airport runways. In addition to bearing capacity, other pavement properties that can be calculated through the surface characteristics determined by an FWD include:

- Layer thickness
- Resilient Moduli
- Expected surface life

Each time a vehicle drives over a pavement, a deflection will occur, varying in intensity dependent on the force being applied through the wheels. Through an FWD test, a dynamic load is applied to a pavement surface, acting with similar magnitude and duration to a singular moving wheel load. A measurement of deflection, or vertical deformation is the response given from the pavement system over the area through geophones. The FWD test is used widely throughout pavement design and was used for this project as it is non-destructive, unlike other pavement testing methods (Kuta, Chatti, and Lei 2011).

A traditional FWD is attached to the end of a trailer. A weight is raised hydraulically to a programmed height and then dropped, transferring a force onto a 300mm circular load plate. Nine seismic geophones measure the deflection and are offset from the centre of the load plate. This process is repeated. Figure 2.3 below shows the setup of a traditional FWD.

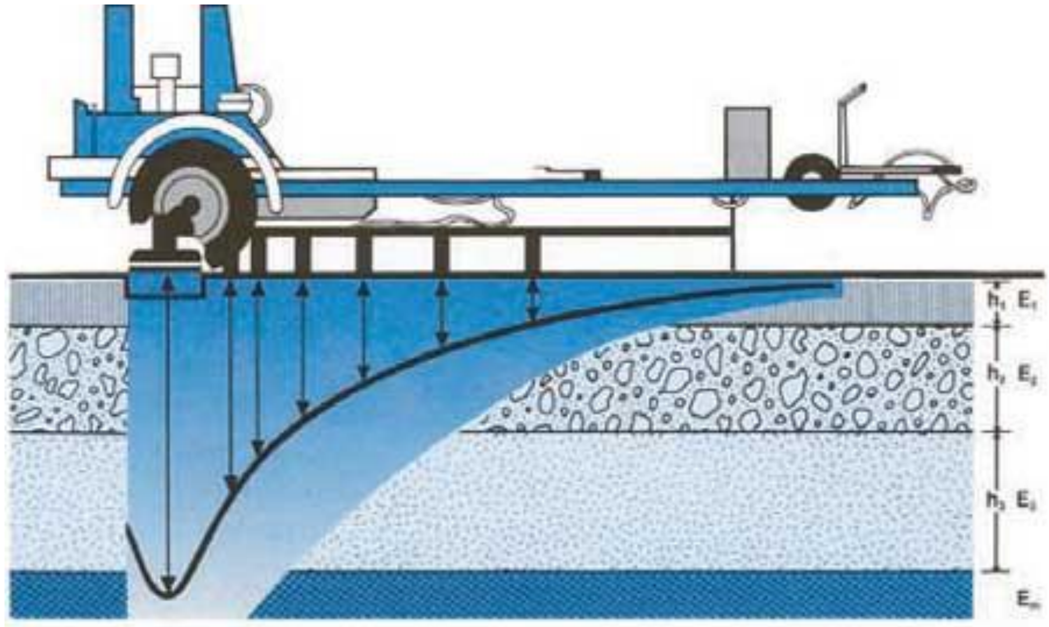

Figure 2. 4: Schematic of a standard FWD test (Dynatest 2016)

As shown in Figure 2.3, the force pulse produced from the FWD temporarily deforms the pavement under the load plate in a bowl shape and is dependent on the stiffness of the modulus. This shape of the deformed pavement is a deflection basin when viewed side on. The bowl shape nearby the loading plate defines the stiffness of the layers near the surface, whereas the outer deflections represents the subgrade stiffness (Tonkin & Taylor 2013). The pavements upper layers are considered stiff with regard to the subgrade when a broad bowl is shown with little curvature and conversely, high curvature around the loading plate indicates that the upper layer moduli is low.

The Falling weight deflectometer deflection data gathered in the field is then processed by a pavement structural analysis program. Resilient Moduli (stiffness) is determined from the observed deflection bowl through an iterative back calculation procedure. Some of the current and most common FWD analysis software includes:

- ELMOD6 - by Dynatest
- EFROMD2 – by the Australian Road Research Board
- MODULUS – by the Texas Transportation Institute
- BISAR

Supplied by Dynatest, Evaluation of Layer Moduli and Overlay Design (Elmod) was the pavement structural analysis program chosen for this investigation. Back analysis is calculated using the Odemark-Boussineq transformed section approach (Tonkin & Taylor 2013). The benefits of this program are its rapid analysis to evaluate the structural capacity of any pavement design material.

2.2.3 Atterberg Limits

Atterberg limits are the borderline water contents that separate the different consistencies of soils (Raj 1995). There are three stages for distinguishing these borderline water contents including; shrinkage limit, plastic limit, and liquid limit.

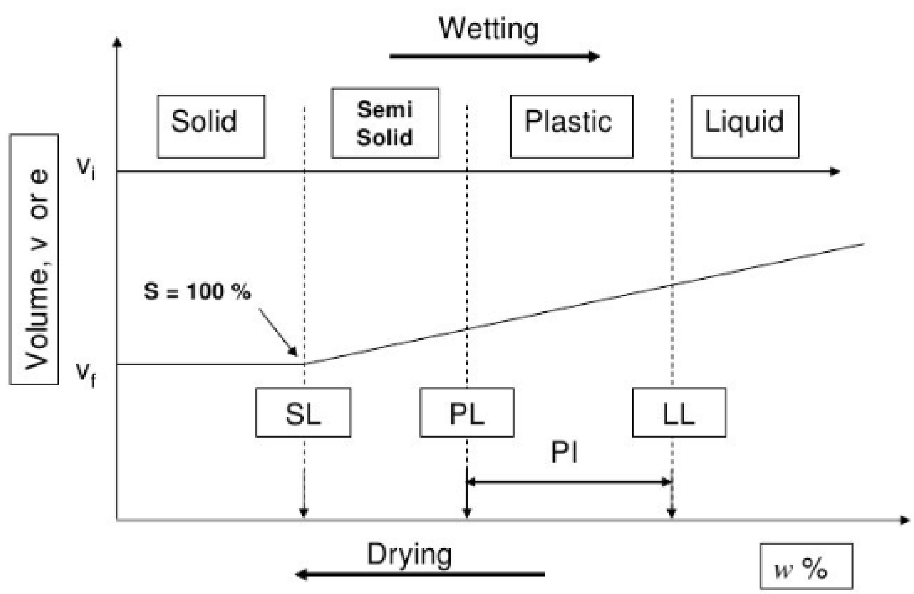

Figure 2. 5: Atterberg Limits (About Civil 2017)

Shrinkage limit (SL) is the boundary at which a soil contains water yet does not reduce in volume when dried. Soils below this limit are considered weaker in behaviour.

Plastic limits (PL) is when the water content is at its lowest during which the soil displays plastic behaviour. This plastic nature of a soil can simply be described as crumbling or powdering when rubbed together.

Liquid limit (LL) is the point at which a soil displays a liquid like behaviour, therefore changing from its previous plastic nature. The difference between the liquid and plastic limits is known as the plasticity index (PI). With water content between these limits, the soil will remain with plastic behaviour.

The plasticity index indicates a soils potential to change in volume with respect to changes in water content. Soils with a PI of less than 18 is considered to have a low extent of volume change whereas soils with a PI of greater than 35 usually have a high degree of expansion (Pandey & Rabbani 2017). The soils with a plasticity index of less than 18 are mostly considered suitable with containing few problems for pavement design.

2.2.4 Moisture Sensors

As moisture determines the strength/stiffness of an unbound pavement subgrade material, it is important to understand how the moisture content will be affected under certain weather conditions. The effect of moisture on a pavement's engineering properties have been discussed previously. Moisture sensors can be used to better understand moisture transformation in pavement systems and its effects on performance.

Moisture of a soil can be determined by measuring its dielectric constant, an electrical property highly dependent on moisture. This is achieved when an electromagnetic field measures the permittivity of nearby materials. Calibration is required to convert the dielectric measurement to moisture content percentage and is sit and material specific. The dielectric constant for air is one, dry soil 3-5, and water 80, therefore any changes in soil moisture content will produce a significant change. Dielectric moisture sensors will be used in this investigation to determine moisture content and more specific details can be found in the methodology section.

Other new in-situ soil moisture dynamics measuring methods include;

- electrical resistivity tomography (ERT)
- multi offset ground penetrating radar

2.2.5 Optimum moisture content/Compaction

To ensure better engineering performance, reaching a soils maximum dry unit weight is vital, and pavement sub layers must be compacted at optimum moisture content (Han & Vanapalli 2016). As moisture is increased throughout compaction, superior density will be achieved, as lubrication of the particles allows for greater particle rearrangement. When the soil voids become entirely filled with water and there becomes minimum voids that are unable to be removed through compaction, the optimum moisture content occurs. Prior to this point (the OMC), or the 'too dry for compaction', air can be forced out as there are a greater number of pore spaces.

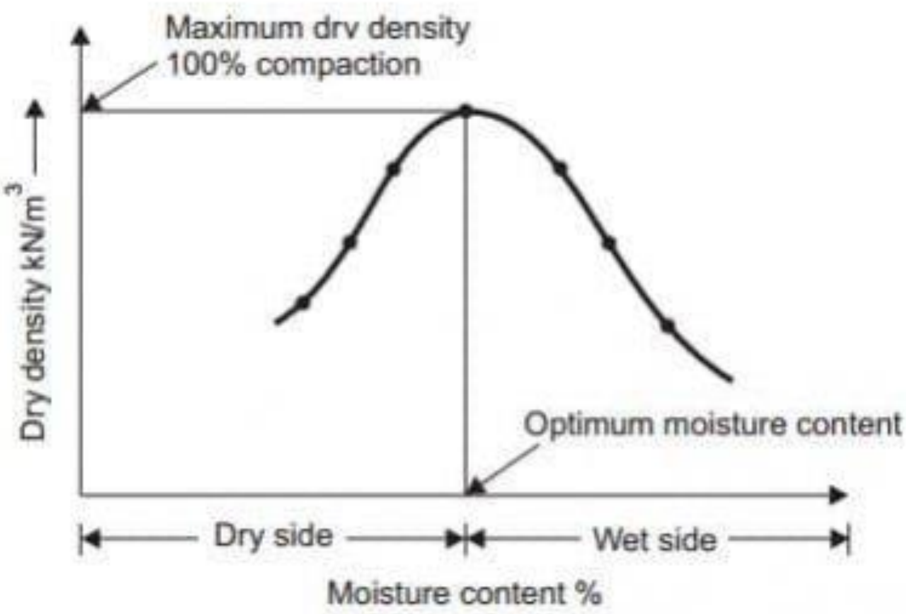

Figure 2. 6: Optimum moisture content curve

Figure 2.5 above shows the compaction curve where dry density values change with respect to water content. Li (2016) states that density will be decreased if moisture is added past this point as the number of voids will be increased. Furthermore, exceeding the optimum moisture content will result in increased pressure of the inner soil particles due to its confined air, therefore resisting compaction and ensuing a material density decrease.

2.3 STABILISATION TECHNIQUES

When a construction soil is considered weak, susceptible to small changes in moisture content, and faced with large/heavy loads, soil stabilisation can be utilised to improve its performance. Stabilisation can be applied to a subbase, subgrade, or sealing material, and can be used on a material in its natural position or added to a fill. Stabilisation improves the quality of soils through; reduction in plasticity index, limiting swelling potential, and increasing durability and strength through better soil gradation. Furthermore, soil stabilisation can reduce the design thickness of a subgrade or subbase course thus lessening construction time and costs. Factors must be considered when selecting a stabiliser for pavement design including; type of soil to be used, type of soil quality desired, cost and environmental conditions of which the pavement is to be constructed (Guyer 2017). Table 2.3 below shows types of stabilisation used within Australian pavement design and the material best utilised on. Following, each method will be discussed in-depth including; uses, material types, properties, and purpose of use.

Table 2. 4: Types of stabilisation used in road design

Stabilisation Technique	**Type**	**Application**
Cement	Chemical	Used for well graded granular materials and fine-grained soils. Strength and stiffness
Lime	Chemical	Used for high plastic clay type soils. Reduce swell and increase strength
Fly Ash	Chemical	Pozzolanic material best used in combination with lime or cement for clay type soils
Asphalt/Bituminous	Physical/Chemical	Well graded granular materials
Granular/Mechanical	Physical	Clay type and granular materials

2.3.1 Cement

Cement is a widely used soil stabiliser. This compound of silica, alumina, and iron creates four basic reactions to improve strength and dry out road pavement materials;

- Hydration
- Cation Exchange
- Carbonation
- Pozzolanic

The addition of cement to a subgrade material will modify its engineering properties, however not all types of soil will be altered to the same degree. Cement stabilisation will mostly increase the treated material's resilient modulus and California Bearing Ratio. Cement can be used as a successful stabilisation agent in most soils however is most effective when used to treat a sand/silt/gravel soils with low plasticity range, where it significantly reduces its permeability.

Quantities of cement required for stabilisation include; 6-10% for sandy soil, 8-12% for low plastic clays and silts, 10-14% for high plastic clays (Raj 1995). Mixing can become difficult when treating soils with a plasticity index above 30, or a liquid limit above 50. To counter this, lime or cement can be used for pre-stabilisation. Furthermore, the addition of cement to a subgrade soil changes both the maximum dry density and the optimum moisture content. Cement has a higher specific gravity therefore generates a higher density. It is suggested by Lightsey (1970) that compaction take place without delay after treatment, otherwise moisture content may be increased by 2-4% above optimum. Additionally, it is recommended by Ausroads (2006) that pavement materials stabilised with cement or cement blends must be compacted before the stage at which proper compaction is inhibited due to particle bonding.

2.3.2 Lime

Lime stabilisation is a commonly applied soil treatment method and is considered both effective and economic. Unlike cement stabilisation, lime is better suited to more plastic clay type soils, with a plasticity index of greater than 15, and a clay content of more than 20-30% (Pandi & Rabani 2017).

Lime addition to clay type soils will create cation exchange, flocculation, and pollozanic reactions when containing water. Cation exchange, where calcium cations replace the free cations available in the water within the soil, is the primary reaction between the lime, water, and clay (Pandi & Rabani 2017). When this water layer begins to decrease, the clay particles will attract each other more directly through flocculation, thus reducing the soils plasticity. It is known that pH can affect soil stabilisation, where soils with a pH of less 7 will not react as positive as with soils containing a pH of above 7.

Guney et al (2007) reports that lime stabilisation increases the optimum moisture content and improves resilient modulus strength, whist lowering swelling potential and reducing the maximum dry density. Lime stabilisation is however ineffective in low cohesion materials such as sand and will require the addition of pozzolanic additives (LTD A 2015). Quantity of lime addition can vary depending on the type of soil, though 4-6% is recommended, where the worse the soil, the higher the amount added.

2.3.3 Fly Ash

Fly ash, the product of the combustion of coal, is used as a subgrade soil stabilisation product with the road construction industry. As clayey soils lack amounts of silica and alumina, the pozzolanic reactions caused by fly ash strengthens the soil and prevents the likelihood of failure (Razali 2016). Furthermore, when fly ash is exposed to water, it will become hydrated, thus can be used as a drying agent for wet soils. Essentially, this makes fly ash act as a weak cementing agent that adds strength to a vulnerable soil. Several factors determine the hydration properties of fly ash including; coal source, ash collector system, and boiler design

White (2005) states that fly ash stabilisation can have the following limitations;

- Soil requires less moisture content
- If cured below zero and soaked in water, the mixture can become susceptible to slaking
- Sulphur within the soil may produce expansive minerals, thus reducing long term durability

Generally, fly ash from black coal is well suited to stabilisation through high amounts of aluminia and silica, and low carbon. However fly ash from brown coal is considered unsuitable for stabilisation due to it containing high amounts of calcium, chloride, and other soluble salts (Symons & Poli 1996).

2.3.4 Asphalt/Bituminous

Asphalt stabilisation is often used throughout pavement construction and is a mix of asphalt binder, water, and emulsifying agent. These mixtures can generally be designed as; 60% asphalt, 40% water, and a small addition of the emulsifying agent. Contrasting to the previously discussed stabilisation methods, the asphalt method is relying more on physical mechanisms than chemical reactions. Waterproofing of the soil is created when asphalt coats the aggregate particles and develops an adhesive bond with the binder, therefore making this process dependent on surface energies of the asphalt, binder, and material (Little & Nair 2010). The oils created by asphalt stabilisation at the time of addition must be given time to evaporate before complete compaction and finished surfacing are performed (Saleem 2012).

Foamed asphalt can be used for subgrade stabilisation, however is generally less effective on clay type soils with high fines content and more expensive than previous methods. Foam is produced when specialised equipment injects water and air into an asphalt binder. This foam sticks to fine particles, forming a mastic that binds the larger particles together (Jones & Jones 2010). Asphalt stabilisation is generally limited to gravel or sand type materials. Austroads (2006) state that to ensure a uniform distribution of the binder, pavement materials stabilised with foamed bitumen or bitumen emulsion must be compacted within a certain time. It must be noted that this type of stabilisation can be expensive due to the process and equipment used throughout the procedure. Figure 2.5 below shows the process of mixing the pavement material with foamed bitumen.

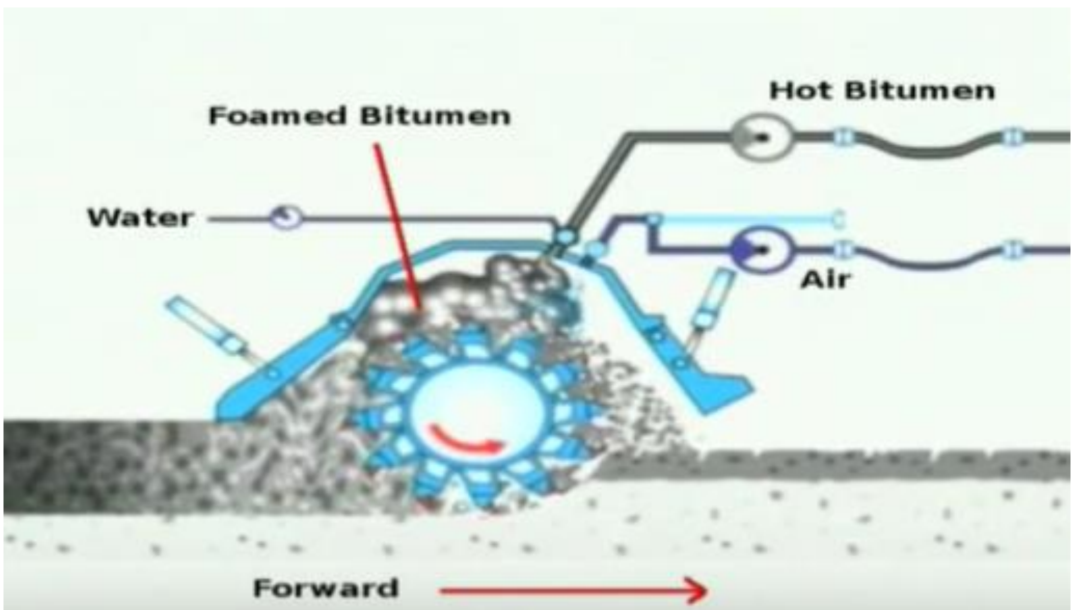

Figure 2. 7: Bitumen stabilisation process (Chan 2009)

2.3.5 Granular

Granular stabilisation is the improvement of the pavement material through the addition of another granular material. These materials can include fine grained soils, crushed rock, and natural gravels, used to fix any deficiencies of the parent materials intrinsic properties (Austroads 2006). Particle size distribution is altered through granular stabilisation thus improving the inner particle friction (LTD A 2015). Furthermore, the plasticity and Atterberg limits of the material change for better compaction after particle size distribution alteration. The improvement in load bearing performance of granular stabilised materials are a result of

- Increased mechanical interlock
- Decreased aggregate breakdown
- Increased inter-particle friction
- Increased resistance to failure by water entry

As granular stabilisation produces a material with similar properties to that of a traditional unbound material, conventional testing can be used to evaluate its performance (LTD 2015). Granular stabilisation can comprise of the following (Austroads 2006):

- Recycled materials mixed with an existing pavement
- The mixing of materials from different parts of a deposit at the supply source
- The mixing of in-situ materials with imported materials
- The mixing of two or more soils, natural gravels, or quarry materials on site or in a mixing plant.

2.3.6 Consolid

Consolid is a soil stabilisation product used to increase a subgrade's bearing capacity through solidification. Unlike the previously discussed methods, this system was developed specifically for soil stabilisation. It is a two-part system and unlike some traditional stabilisation methods, does not react as a binder or oxidant. Consolid reduces the permeability of the treated material whilst also decreasing its capillary action. The two components used in conjunction for the Consolid system include Consolid 444 and Solidry. These products combine to consolidate a soil, thus increasing its CBR value and improving its unconfined strength and stiffness. Consolid 444 is a liquid, whereas the Solidry component comes in a powder like form.

Consolid 444 is a liquid chemical ingredient that reduces the capillary rise of water through breaking up the adhering water film, which in turn develops an agglomeration of the fines (Erin & Filiz 2009). Furthermore, this will increase soil density and therefore create better compaction.

Solidry is a dry chemical/organic substance aimed at preserving the treated materials whist increasing its specific bonding characteristics (Consolid UK). Solidry is applied to the upper layer of the pavement, above which was applied with Consolid, to limit the intake of surface water by closing the capillary. The recommended soil mixture for Consolid stabilisation is 1/3 clay/silt (0-0.2mm), 1/3 sand (0.2-2mm), and the remaining with gravel/stones.

As the thermal conductivity of materials treated with Consolid is much lower, the likelihood of freezing will be much less, therefore better suited to cold climates than some traditional stabilisers. Moreover, the Consolid system functions effectively in areas of high humidity. Consolid can be applied to a subgrade material either in-situ or plant mixed where then transported to site for use. Each ingredient can be mixed at the same time; however, the treated material must be at optimum moisture content before compaction. The recommended practice for applying each part is as follows;

- Consolid 444 – Full depth at 0.8L per m3
- Solidry – Top 40% at 40kg per m3

It is recommended that a surfacing be applied to the pavement structure after treatment to prevent abrasion (Consolid UK). The ion exchange that occurs after treatment repels the moisture within the soil once compacted, thus increasing dry density throughout time. The Consolid system is created to prevent degrading and improve over time. Sections 3,4,5 of this report will aim at providing evidence to support these improvements made by this product mentioned previously.

2.3.7 Factors Effecting stabilising materials

The strength of stabilised materials may become unfavourable due to the presence of the following substances;

- Organic matter – Soil organic matters can react with the hydration product being used for stabilisation, resulting in a low pH value, and thus potentially affecting the hydration process and compaction ability.

- Sulphates – When exposed to excess moisture, sulphate rich soil when stabilised may react to form calcium sulphoaluminate, a product with a greater volume than that of the combined reactants (Little and Nair 2009).
- Sulphides – Sulphides present within the soil may produce sulphuric acid when stabilised. This in turn will produce hydrated sulphate and similar sulphates, will attack the stabilised material in the presence of water (Little and Nair 2009).

Sherwood (1993) states that in cold regions, it is recommended that subgrade soil stabilisation be conducted during the warm season to eliminate the effect of temperature on product quality. As temperature varies throughout the day, pozzolanic reactions may be altered as they can be sensitive to temperature changes. Lower strength of the stabilised soil will be the result of slow pozzolanic reactions between particles and binders (Sherwood 1993). Furthermore, frost damage can occur within stabilised soils as some methods cannot withstand freeze-thaw cycles as seen in the field.

Other non-traditional methods can be used for soil stabilisation however are not discussed throughout this report including;

- Bio-oils
- Geo-synthetics
- Waste by-products

2.3.8 Manufacture/Procedure of Stabilisation

Pavement stabilisation materials can be manufactured either in-situ or through a plant-mixed procedure. In-situ stabilisation is a portable process, where the stabilisation binder is added then mixed to an existing pavement material using purpose made machinery such as a road recycler. Other unbound materials may be added to the stabilised materials to improve its quality and modify any deficiencies in particle size distribution and plasticity index (Austroads 2006). Kowalski & Starry Jr (2007) state that during in-situ stabilisation, additional material may have to be added to thicken the subgrade due to material loss from the stabilisation procedure. The activities that include; stabilisation binder component addition to the parent material, mixing and adding water, and compaction, are generally referred to as 'working time' (Gnanendran & Piratheepan 2008).

Working time is imperative in pavement stabilisation and must be considered when selecting the type of stabilisation procedure to be used.

Plant mixed stabilisation generally involves mixing the binding agent with an unbound granular material sourced from quarrying using a stationary pugmill, where then transported to site for use. The quality of materials used must adhere to the relevant pavement guidelines and specifications for plasticity and particle size distribution (Austroads 2006). The stabilised material is then transported to site using trucks however, consideration must be made to maintain the suitable amount of time between mixing and compaction, dependent on the binder used. Additionally, Austroads (2009) recommend that covered trucks should be used for delivery with maximum delivery time half that of the working time of the binding agent. The stabilised material is to be placed, compacted, shaped, and cured for preparation for the above pavement layers to design specifications and the stabilising agent's manufacturers guidelines.

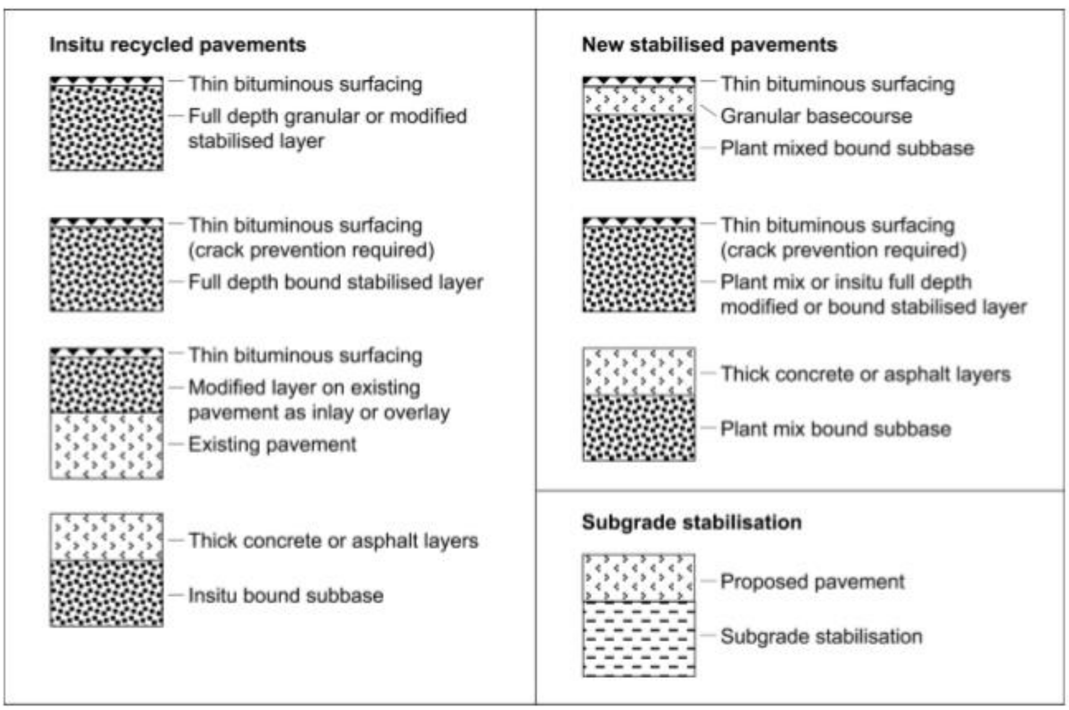

Figure 2. 8: Pavement configurations after stabilisation

Figure 2.6 shows the variety of configurations of pavement material stabilisation and the different materials/methods used. This includes in-situ recycled pavements, new stabilised pavements through plant mixing, and subgrade stabilisation. Bound stabilisation is the addition of the binders previously discussed to granular pavement materials.

2.3.9 Compaction of stabilised materials

The performance of a stabilised pavement layer is extremely reliant on the quality of compaction. A high degree of compaction is best achieved through the consistency between optimum moisture content and depth, and by being graded suitably. Whilst traditional windrow grader mixing can succeed, the use of proper stabilisation equipment will allow for greater distribution of compaction moisture content through the granular layer's full depth (Austroads 20006).

Compaction time after stabilisation is critical when trying to achieve maximum strength and density. Delayed compaction can disrupt the accumulations of particles required to densify the material, as hydration products begin to bond in a loose state (Milburn & Parsons 2004).

2.3.10 Resilient Modulus of Stabilised Materials

The resilient modulus (stiffness) characterises stabilised granular materials within current mechanistic pavement design outlines and is considered a critical factor when evaluating the structural behaviour of a stabilised pavement material. Several influences contribute to a direct effect on the resilient modulus of a stabilised pavement material including; moisture content, particle size distribution, and compaction. Austroads 2006 affirm that the resilient modulus is highly dependent on the fatigue relationships used in design for stabilised pavement materials.

2.3.11 Industry Standards

The stabilisation of pavement materials in Queensland must be performed in conjunction with the technical specifications outlined by the department of transport and main roads. These series of specifications outline the requirements required for each type of stabilisation including; materials, construction methods and processes, material and construction compliance testing, quality requirements, and product standards. Table 2.3 below shows each stabilisation method discussed previously and the current specifications used for each in design.

Table 2. 5: Technical specifications for pavement material stabilisation in Queensland

Stabilisation Method	Technical Specification/ Comments
Cement/Cementitious blends	• MRTS07B Insitu Stabilised Pavement using Cement or Cementitious Blends • Austroads (1988) Guide to Stabilisation in Roadworks • AS3972
Lime	• MRTS07A Insitu Stabilised Subgrades using Quicklime or Hydrated Lime • MRTS23 Supply and Delivery of Quicklime and Hydrated Lime for Road Stabilisation • AS1672.1
Bitumen	• MRTS07C In-situ Stabilised Pavements using Foamed Bitumen • MRTS09 Plant-Mixed Pavement Layers Stabilised using Foamed Bitumen • TN150 Testing of Materials for Foamed Bitumen Stabilisation • AS2008 • AS2341
Fly Ash	• AS3582.1 • MRTS07B In-situ Stabilised Pavement using Cement or Cementitious Blends
Consolid System	• Currently the Consolid System is not recognised within industry standards

In addition to other new and non-traditional stabilisation methods, the Consolid System is currently not integrated into pavement construction standards and guidelines throughout Australia. This lack of standardised test procedures for assessing product potential is persistent in acting as an obstacle for the acceptance of non-traditional stabilisation methods. Previous studies and the material provided by this investigation will support the inclusion of the Consolid system into the construction specifications shown in table 2.3 above.

2.3.12 Soil Stabilisation Guidelines & Overview

Pavement material additive interaction is influenced by the characteristics of fine-grained soils including gradation, minerology, and physical/chemical properties. Furthermore, the stabiliser that is selected must be the most effective at improving these properties of the treated material. As most pavement projects needing soil stabilisation are site specific, the development of suitable solutions requires the integration of correct test methods, soil types, and design procedures. When selecting a stabilisation binder, the required working time must be considered in conjunction with construction parameters. The main ideology behind soil stabilisation within pavement design is the following;

- Increase the resilient modulus of the of the material
- Increase the bearing capacity of the material
- Reduce the capillary rise of moisture and prevent water infiltration of the material
- Improve the levels of compaction
- The stabilisation method selected must consider costings and environmental conditions

2.4 SUMMARY

This section provided a brief review of the fundamentals of pavement design and the parameters in which soil strength, moisture, and overall quality of a pavement material is defined. The current state of soil stabilisation was examined and proved the benefits of why this must continue to be incorporated into pavement design. The Consolid system was briefly discussed, highlighting its stabilising qualities and feasibility compared with traditional methods despite a lack of long-term research in Australia. Henceforth, the remainder of this report will address this shortage of research and provide further analysis of the characteristics and long-term suitability of this product.

3 METHODOLOGY

The objective of this research is to test the long-term performance of the Consolid stabilisation system and provide additional support for the recognition of this product throughout Australian pavement design. The following section provides a detailed discussion of the methods used to attain the results required to address the primary objective of this project. This includes all materials, testing methods, testing equipment, specifications, and exterior help provided throughout this study. Parts of this investigation build upon the pilot study by Hayden Curran in which the Bracalba Quarry trial site was constructed including excavation, treatment, and compaction. Henceforth, only a brief synopsis of this will be provided in this report. Each procedure and basis of testing for this project contained in this section are as follows:

1. Falling Weight Deflectometer testing – to calculate the parameters used for Resilient modulus estimation by back calculation
2. Elmod6 pavement software – to calculate the resilient modulus of the treated road through back-calculation and compare with previous results
3. Moisture testing – to determine whether moisture content of treated pavement is increased by excessive rainfall and if so is strength is affected
4. Laboratory CBR testing – to verify the aims of the Consolid system in increasing bearing capacity, and which materials are best suited to treatment
5. Visual inspections of the treated road – to identify any cracking, potholing, or deformation

These investigations and testing processes were conducted at Bracalba Quarry and the University of the Sunshine Coast between June and September 2018. The methods mentioned above will be presented in this section below, where all results are shown in section 4.

3.1 TREATMENT AND ROAD CONSTRUCTION

The following points provide a brief synopsis of the construction of the Consolid treated unbound quarry haul road performed by Hayden Curran and the Bracalba quarry management used for testing throughout this report.

- The treated area was boxed out at 30m x 8m x 250mm depth
- Bottom 125mm layer was treated with C444 solution first and compacted
- Top 125mm layer was treated with C444 and Solidry and compacted
- All materials were mixed thoroughly and to Consolid design specifications after treatment
- Water was added to the treated material to obtain OMC for compaction
- Placement and compaction were performed as per normal road construction with graders and rollers

The full treatment and construction process can be found in Curran (2016) including the following:

- Treatment
- Watering
- Levelling
- Compaction
- Quality

Figures 3.1 and 3.2 below show the location of Bracalba Quarry generated from google earth and the trial section of road at first inspection respectively. Figure 3.3 shows samples of Consolid444 found in Curran (2016).

Figure 3. 1: Screenshot from Bracalba Quarry from google earth

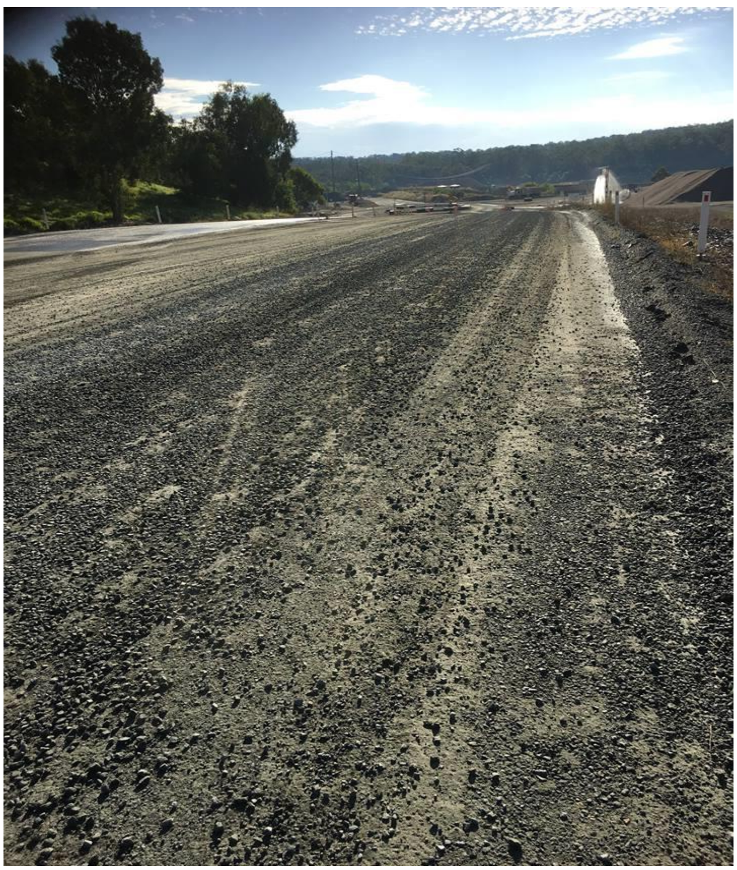

Figure 3. 2: Bracalba Quarry trial site facing North East – lane width approx. 5m

Figure 3. 3: Consolid444 used by Curran (2016) for treatment of trial site

3.1.1 Material

The material used for treatment is classified as a type 2.5 unbound granular road base sourced from Bracalba quarry. The type 2.5 material is considered suitable for such an investigation as it is used as a subgrade replacement and pavement base course material throughout Queensland. Testing of this material was provided by the quarry prior to treatment/placement in 2016 and can be found in Curran (2016). Testing of the material prior to treatment was imperative as it allowed for analysis of the material properties, some of which may affect the treatment, compaction, or long-term suitability of Consolid.

3.2 FALLING WEIGHT DEFLECTOMETER (FWD)

A Falling weight deflectometer test is considered the most practical method for accurately measuring a pavements response, thus used to determine resilient modulus. An FWD test was conducted to determine the stiffness of the treated and untreated sections of road for long term analysis and comparison with results from past testing. It was determined after consultation with my project advisor, that Pavement Management Services will be engaged to perform the FWD test for the reasons; the same equipment and personnel was employed for FWD testing by Hayden Curran, PMS have a history with University of the Sunshine Coast and are committed to assist in final year projects.

The 30m treated section of haul road facing North East at Bracalba quarry and an untreated section of the same distance and load exposure heading South East was tested. Pavement Management Services falling weight deflectometer was used for deflection testing on the 24 August 2018. The testing configuration for both sections of road was designed to incorporate staggered drops at 5m intervals in both directions. The testing design is shown below in figure 3.4 where each drop and chainage are indicated.

Figure 3. 4: FWD test drop points on both treated and un-treated road – Bracalba Quarry

Figure 3.4 shows the Co-ordinates were used to ensure the test points were as close as possible to the FWD testing conducted in Hayden Curran's investigation. If testing was performed at different locations than previous, a true representation of the long-term difference in results may vary, albeit slightly. The target load for the first three drops at each test point was 40kN (between 565 – 575 kPa) and the fourth drop was 60kN. The first drop is considered a test drop, whereas drops two and three should be used for analysis and will produce similar results. A drop of 60kN (drop 4) was performed as an alternative and to provide further structural and material analysis.

The Falling weight deflectometer equipment set-up, testing, calibration and survey procedure was performed in accordance with Australian standards and recommendations including;

- Materials and testing methods – Part 4, Queensland Department of transport and main roads
- AGAM-S002-07, Specification for Pavement Deflection Measurement with a Falling Weight Deflectometer (FWD) – Austroads

The FWD included nine geophones at distances 0,200,300,450,600,750,900,1500 mm, and a plate radius of 150mm. Figure 3.5 below shows the FWD machine used for testing. Several FWD tests were intended to be conducted for greater data analysis and comparison, however equipment availability and time constraints limited this objective.

Figure 3. 5: Pavement Management Services FWD machine used for testing at Bracalba Quarry

3.2.1 Modulus Back-calculation

The pressure and deflection results achieved by the FWD in the field are required to be processed by a structural pavement analysis program. This software determines the stiffness of each layer which is vital for meeting the aims of this research. The raw deflection data gained from the Falling Weight Deflectometer test was used in the computer program Elmod6. Elmod6 uses the measured deflection basins obtained from an FWD to automatically execute a structural analysis and overlay design of the pavement through modulus back-calculation. The raw data was set up within Microsoft Access in the way which Elmod6 can read the data before it was imported to the program. This FWD data can be found in appendix C. A set of parameters were chosen to be used in the calculations, customising the analysis to represent the pavement specifications and conditions. These included:

- Surface temperature – recorded from FWD testing
- Seeding of values
- Pavement structure - layer thickness
- Number of drops
- Layer type/materials – granular, clay

After these were included within the program, the moduli, stresses, and strains in each layer were calculated through the back-calculation procedure, where the calculated deflection bowl was iteratively calculated to best fit the raw deflection bowl. The resulting data was exported to Microsoft Excel. The following figures 3.6 and 3.7 show the program interface and the moduli data screen used. Problems were encountered when first attempting to utilise the FWD data through Elmod6 due to no prior experience with the software. Clarification and assistance were provided through a meeting with Trent McDonald from Pavement Management Services. This included the set-up and the parameters stated above. It was this assistance that proved invaluable and allowed me to obtain the results required to satisfy the aims of this project.

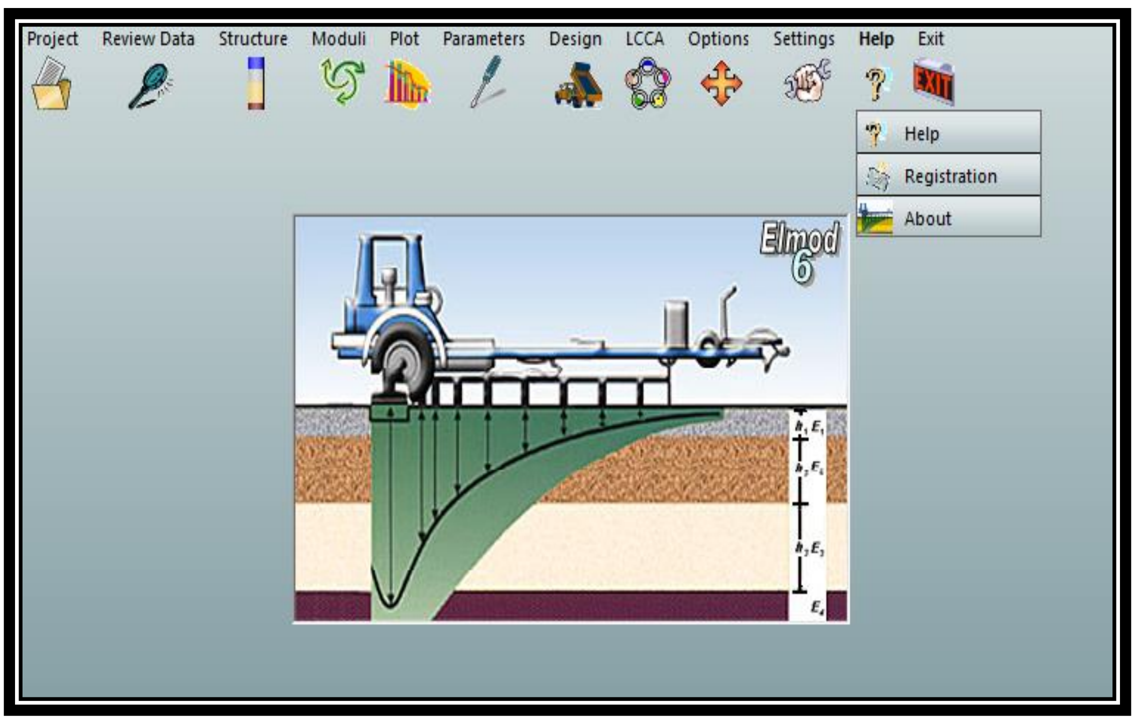

Figure 3. 6: Screenshot of the Elmod6 user interface

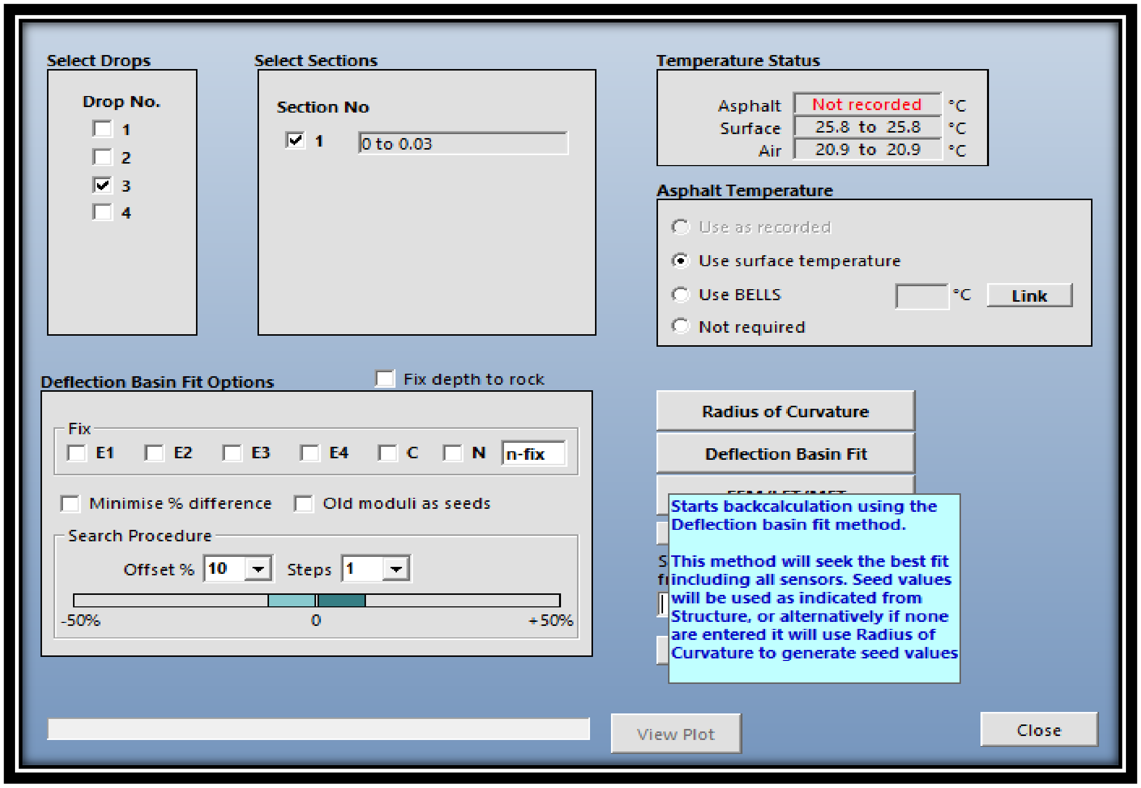

Figure 3. 7: Screenshot of the Elmod6 moduli data input screen

3.2.2 Laboratory Resilient Modulus Testing

Laboratory modulus testing was not conducted of the treated material from Bracalba quarry due to the unrealistic nature of such a test and its uncertainty, cited by prior research including (George 2003). Sample disturbance and variances in particle positioning, compaction levels, and moisture properties make laboratory modulus testing not entirely representative of the treated material conditions. It was determined from considering the following limitations that laboratory modulus testing was not to be undertaken for this investigation

- Laboratory samples will only represent small properties of the treated material, unlike in-situ where larger masses are exposed to an FWD test.
- The process of sample acquisition and correct statistical sample testing would have produced time and expense limitations not worthy of such impractical results.
- The lack of equipment and verification measures would have produced differences between each individual laboratory test and between lab and in-situ test results.

Despite the intentions of laboratory modulus testing, the above-mentioned issues ultimately proved to unwarranted for this investigation. It was determined that a non-destructive test like both the FWD and moisture sensor will be more beneficial in identifying the stiffness and water prevention of the treated pavement material.

3.3 MOISTURE SENSORS

As the Consolid system's primary means of strengthening a material is through limiting water intake, moisture sensors were installed to assist in subsurface investigation. Moisture sensors were installed by Pacific Data Systems on the 14^{th} May 2016. A more detailed description of the installation of these sensors can be found in Curran (2016). Dielectric, electrical conductivity, and temperature are recorded by the sensors at 15-minute intervals. These readings are uploaded to Spoke data and can be accessed by the appropriate person. Pacific data systems were contacted to obtain the log-in information required to retrieve the data. This data was first accessed on the 18 July 2018.

Figure 3.8 below shows the sensors are located at a depth of 125mm and 250mm from the surface between the treated layers. This image was acquired from Curran (2016). The sensors have remained in place and data has been recorded since installation for long term data evaluation and the purpose of this investigation. It must be noted that these moisture sensors were calibrated accordingly prior to installation to prevent anomalies in the data. Figure 3.9 below shows the solar panel and moisture sensor transmitter at Bracalba Quarry.

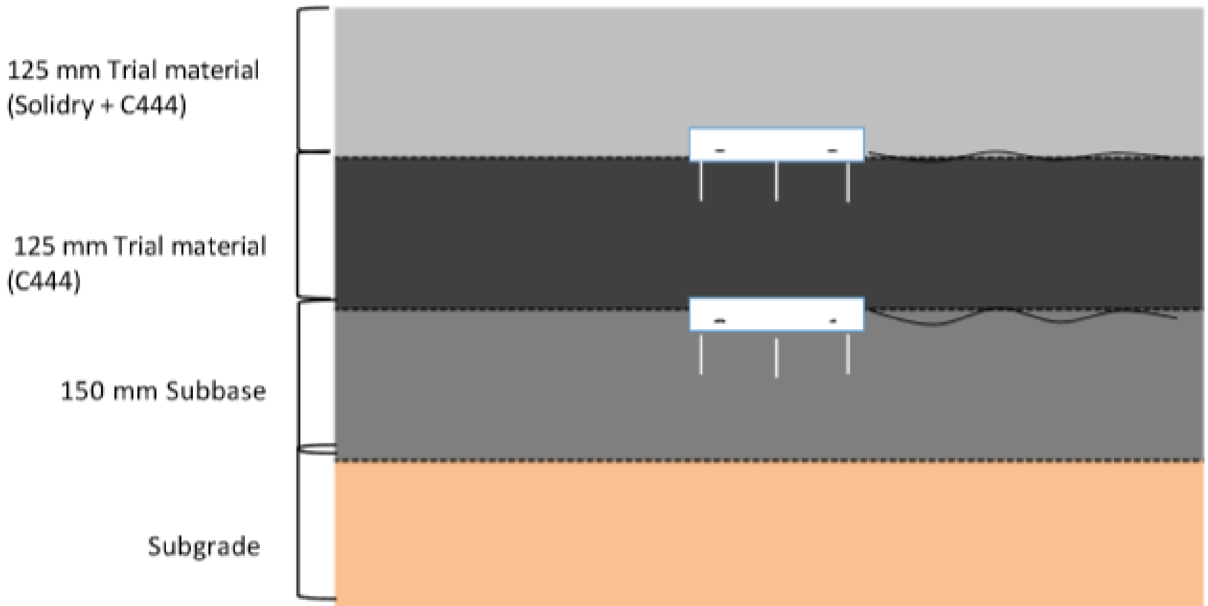

Figure 3. 8: Moisture gauge arrangement within the treated pavement (Curran 2016)

Figure 3. 9: Solar panel and moisture sensor at side of treated road – Bracalba Quarry

3.3.1 Analysis of moisture content

Rainfall data was obtained through the burau of meteorology to be used in conjunction with sensor data to better understand the product's efficiency. This data included;

- Daily rainfall for the entire period since the moisture sensors were installed
- Daily rainfall for March 2018 – in which significant rainfall occurred
- Monthly rainfall for the two-year period between September 2016 – September 2018

Burau data was downloaded into excel format and compiled within the same spreadsheet as moisture sensor data for analysis and collation.

3.4 LABORATORY CBR TESTING

The CBR is a fundamental test for determining the bearing capacity of soil. Laboratory testing was performed by Soil Engineering Services (SES) on Consolid treated materials for comparative analysis. The purpose of obtaining these test results was to verify and compare data to the relevant theory of unbound granular material CBR's and the suitability of Consolid treatment for various soils. CBR tests were performed on two different soils to determine the strength of each material after treatment with the Consolid system. The following soil types were used for testing:

- Type 2.5 granular unbound material (road-base) sourced from Hanson quarry Ferny Grove
- Gravelly brown/Dark silt composite soil sourced from a Queensland Railway site

Soaked and Un-soaked samples of each material without additive were tested. The same testing was performed on each material after the addition of Consolid. Standard compaction was performed on each sample at optimum moisture content and left to cure in a sealed container for a four-day period before penetration. The testing methods were carried out in accordance with AS1289 – Methods of testing soils for Engineering purposes. Testing of the 2.5 road-base occurred on 14 December 2016 and testing of the composite occurred on the 20 July 2018. These tests can be found in appendix D.

3.5 VISUAL INSPECTIONS

Visual inspections of the trial site at Bracalba quarry were undertaken throughout to identify possible;

- Potholes
- Cracks
- Deformation
- Overall visual structure

The first site visit/visual inspection took place on the 19 July 2018. The second visual inspection was undertaken on the 23 August 2018 (same day as the FWD test). The third and final visual inspection took place on the 9 October 2018. The visual nature of the trial site will be examined in detail within the discussion section of this report.

3.6 SUMMARY

This section has summarised all the methods utilised to obtain the results and data for this investigation. The methodology discussed throughout this section will be used for the following

- Outline and plot resilient modulus of each pavement layer from treated and un-treated section of road for a drop of 40kN and 60kN
- Plot moisture content in conjunction with rainfall totals
- Plot and compare CBR results from laboratory soil testing for two material types stabilised with Consolid
- Plot and compare resilient modulus calculations of pavement layers to that obtained in 2016.
- Provide images of the treated pavement and identify its condition

The equipment and methods employed have been proven in similar research in the past, therefore providing the knowledge in which reliable practices were used. Minimal issues were encountered throughout testing and data acquisition, and any problems faced were discussed briefly throughout this section. The testing conducted was deemed reliable and enough in addressing the aims outlined previously. The next section will provide the results from the methodology discussed throughout this section.

4 RESULTS

The following section shows the results obtained from the methods discussed in the previous section. This includes compilation of tables and graphs to accurately represent the data obtained through FWD testing, laboratory testing, and moisture sensor testing. An extensive analysis and review of the results shown will be presented in the discussion following this section. Furthermore, the results of material treatment, compaction and overall road construction can be found in Curran (2016).

4.1 FALLING WEIGHT DEFLECTOMETER

All deflection results from the falling weight deflectometer test on both the treated and non-treated section of Bracalba quarry road can be found in appendix C. This FWD test was performed on the 23 August 2018, approximately 28 months since treatment and construction. These results were used in the program Elmod6 to determine the material stiffness (Elastic Modulus), after which they were formatted and shown below. Figure 4.1 below shows an example of the raw data obtained from the FWD test drop 3 – treated material and converted to excel format before use in Elmod6.

Table 4. 1: Raw data from the FWD test in Microsoft Excel format

Survey Date	Station (km)	Lane	Wheel-path	Load kPa	Measured Deflection Results (µm)								
					Distance from Load (mm)								
					0	200	300	450	600	750	900	1200	1500
23/08/2018	0.000	1	OWP	567	299	220	177	117	80	54	42	29	20
23/08/2018	0.005	1	IWP	567	262	209	163	108	76	57	44	31	23
23/08/2018	0.010	1	OWP	568	293	212	157	108	75	65	54	34	31
23/08/2018	0.015	1	IWP	569	310	233	169	128	87	77	52	38	32
23/08/2018	0.020	1	OWP	574	744	609	476	336	231	168	122	73	46
23/08/2018	0.025	1	IWP	567	671	447	353	245	177	131	100	63	45
23/08/2018	0.030	1	OWP	569	456	309	217	138	100	77	62	42	32
23/08/2018	0.000	2	OWP	569	428	236	162	112	89	73	60	44	31
23/08/2018	0.005	2	IWP	566	263	199	160	101	74	57	46	35	27
23/08/2018	0.010	2	OWP	566	419	266	195	138	105	85	69	48	35
23/08/2018	0.015	2	IWP	572	412	262	182	121	90	71	56	43	30
23/08/2018	0.020	2	OWP	566	365	252	171	102	87	50	45	29	24
23/08/2018	0.025	2	IWP	567	431	300	203	127	93	71	56	37	26
23/08/2018	0.030	2	OWP	566	468	351	258	169	122	91	69	45	30

4.1.1 Resilient Modulus

The resilient modulus for each pavement layer calculated through Elmod6 is shown in table 4.1 and figure 4.1 below. These results are from drop 3 (40kN) of the FWD test performed on the treated section of road. As discussed throughout this report, drop three of the FWD with a 40kN load is standardised procedure and considered the most reliable for modulus results.

Table 4. 2: Resilient moduli from FWD test on treated pavement drop 3

Station (Chainage)	Base (MPa)	Sub-base (MPa)	Subgrade (MPa)
0	1407	239	88
0.005	1824	223	96
0.01	1105	403	125
0.015	1160	425	100
0.02	755	82	25
0.025	480	175	54
0.03	677	236	80

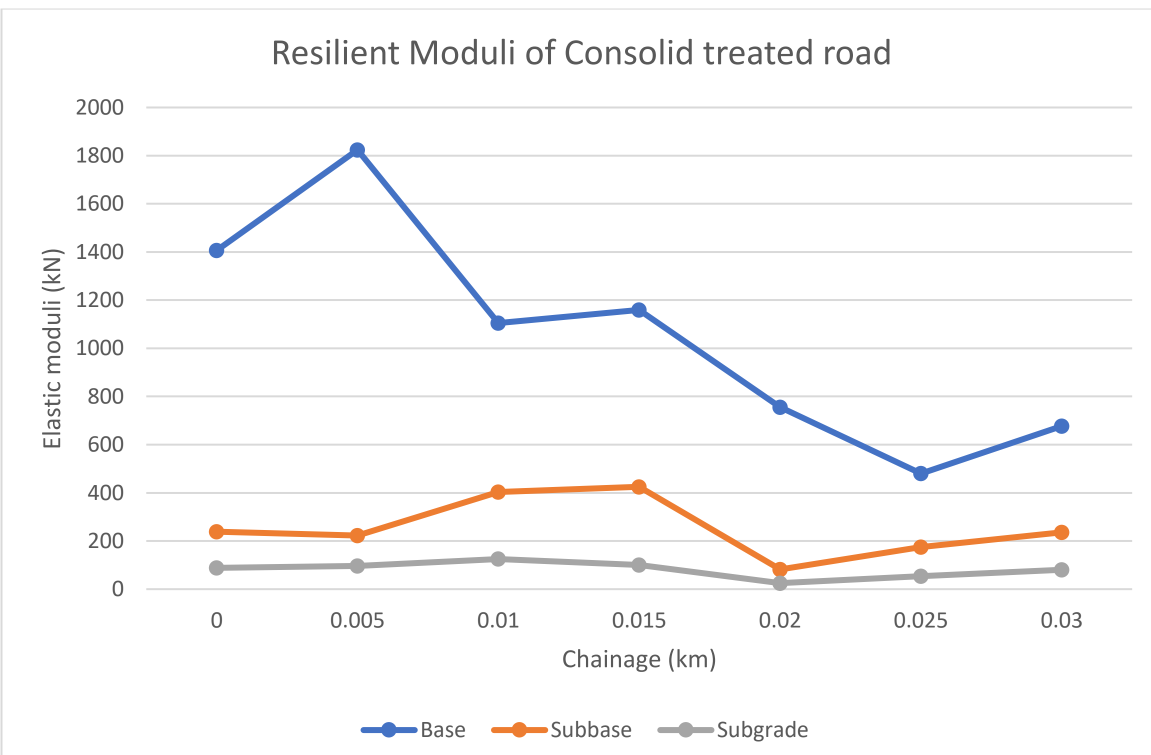

Figure 4. 1:Resilient modulus of pavement layers for treated pavement drop 3

The elastic modulus for each pavement layer at each drop station calculated through Elmod6 are shown in table 4.2 below. These results are from drop4 (60kN) of the FWD test performed on the treated section of road. As discussed throughout, varied drops of more than 40kN can be performed to further identify properties of the soil.

Table 4. 3: Resilient moduli from FWD test on treated section of pavement drop 4

Station (Chainage)	Base (MPa)	Sub-base (MPa)	Subgrade (MPa)
0	1452	330	70
0.005	1779	288	94
0.01	1212	360	117
0.015	1276	310	104
0.02	812	83	24
0.025	548	174	46
0.03	809	254	65

The resilient modulus for each pavement layer at each drop station calculated through Elmod6 are shown in table 4.3 and figure 4.2 below. These results are from drop 3 of the FWD test performed on the un-treated section of road.

Table 4. 4: Resilient moduli results from FWD on un-treated pavement drop 3

Station (Chainage)	Subase (MPa)	Subgrade (MPa)
0	459	129
0.005	1278	41
0.01	586	62
0.015	639	44
0.02	783	34
0.025	603	39
0.03	576	37

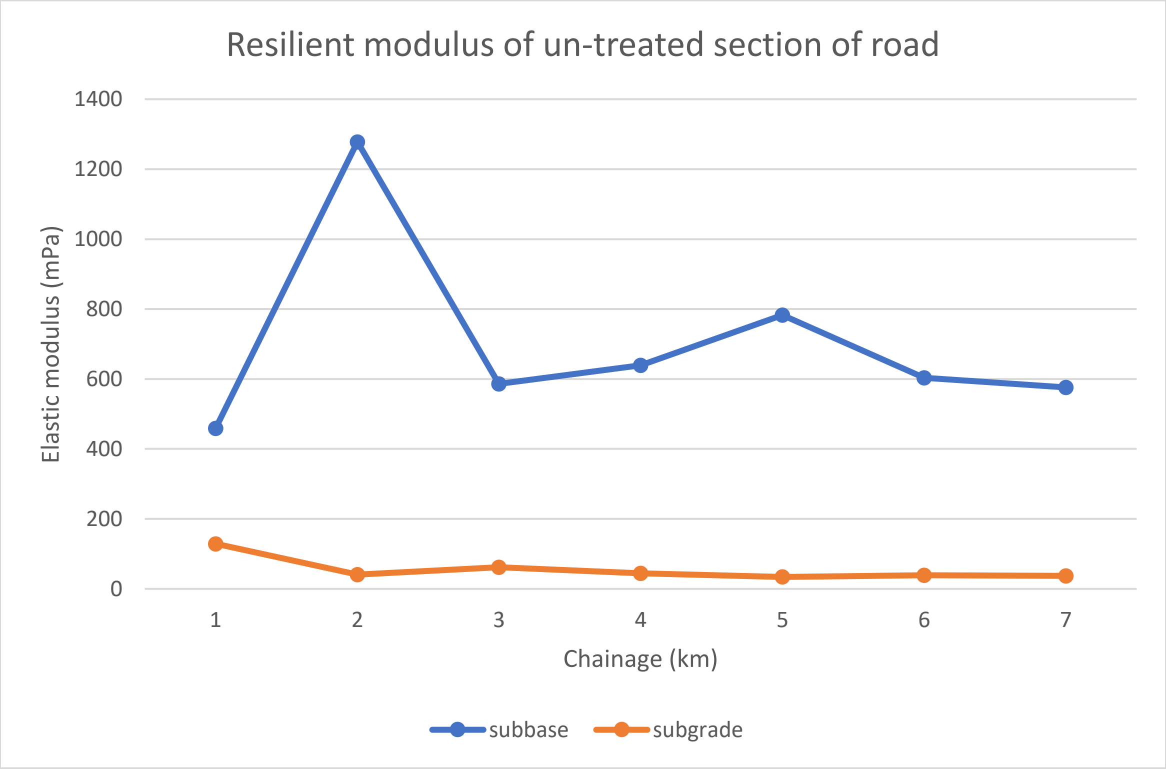

Figure 4. 2: Resilient moduli of pavement layers for untreated pavement drop 3

The elastic modulus for each pavement layer at each drop station calculated through Elmod6 are shown in table 4.4 below. These results are from drop 4 60kN of the FWD test performed on the un-treated section of road.

Table 4. 5: Resilient moduli from FWD on un-treated pavement drop 4

Station (Chainage)	Subbase (MPa)	Subgrade (MPa)
0	505	113
0.005	1421	58
0.01	678	61
0.015	760	67
0.02	634	82
0.025	597	57
0.03	494	45

4.2 MOISTURE CONTENT

Moisture sensors were installed at the time of construction and have been monitoring the moisture content of the treated pavement section at Bracalba quarry consistently for the past 24 months. The average daily moisture content for each sensor and daily rainfall amounts for March 2018 are shown in figure 4.3 below. The average monthly moisture content and the monthly rainfall totals for each sensor is shown in figure 4.4 below. This is for a 24-month period from September 2016 to September 2018.

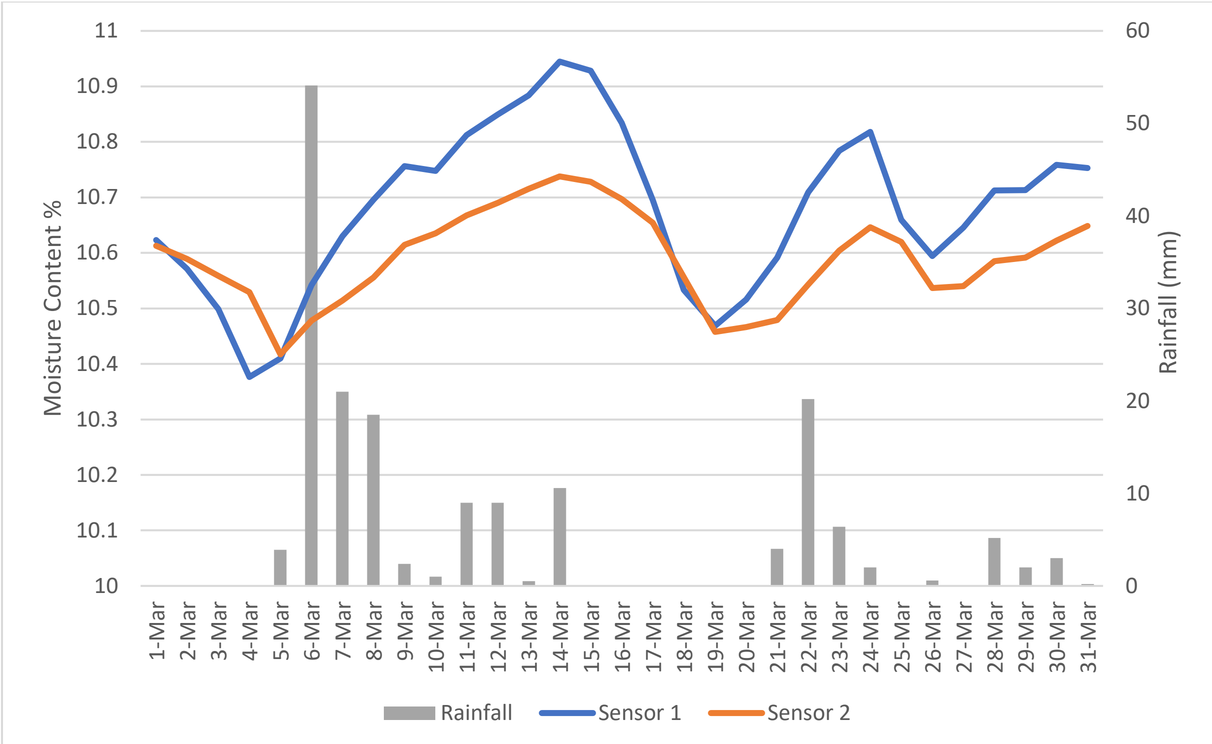

Figure 4. 3: Daily pavement moisture content and daily rainfall for March 2018

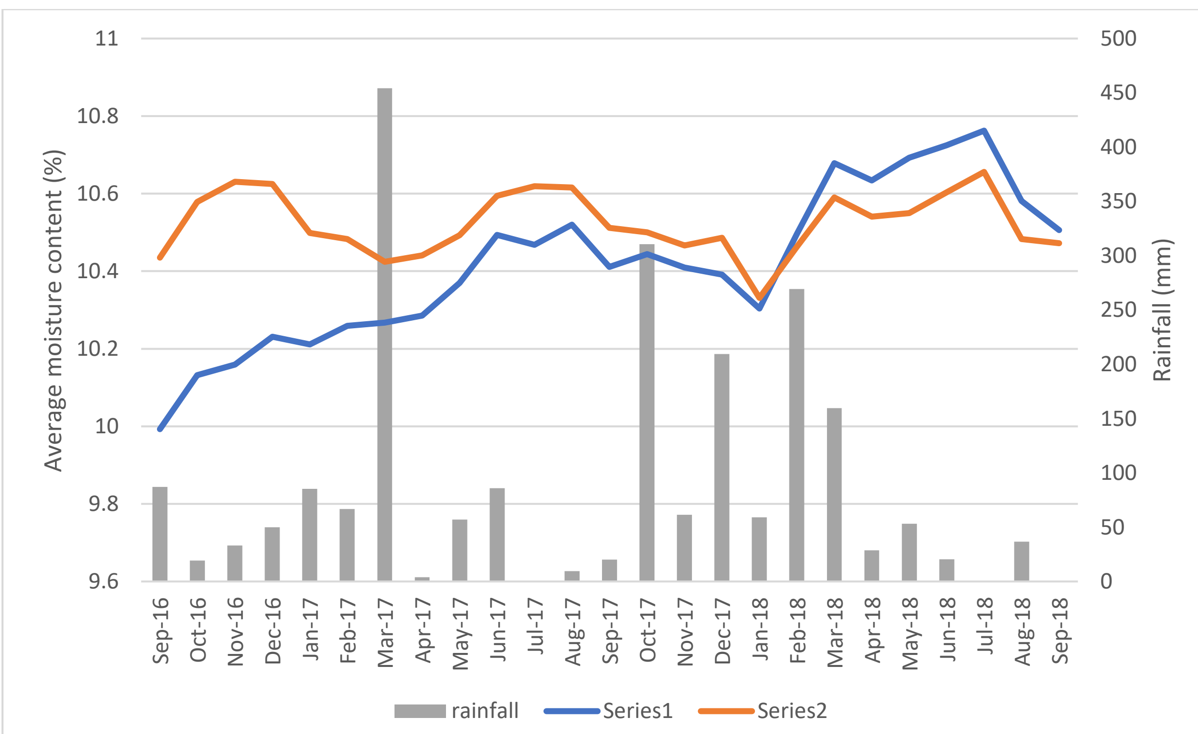

Figure 4. 4: Monthly average moisture content of pavement and monthly rainfall totals

4.3 SES Testing

Comparative testing was undertaken by Soil Engineering Services (SES) on two partially different materials to determine their California bearing ratio when stabilised with Consolid. Table 4.5 below shows the results from a CBR test performed by Soil Engineering Services (SES) on a composite soil mix sourced from a Queensland Rail facility. This test occurred on the 20 July 2018. The full test and results can be found in appendix D.

Table 4. 6: Results from CBR testing of a composite soil

Material Conditions	CBR %	MDD (t/m3)	OMC %	MC After Soak
Un-soaked	42	1.173	24.5	
Un-soaked + Treated	78	1.242	26.1	
Soaked	32	1.173	24.5	27.2
Soaked + Treated	80	1.242	26.1	27.9

Table 4.6 below shows the results from a CBR test performed by Soil Engineering Services (SES) on a 2.5 road-base sourced from Hanson quarry Ferny grove. This test occurred on the 14 December 2016. The full test and results can be found in appendix D

Table 4. 7: Results from CBR testing on a type 2.5 road-base material

Material Conditions	CBR %	MDD (t/m3)	OMC %	MC After Soak
Un-soaked	14	2.218	7.8	
Un-soaked + treated	230	2.167	7.8	
Soaked	16	2.218	8	11.9
Soaked + treated	210	2.168	8	7.5

Figure 4.5 below shows CBR value increases for the 2.5 road-base compared with the composite mix soil when treated with the Consolid System.

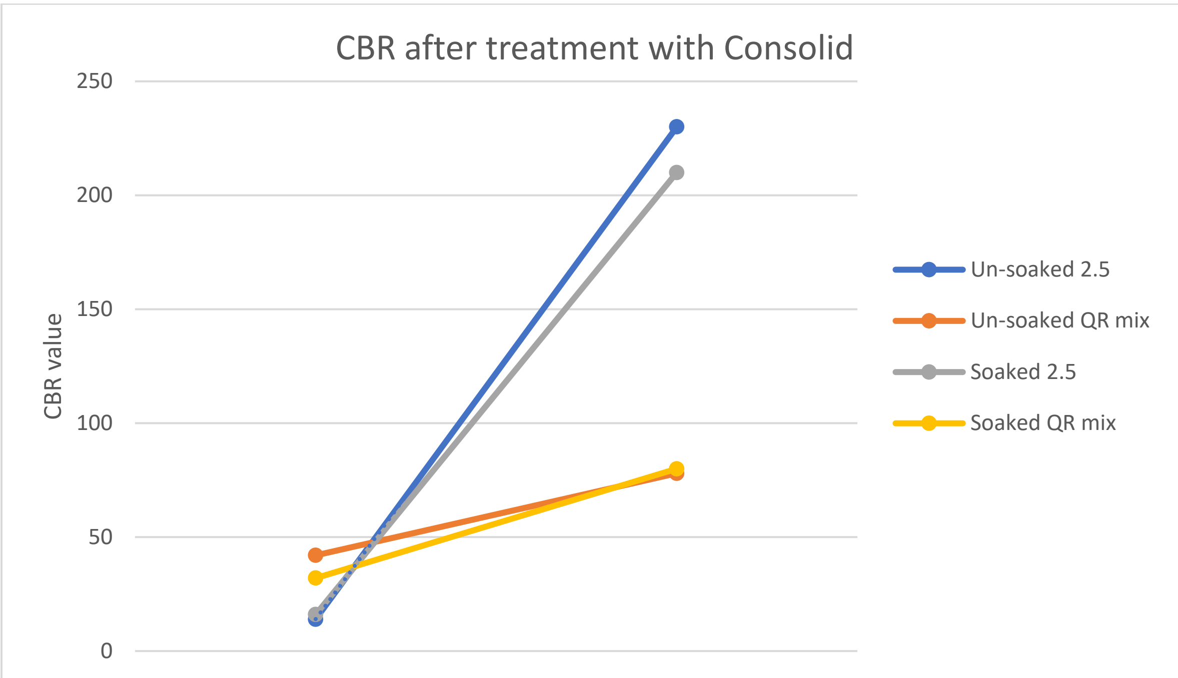

Figure 4. 5: CBR values of each material when treated with Consolid – soaked and un-soaked

4.4 RESULTS SUMMARY

The results presented herein address the objectives outlined in section 1. The following section will include a discussion of the implications from these results. Visual inspections were undertaken throughout the project where photos and their analysis can also be found in the discussion section. The results acquired show a distinct improvement of a material when treated with the Consolid System and all assumptions, critical findings, and limitations will be discussed in detail in the following section. All raw data/results can be found in the appendices section.

5 DISCUSSION

From the results obtained through the methodology previously discussed, the following section will present my analysis of the suitability and long-term effectiveness of the Consolid System as a soil stabilisation product. Field test and laboratory results will be discussed against the relative theory and in conjunction with previous experimental data. An in-depth analysis and conclusion of the resultant data will include the following;

- FWD test results and resilient modulus
- Comparison of FWD test results with past data
- Moisture sensor data and the impact of rainfall
- Laboratory CBR testing results
- Quality and effectiveness of the field and laboratory testing
- Site inspections and visual investigation

Testing limitations and the validity of data for each result segment will be discussed throughout this section.

5.1 FWD

The resilient modulus for each pavement layer within the treated section of road was determined through back-calculation by FWD pavement computer program Elmod6. A modulus of 1407 mPa was calculated at drop station (chainage) zero for the base (treated) layer. The modulus increased significantly to 1800 MPa at the next drop, however decreased to approximately 1100 MPa for the next 10m section of road. A gradual reduction in stiffness is shown from chainage 15m to a minimum of 480 MPa. These resilient modulus values are considered high for an unbound granular material, where typical values were discussed in the literature review section. Several factors may have contributed to the variations in stiffness over the 30m treatment zone. At treatment, the distribution of the Solidry and C444 may have slightly varied, and given its strengthening ability, even minimal concentration differences could have influenced the moduli. Additionally, compaction may contribute to this deviation in stiffness, as compaction time and methods are critical when stabilising.

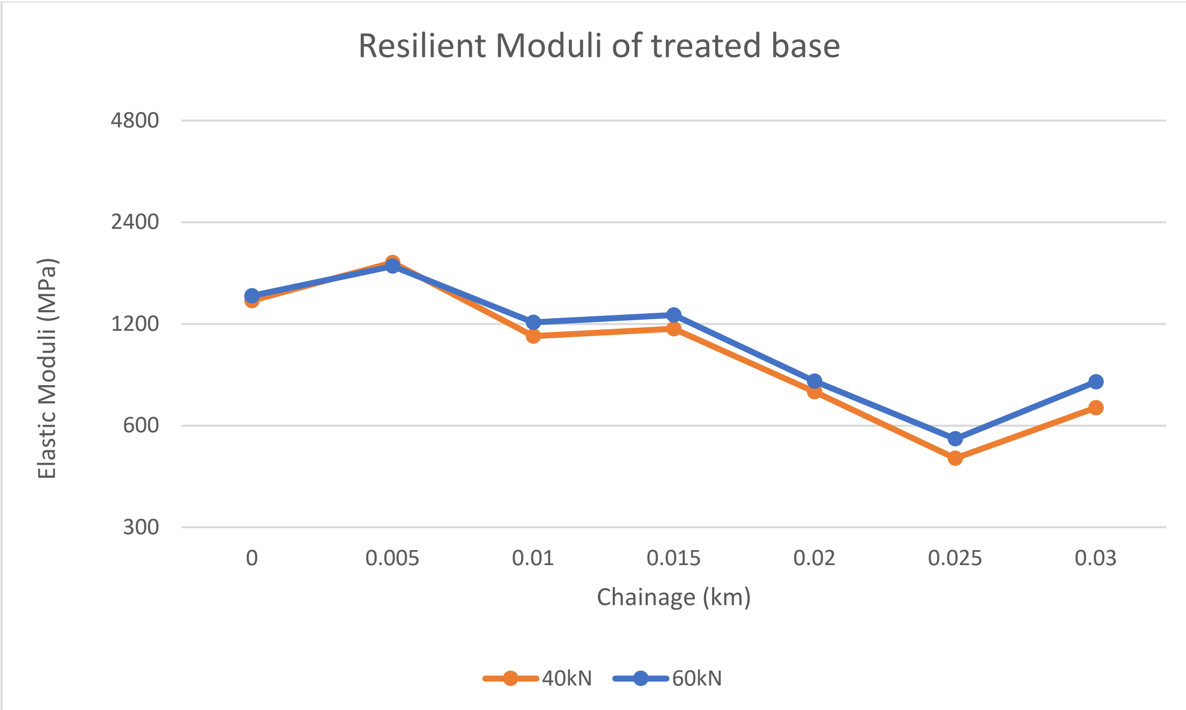

Figure 5. 1: Resilient moduli of treated pavement for 40kN and 60kN drops

Figure 5.1 shown above indicates that a higher drop force applied by the FWD results in a greater stiffness in the stabilised base material. This can be attributed to the material properties more so than the stabilisation affects, as an unbound granular material will become stiffer with the more stress applied (Zaman, Chen & Laguros 1994). Modulus results from the untreated 30m section of road were shown to be considerably lower than that of the treated. However, like the treated section, an increase in stiffness was seen at chainage 5m, despite a consistent subgrade resilient modulus. Resembling the treated section, a slight increase in stiffness is shown when a 60kN force is applied to the material. Difficulties occur in making a critical comparison between both the treated and un-treated section of road due to construction time and difference in materials. It does however assist in the long-term modulus assessment.

The results obtained from the FWD test performed shows an increased resilient modulus to that calculated approximately two years before by Hayden Curran's research. At chainage 0, the difference in stiffness is 780MPa, however due to the outlier from current testing at chainage 5m, the variance is approximately 1100MPa. Identically to the results obtained for this investigation which have been previously discussed, the resilient modulus calculated in 2016 drops gradually from chainage 15m. This decrease can be attributed to and supports the assumptions stated previously that compaction and Consolid concentration distribution will affect stabilisation efficiency. At chainage 25m, the modulus calculated by Curran (2016) is approximately 50MPa higher than that of 2018.

This overall increase in stiffness since construction and stabilisation is consistent with the theory previously stated that materials stabilised with the Consolid system will improve in quality over time. This increase in resilient modulus is despite the daily movement of 1000 trucks. Furthermore, this stiffness increase is despite the stabilised pavement not consisting of the recommended asphalt surfacing layer to prevent from structural deformation. It must be noted that no modulus testing was performed on this trial site for the two-year period between the testing discussed, a significant period of time in which modulus changes must be observed. Overall, the results calculated from the falling weight deflectometer test show a significant increase in stiffness of the treated material over time. The resilient modulus calculations for 2016 and 2018 are shown in figure 5.2 below.

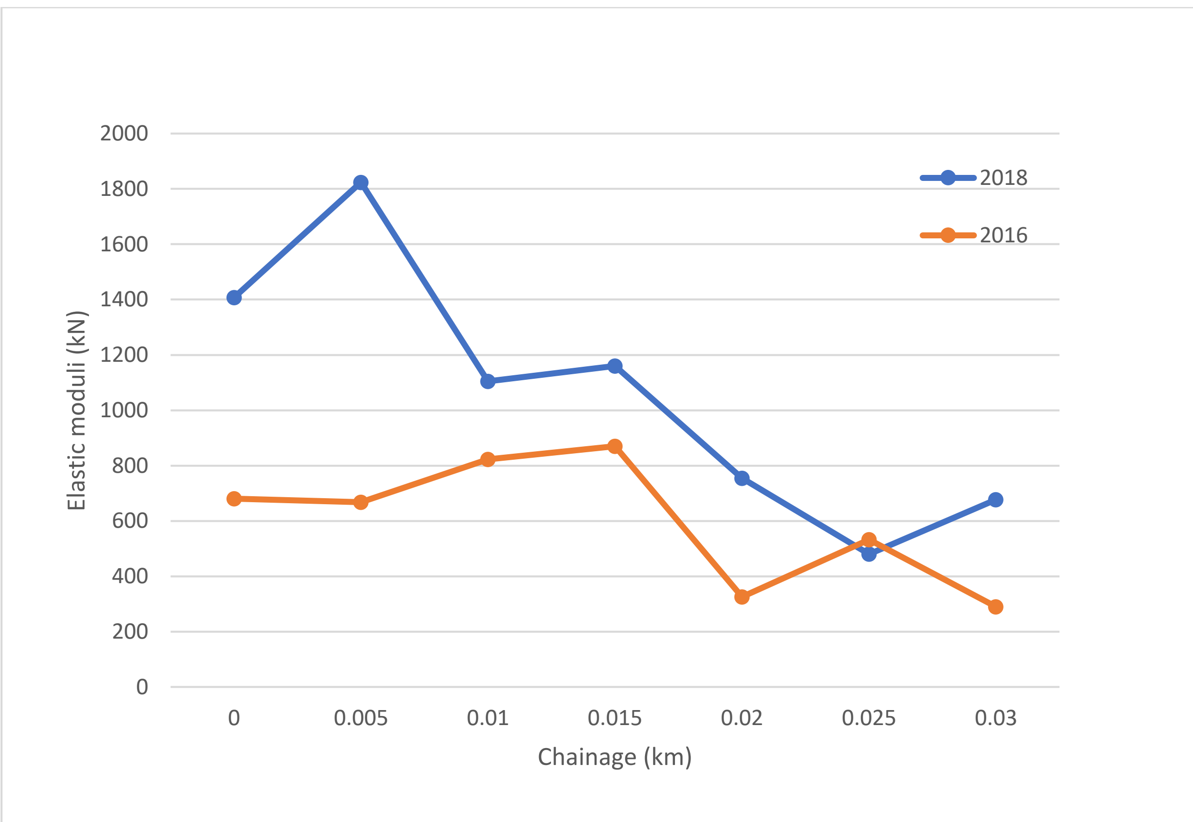

Figure 5. 2: Resilient modulus of treated pavement in 2018 and 2016

5.2 MOISTURE CONTENT

The moisture content for each layer treated with the Consolid system has been continuously recorded by the sensors installed as part of road construction. The average moisture content for layer one (125mm below surface) and layer two (250 mm below surface) in September 2016 was 10.4% and 9.9% respectively. As shown in figure 4.3, the average monthly moisture content for layer one increased consistently for the first 6 months after treatment, albeit slightly, at a total of 0.2%. A four-month, 0.2% reduction occurred from December 2016 to April 2017. The moisture content of layer two increased a total of 0.5% over the 11-month period between September 2016 and August 2017. The moisture content of both layers has fluctuated over time, however layer two has shown a greater increase. At September 2018, the moisture levels sit at 10.5% and 10.45% for layers two and one respectively. These moisture readings show an increase from the type 2.5 material's optimum moisture content of 8.6%, as shown in appendix E. The rise in moisture content occurred soon after stabilisation and has fluctuated steadily since, indicting the possibility of a higher OMC for Consolid stabilised material.

Sensor two currently detects more water than layer one despite initially having less. As moisture sensor two is situated between the stabilised layer and the un-stabilised subbase layer, moisture may be inflowing through the gap between layers from beyond the 30m road box. This is opposed to penetrating through the stabilised layer. As seen in figure 4.3, the moisture percent within the pavement is increased after months with significant rainfall, however delayed.

March 2018 received large rainfall totals, making it useful for pavement moisture content analyses for this investigation. As shown in figure 4.4, daily moisture content recorded by both sensors fluctuated throughout March between a total of 0.5%. Again, this rise in moisture content was delayed after rainfall. Although the Consolid system does not completely inhibit water infiltration into the treated unbound granular material, the effects of moisture do not appear to reduce its stiffness as shown by modulus results.

5.3 LABORATORY CBR TESTING

The CBR was tested on two different styles of materials to determine the bearing capacity when treated with the Consolid system. CBR tests were performed by Soil Engineering Services on a composite soil from a Queensland Rail facility on 20 July 2018. Table 4.5 in the previous section shows results from testing of a composite silty/gravelly soil mix, where CBR values increase by approximately 50% for both soaked and un-soaked samples. The bearing capacity of the soil both soaked and un-soaked increased significantly after Consolid treatment. Despite the positive results, it must be noted that the samples used were of poor quality for testing Consolid. The soil used was considered unnatural and more of a composite, not to be considered as a pavement material. Although showing strong CBR increases, these results will not present a true representation of the capabilities of Consolid as the amount of clay present is well below the recommended 1 in 3. The samples lacked clay and contained amounts of coal dust and possibly fly ash. The possible addition of fly ash to the soil may have further enhanced the positive results in bearing capacity given its use as a subgrade soil stabilisation product. The aforementioned reasons are highlighted by a tested OMC of roughly 25%, significantly higher than that of a type 2 material used for road base. This material had a relatively high CBR value of 42% before testing, comparable to that of a type 2.3 material.

Table 4.6 in the results section show results from the testing of 2.5 road-base from Hanson Quarry Ferny Grove on the 14 December 2016 and can be comparable to the trial material used at Bracalba Quarry. Although these tests were performed almost two years ago, they were deemed suitable for use within this investigation due to material comparison potential and the same testing consultant. The CBR of the un-soaked sample increased from 14 to 230% after treatment with Consolid, and 16 to 210% for the soaked sample after treatment. This is a significant increase in bearing capacity and highlights the requirement of clay to create the bonding required for improvement. Figure 4.5 shows that Consolid improves the bearing capacity of a type 2.5 unbound granular material at a significantly greater rate than a composite soil containing little to no clay, further highlighting the need for Consolid to be used on a suitable material. It must be noted that this testing was conducted within the laboratory on small samples, not entirely representative of field conditions.

5.4 VISUAL INVESTIGATION

A first site visit was conducted on Friday 20th July where a thorough visual inspection of the treated section of road was undertaken. The section was in good condition and showed no visible defects or signs of degradation. Erosion was minimal. No major repairs have been undertaken however dressing and watering occur frequently. Grading occurs at approximately two-week intervals, where 26mm greenstone scalps are added for protection and cover, partially acting as the recommended asphalting layer. This constant addition of material may assist in a change to the road structure since construction. A water truck is used for dust suppression, spraying approximately 2L/m2 5-10 times daily depending on weather conditions.

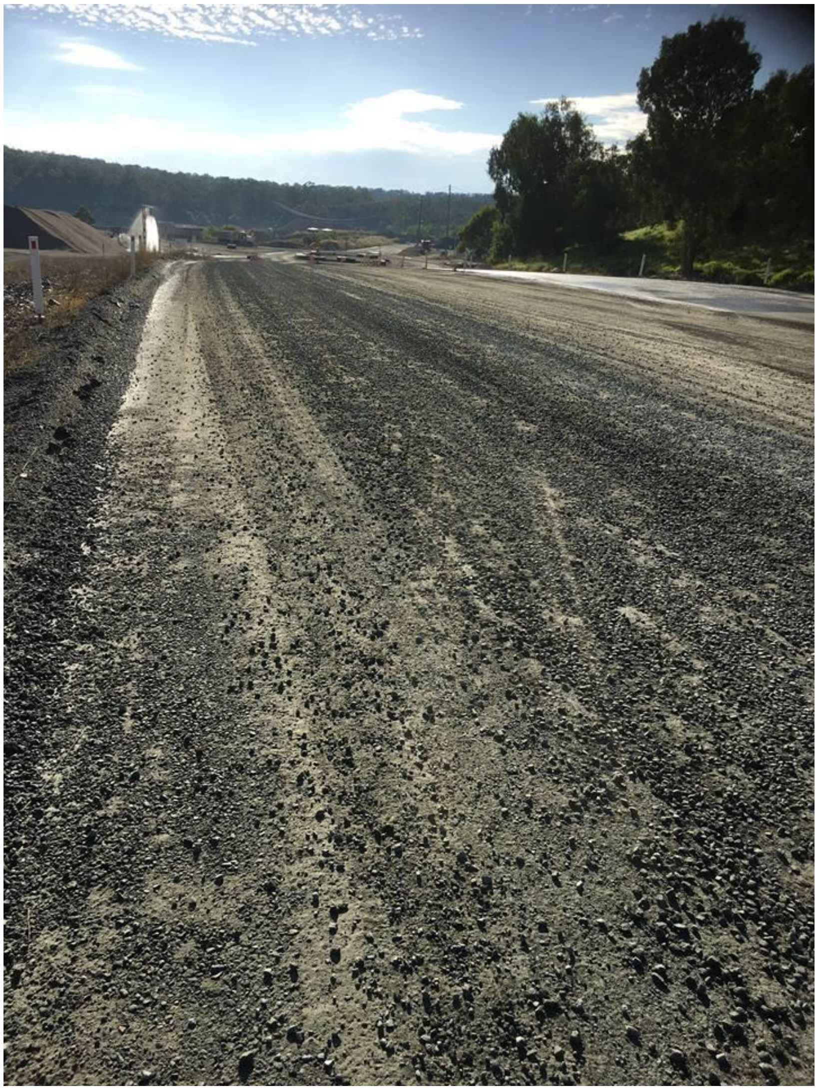

Figure 5. 3: Treated section of pavement facing North West on 20 July showing no visible defects

Figure 5. 4: Treated section of pavement facing South West on 23 August showing no major defects

Figure 5. 5: Treated section of pavement on 9 October showing no visible defects

The above Figures 5.3, 5.4 and 5.5 shows the treated section of pavement on the first site visit, second visit, and third site visits respectively. As can be seen, no major abnormalities can be found and there is no difference in condition between the three visits. It must be noted that no differences were visually identified at chainage 15m where stiffness of the treated pavement was decreased. This minor concern must be attributed to the reasons mentioned previously such as mixing and compaction, or an underlying problem such as untreated subgrade weakness.

5.5 Summary

This section examined the resilient modulus results from the Falling Weight Deflectometer testing performed at Braclaba Quarry via the methods discussed in section 3. This included the comparison with results from Curran (2016), showing increased stiffness over time as summarised in figure 5.2. Moisture content was shown to slightly increase with rainfall after a delayed amount of time despite not affecting the strength of the pavement. CBR tests showed the increase in bearing capacity when stabilised with Consolid and highlighted material suitability. My investigation into soil stabilisation in pavement design with the Consolid system is concluded in the following section.

6 CONCLUSION

This research encompasses various material focussed on pavement design including the suitability of the Consolid System as a means of soil stabilisation to ensure better performance. This section will conclude and summaries this investigation by; addressing the original aims of this research, addressing any limitations encountered throughout this work, and providing recommendations for future work.

6.1 PROJECT AIM

The aims of this project were to investigate the worth of the Consolid System as a soil stabilisation alternative within pavement design and provide additional support to the positive results found by Curran (2016) including:

1. Assess the long-term viability of the product via modulus testing and moisture sensor data
2. Evaluate laboratory testing of the product and assess the visual condition of a treated pavement

A section of pavement at Bracalba Quarry was treated with Consolid in 2016 by Hayden Curran and the testing that ensued showed increases in material resilient modulus. For my work, the equivalent modulus testing was conducted on the same section of treated road using a Falling Weight Deflectometer and results showed a further increase in resilient modulus, more than two years since treatment. This supports the statement made by Consolid that strength of treated material will increase over time after compaction. Through sensors placed within the pavement, pavement moisture content was analysed and, despite showing a slight increase after significant rainfall, showed no loss of strength.

Laboratory CBR testing performed by Soil Engineering Services showed bearing capacity can be improved when treating a material with Consolid. Additionally, this testing underlined the importance of material compatibility when treating, as a type 2.5 road-base showed significantly greater improvement than a silty composite soil. This is due to having a clay percentage recommended by Consolid. The visual condition of the treated pavement was analysed throughout this investigation and showed no clear degradation, supporting the test results and assumptions discussed in this report. The methods employed were beneficial in providing the results needed to satisfy the original aims of this project. The information presented in this research is evidently valuable to the Australian pavement industry, as the importance of natural resource use, and cost effective and environmentally friendly road construction will only increase over time. Furthermore, this investigation can be used to assist in the Consolid stabilisation system gaining inclusion into future Australian pavement design guidelines and specifications.

6.2 LIMITATIONS

The methods used included only a handful of the techniques that can be utilised in strength testing for a pavement material. These may have been used to more accurately determine the properties of the stabilised soil, however were not included due to logistical difficulties and equipment availability. Moreover, this includes several additional FWD tests to better support the results gained from the one performed that were not done due to the same reasons previously stated. These extra tests would verify or refute the variances that can be seen in the modulus results data.

Laboratory CBR tests were performed on treated material samples and therefore not indicative of in-situ conditions. CBR testing may have accompanied FWD modulus testing at the Bracalba Quarry treated road to provide additional in-situ data to better understand the long-term performance of the Consolid system. Additionally, the first laboratory CBR testing occurred almost two years ago and although the results would not change, more recent testing would be considered more appropriate. The testing included in this research did not include the evaluation of permeability measurement or capillary action of the samples. Despite these limitations, this investigation provides beneficial information and contributions to which further research into the Consolid system can be based.

6.3 FUTURE WORK/RECOMMENDATIONS

This investigation met its original aims and showed the advantages of Consolid as a stabilisation product, however typically for research projects of this nature, further investigation is required, and several matters can be incorporated into future investigation. These include;

1. Research should continue examining the treated pavement section at Bracalba Quarry to further assess the long-term data. This includes the same testing including; FWD, site inspections, moisture sensors.
2. Additional testing at Bracalba quarry may include; In-situ CBR and Dynamic Cone Penetration tests
3. Construct and treat a high-volume road with Consolid on natural materials with different properties
4. This product should be tested as a means of erosion and sediment control, as results from this study indicate that this will be of use in the construction industry for purposes other than pavement design.
5. A sample/borehole should be extracted for the treated site to determine the pavement profile after considerable time and addition of 26mm aggregate.

6.4 CONCLUSION

This investigation has built upon Hayden Curran's work and has provided further analysis of the Consolid System as a soil stabilisation product. It has provided a foundation for the continued research into the Consolid System and, on a wider scale, non-traditional soil stabilisation products for use within pavement design. Consolid is a versatile and effective stabilisation method upon which many additional uses may apply. Overall, this research project highlights the potential of Consolid and should facilitate it gaining recognition into Australian pavement design guidelines.

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8 APPENDICES

APPENDIX A – LOGBOOK

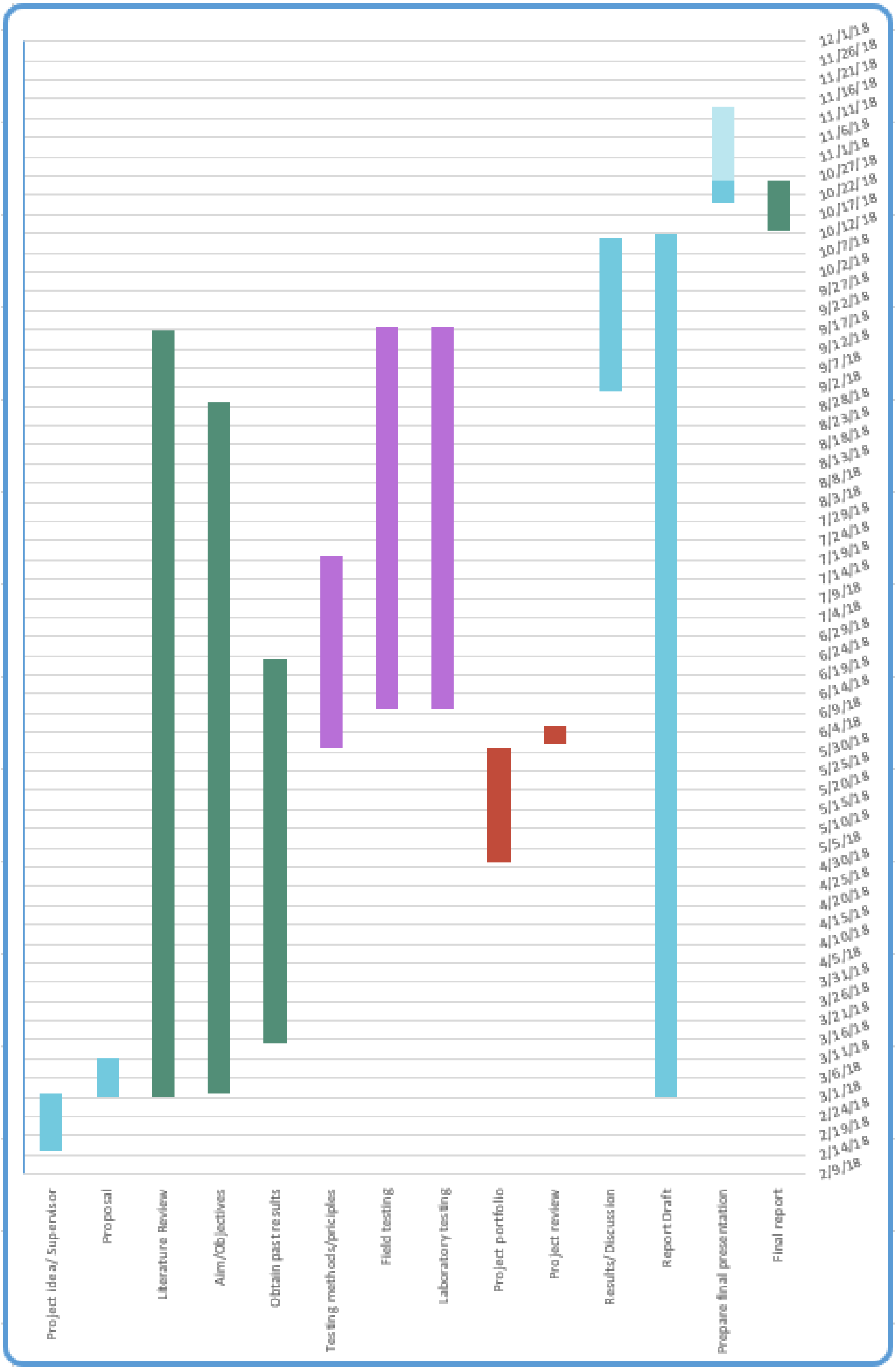
Date	Activity	Comments	Involved	Duration
20-Feb	Email/Meeting	Discuss project scope	Adrian	1
25-Feb	Study	Research on project, literature review		8
6-Mar	Meeting/Study	Meeting with Adrian and Mike Farrar from Consolid	Adrian, Mike Farrar	2
8-Mar	Study	Report - Proposal, Literature review		6
15-Mar	Study/Email	Literature review Discuss proposal with Adrian	Adrian	5
28-Mar	Study	Report - Literature review		4
10-Apr	Study	Report - Literature review		6
20-Apr	Study	Report - Literature review		8
5-May	Study	Report - Literature review		3
15-May	Study	Report - Literature review, project task 2 port-folio		8
20-May	Study	Report - Literature review, project task 2 port-folio		8
31-May	Meeting	Meeting with Adrian to discuss project work and testing	Adrian	1
10-Jun	Study	Report - Methodology, Literature review		8
20-Jun	Study	Report - Methodology, Literature review		8
15-Jun	Email/Phone	Discussed with Mike regarding the project and Bracalba Quarry	Mike Farrar	1
16-Jul	Email/Phone	Contacted John Yeamen and Hayden Curran for information regarding moisture sensor data	John Yeamen, Hayden Curran	2
18-Jul	Email/Phone	Contacted pacific data systems to determine if moisture sensors are still operational and how to access		1

19-Jul	Meeting/Site Visit/Testing	Site inspection, Photos, Discussed and future project scope. Discussed results from external testing	Mike Farrar, Brad Keagan	6
19-Jul	Study/Email	Research on consolid, subgrade and stabilisation standards, TMR. Email Adrian for meeting on 24/7	Adrian	8
27-Jul	Study/Meeting/Testing	Report - research, access moisture sensor data. Meeting with Adrian to discuss possible FWD testing at the quarry	Adrian	6
28-Jul	Email	Emailed Adrian following up FWD testing at the quarry	Adrian	1
2-Aug	Study	Report - Literature review, methodology (moisture sensors)		8
6-Aug	Study/Email/Testing	Emailed Adrian following up FWD testing and Mike regarding SES testing results as discussed	Adrian, Mike Farrar	2
7-Aug	Study/Email/Testing	Obtained SES testing results from Mike	Mike Farrar	1
8-Aug	Study	Project work - Literature review		5
15-Aug	Study	Project work - Literature review, discussion		6
21-Aug	Email/Phone	FWD at the quarry was discussed and scheduled in for the following day	Adrian, Bracalba quarry, Trent McDonald	1
22-Aug	Testing/Study	Bracalba quarry was visited for FWD however equipment broke on previous job. Site inspection was conducted. Project poster work was undertaken		3
23-Aug	Testing/Study	FWD at the quarry was performed	Trent McDonald, Bracalba quarry	4
4-Sep	Study	Report - Methodology, Literature review		6
5-Sep	Study/Email	Report - Analyse FWD results	Adrian	3

12-Sep	Study	Report - Methodolgy, Analyse SES test results		8
15-Sep	Study	Report - Literature review		6
19-Sep	Study	Report - Results, Literature Review		8
22-Sep	Study	Report - Methodology		6
25-Sep	Study	Report - Results analysis		4
27-Sep	Testing/Results	Met with Trent McDonald from pavement management services for pavement and Elmod6 advice	Trent McDonald	5
2-Oct	Testing/Results	Raw FWD data analysed through Elmod6 and results exported to excel for use		7
3-Oct	Study	Report - Results/Discussion		8
6-Oct	Study	Report - Discussion		2
8-Oct	Meeting/Study	Met with advisor to discuss project progress, report work	Adrian	8
11-Oct	Study/Email	Report - Prepare rough draft and send to advisor	Adrian	8
13-Oct	Study/Email	Report - Received draft from advisor, Introduction	Adrian	6
15-Oct	Study	Report - Introduction, Objective		8
16-Oct	Study	Report - Literature review		5
18-Oct	Study	Report -Methodolgy		5
19-Oct	Study	Report - Results		5
20-Oct	Study/Email	Report - Discussion, Final draft to advisor	Adrian	8
22-Oct	Study	Report - Format		8
24-Oct	Study	Report - Format		8
25-Oct	Study/Meeting	Report – Conclusion, Abstract, Meeting with advisor to go over final draft	Adrian	10
26-Oct	Study/Email/Blackboard	Prepare Final submission		5

APPENDIX B – PROJECT PROGRAM

Task Name	Start Date	End Date	Duration (Days)	Days Complete	Days Remaining	Percent Complete
Project idea/ Supervisor	15/02/2018	2/03/2018	15	15.00	0.00	100%
Proposal	1/03/2018	11/03/2018	10	10.00	0.00	100%
Literature Review	1/03/2018	17/09/2018	200	200.00	0.00	100%
Aim/Objectives	2/03/2018	29/08/2018	180	180.00	0.00	100%
Obtain past results	15/03/2018	23/06/2018	100	100.00	0.00	100%
Testing methods/priciples	31/05/2018	20/07/2018	50	50.00	0.00	100%
Field testing	10/06/2018	18/09/2018	100	100.00	0.00	100%
Laboratory testing	10/06/2018	18/09/2018	100	100.00	0.00	100%
Project portfolio	1/05/2018	31/05/2018	30	30.00	0.00	100%
Project review	1/06/2018	6/06/2018	5	5.00	0.00	100%
Results/Discussion	1/09/2018	11/10/2018	40	40.00	0.00	100%
Report Draft	1/03/2018	12/10/2018	225	225.00	0.00	100%
Prepare final presentation	20/10/2018	14/11/2018	25	6.00	19.00	20%
Final report	13/10/2018	26/10/2018	13	13.00	0.00	100%



Project idea/ Supervisor
Proposal
Literature Review
Aim/Objectives
Obtain past results
Testing methods/priciples
Field testing
Laboratory testing
Project portfolio
Project review
Results/ Discussion
Report Draft
Prepare final presentation
Final report
2/9/18
2/14/18
2/19/18
2/24/18
3/1/18
3/6/18
3/11/18
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11/16/18
11/21/18
11/26/18
12/1/18

APPENDIX C – FWD TESTING RESULTS

StationID	DropID	History	Stress	Force	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
1	1	☐	566	40.01	302.8	223.4	179.4	118.5	80.3	54.5	42.1	28.5	20.1	0.0
1	2	☐	566	40.01	298.6	221.0	177.3	117.2	79.9	54.2	41.9	28.6	20.1	0.0
1	3	☐	567	40.04	299.2	220.2	177.3	117.4	79.6	54.1	41.7	28.5	19.9	0.0
1	4	☐	880	62.17	470.2	351.7	281.5	192.7	134.8	95.4	69.3	44.4	33.6	0.0
2	5	☐	572	40.40	301.3	214.7	158.0	109.5	76.7	65.9	53.6	33.9	29.7	0.0
2	6	☐	569	40.24	293.6	213.3	154.8	108.6	76.2	65.4	53.1	34.5	28.4	0.0
2	7	☐	568	40.15	293.3	212.3	157.0	108.3	75.0	65.3	53.6	33.6	31.0	0.0
2	8	☐	855	60.42	444.6	326.8	254.9	175.5	125.4	104.8	84.1	56.5	41.0	0.0
3	9	☐	575	40.67	744.8	621.3	487.6	339.7	232.6	168.4	122.4	72.3	45.1	0.0
3	10	☐	573	40.47	739.2	610.1	478.0	336.4	230.4	167.6	121.9	72.6	45.2	0.0
3	11	☐	574	40.59	744.3	609.1	476.4	335.9	230.9	167.9	122.3	72.7	46.1	0.0
3	12	☐	855	60.40	1093.5	914.7	729.9	522.6	361.3	262.1	188.4	109.6	67.3	0.0
4	13	☐	568	40.14	461.4	308.9	216.6	137.6	99.8	76.4	61.6	41.0	31.4	0.0
4	14	☐	567	40.06	457.8	307.7	216.0	137.5	99.4	76.6	61.5	41.5	30.8	0.0
4	15	☐	569	40.24	456.1	308.6	216.5	138.4	100.3	76.7	61.5	41.8	31.7	0.0
4	16	☐	862	60.90	667.8	478.9	349.7	229.2	165.4	127.5	101.3	69.0	50.0	0.0
5	17	☐	572	40.43	264.0	211.7	164.4	108.7	77.3	57.2	44.5	32.0	23.2	0.0
5	18	☐	567	40.06	261.5	208.3	162.6	107.4	76.3	56.6	44.2	31.2	21.8	0.0
5	19	☐	567	40.10	262.4	208.8	162.6	108.0	76.4	56.6	44.1	31.2	22.5	0.0
5	20	☐	868	61.34	399.6	322.7	254.7	173.0	124.2	93.3	72.2	50.6	37.6	0.0
6	21	☐	568	40.14	309.7	235.6	169.3	131.2	87.1	79.9	51.1	37.3	29.9	0.0
6	22	☐	568	40.14	309.6	233.4	170.6	129.2	86.2	78.1	51.5	37.4	31.3	0.0
6	23	☐	569	40.22	309.6	232.9	169.2	128.0	87.0	77.3	51.8	37.9	31.7	0.0
6	24	☐	865	61.16	472.1	365.3	273.0	206.2	146.3	123.8	89.1	62.5	51.0	0.0
7	25	☐	559	39.51	669.4	442.4	350.6	241.5	174.2	128.5	96.5	60.8	43.5	0.0
7	26	☐	568	40.15	676.8	450.4	356.5	246.4	177.7	131.6	99.9	62.9	44.3	0.0
7	27	☐	567	40.08	671.2	447.0	353.0	244.5	176.9	131.2	99.9	62.9	45.3	0.0
7	28	☐	847	59.84	993.2	694.8	560.8	394.1	287.6	214.3	162.1	100.3	67.7	0.0

StationID	DropID	History	Stress	Force	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
1	1	☐	569	40.18	482.6	361.3	264.5	171.2	123.1	91.8	69.8	44.7	30.1	0.0
1	2	☐	567	40.08	473.6	354.5	260.8	169.7	122.6	91.5	69.5	44.7	30.5	0.0
1	3	☐	566	39.97	467.7	351.0	258.4	169.0	122.1	91.3	69.4	44.8	30.3	0.0
1	4	☐	849	59.98	710.6	556.1	425.5	284.7	203.5	151.5	114.9	72.2	47.2	0.0
2	5	☐	567	40.10	366.5	258.1	166.5	101.7	88.8	49.2	44.3	28.9	23.1	0.0
2	6	☐	568	40.11	365.6	255.9	168.8	102.5	90.6	49.4	45.3	29.1	24.1	0.0
2	7	☐	566	40.01	364.8	251.7	170.9	101.8	87.3	50.0	44.7	29.4	23.6	0.0
2	8	☐	865	61.11	516.0	367.0	258.3	160.5	123.5	82.6	69.3	45.3	28.9	0.0
3	9	☐	569	40.22	435.7	272.0	201.0	140.4	107.1	86.2	69.4	49.0	34.9	0.0
3	10	☐	567	40.06	422.5	267.5	197.7	138.5	106.0	85.3	68.8	48.6	34.4	0.0
3	11	☐	566	39.97	418.7	265.7	195.1	137.9	105.1	85.1	68.5	48.4	34.5	0.0
3	12	☐	861	60.85	630.8	423.5	327.2	229.8	175.9	140.2	112.6	78.5	54.9	0.0
4	13	☐	566	39.97	440.1	240.1	159.8	112.0	88.7	72.9	60.0	43.3	30.9	0.0
4	14	☐	567	40.10	432.5	237.0	158.2	112.3	88.9	73.9	60.8	43.9	31.2	0.0
4	15	☐	569	40.22	427.5	235.7	161.5	112.0	88.5	73.1	60.4	43.6	31.1	0.0
4	16	☐	865	61.13	633.2	384.3	266.5	185.8	147.4	119.4	98.1	67.7	50.5	0.0
5	17	☐	569	40.18	439.7	304.6	204.9	127.8	92.6	71.1	55.3	37.3	26.1	0.0
5	18	☐	567	40.08	433.4	300.8	203.4	127.6	92.7	71.2	55.9	37.7	26.5	0.0
5	19	☐	567	40.08	430.5	299.6	202.7	127.2	92.5	70.9	55.7	37.1	26.1	0.0
5	20	☐	862	60.93	634.9	465.9	331.1	214.3	155.2	117.8	92.2	60.0	42.2	0.0
6	21	☐	569	40.21	423.3	267.7	185.3	120.8	89.1	72.1	55.1	42.9	31.3	0.0
6	22	☐	568	40.17	413.5	260.3	181.1	119.6	88.7	70.2	55.3	40.9	29.9	0.0
6	23	☐	572	40.43	412.3	261.7	181.6	120.8	89.7	70.8	56.0	42.6	30.4	0.0
6	24	☐	870	61.48	586.8	399.1	297.1	200.7	149.2	115.8	93.1	64.7	48.0	0.0
7	25	☐	571	40.38	269.9	216.8	158.4	105.3	76.2	58.9	53.3	35.3	29.9	0.0
7	26	☐	569	40.22	265.1	195.6	161.7	100.5	74.1	56.9	43.9	33.8	28.5	0.0
7	27	☐	566	40.03	263.2	198.7	160.2	100.9	74.3	56.9	45.9	34.5	27.2	0.0
7	28	☐	868	61.38	409.5	314.8	257.5	167.9	124.1	94.7	77.5	55.4	42.4	0.0

APPENDIX D – RAINFALL & SENSOR DATA

Date	Sensor 1	Sensor 2	Rain
1-Mar	10.62296	10.61278	0
2-Mar	10.57135	10.58917	0
3-Mar	10.49865	10.55885	0
4-Mar	10.37646	10.52906	0
5-Mar	10.40969	10.41719	3.9
6-Mar	10.54188	10.47802	54.1
7-Mar	10.63021	10.51406	21
8-Mar	10.69563	10.55552	18.5
9-Mar	10.75615	10.61458	2.4
10-Mar	10.74771	10.63552	1
11-Mar	10.81229	10.66781	9
12-Mar	10.84917	10.69031	9
13-Mar	10.88365	10.71531	0.5
14-Mar	10.94469	10.73781	10.6
15-Mar	10.92844	10.72823	0
16-Mar	10.83448	10.69719	0
17-Mar	10.695	10.65458	0
18-Mar	10.53344	10.55604	0
19-Mar	10.46854	10.45792	0
20-Mar	10.51625	10.46646	0
21-Mar	10.59156	10.47906	4
22-Mar	10.70938	10.54302	20.2
23-Mar	10.78417	10.60406	6.4
24-Mar	10.81823	10.64635	2
25-Mar	10.65958	10.61948	0
26-Mar	10.59438	10.53656	0.6
27-Mar	10.64542	10.54031	0
28-Mar	10.7124	10.5851	5.2
29-Mar	10.71323	10.59125	2
30-Mar	10.75865	10.62219	3
31-Mar	10.75286	10.64881	0.2

Row Labels	Average of Sensor 1	Average of Sensor 2	Rainfall
2016	10.13360095	10.5714653	
Sep	9.992780811	10.4350078	
Oct	10.13217669	10.57877393	19.2
Nov	10.15929514	10.63049306	33.2
Dec	10.23148522	10.62459677	49.8
2017	10.37830708	10.5114503	
Jan	10.21102823	10.4988004	85.4
Feb	10.25954613	10.48324777	66.8
Mar	10.26716398	10.42419019	454.2
Apr	10.28530903	10.44073611	4
May	10.36983535	10.49309036	57
Jun	10.4939375	10.59465625	86
Jul	10.46821909	10.61909946	0
Aug	10.51995968	10.61553763	9.4
Sep	10.41103819	10.51154514	20
Oct	10.44383065	10.50034274	310.6
Nov	10.40960764	10.46644444	61.4
Dec	10.3915121	10.48594422	209.4
2018	10.60866435	10.52687109	
Jan	10.30413642	10.3311996	59.2
Feb	10.49587798	10.46311384	269.2
Mar	10.67848118	10.5900504	159.6
Apr	10.63377083	10.54056597	28.8
May	10.69299059	10.54983871	53.2
Jun	10.72501042	10.60320139	20.4
Jul	10.76257056	10.6561828	0
Aug	10.58099126	10.48332325	36.8
Sep	10.50632911	10.4725	

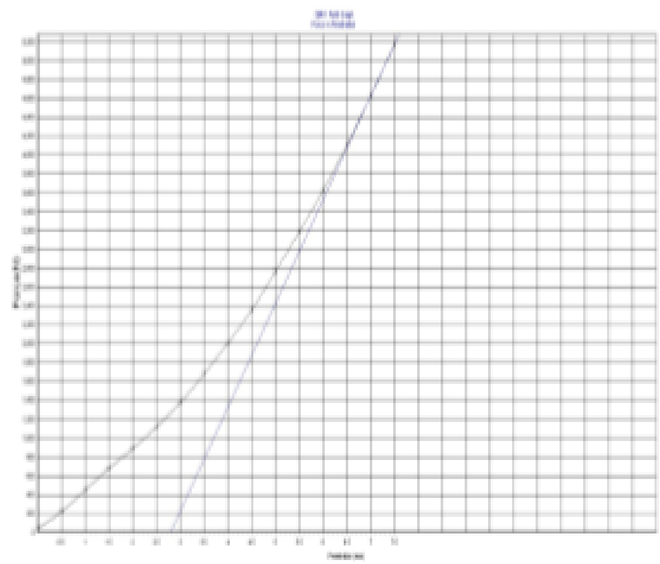
APPENDIX E – SES LABORATORY TESTING

California Bearing Ratio Report (1 Point)

Client :	CONSOLID (COD)	Report Number:	BN5227 - 2/1
Address :	PO Box 595, Cleveland, QLD, 4163	Report Date :	14/12/2016
Project Number :	BN5227	Order Number :	-
Project Name :	SOIL STABILISATION	Test Method :	Q113C
Location:	Laboratory Testing , Banyo		Page 1 of 2

Sample Number :	BN11544	SAMPLE LOCATION
Date Sampled :	30/11/2016	Comparative Testing
Date Tested :	30/11/2016	Type 2.5 Roadbase
Sampled By :	Matthew Rheinberger	No Additive
Sampling Method :	AS1289.1.2.1 - Clause 6.2	
Material Source :	Hanson - Ferny Grove Quarry	Lot Number :
Material Type :	Type 2.5 Roadbase	Test Number :
Remarks :		

Moisture Method :	Q102A
Maximum Dry Density (t/m³) :	2.218
Optimum Moisture Content (%) :	7.8
Compactive Effort :	Standard
Nominated Percentage of MDD :	100
Nominated Percentage of OMC :	100
Achieved Percentage of MDD :	100
Achieved Percentage of OMC :	95.0
Dry Density Before Soak (t/m³) :	2.227
Dry Density After Soak (t/m³) :	2.236
Moisture Content Before Soak (%) :	7.4
Moisture Content After Soak (%) :	7.5
Density Ratio After Soak (%) :	101
Field Moisture Content (%) :	3.7
Top Moisture Content - After Penetration (%) :	7.8
Total Moisture Content - After Penetration (%) :	7.5
Soak Condition :	Soaked
Soak Period (days) :	4
Swell (%) :	-0.5
CBR Surcharge (kg) :	4.5
Oversize (%) :	-
Oversize Material Replaced (%) :	No



Bearing Ratio 2.5mm (%) :	10
Bearing Ratio 5.0mm (%) :	16
CBR Value (%) :	**16**

Site Selection :	-
Soil Description :	Type 2.5 Roadbase

NATA WORLD RECOGNISED ACCREDITATION

Accredited for compliance with ISO/IEC 17025.

APPROVED SIGNATORY

Paul Shaw - Senior Technician
NATA Accreditation Number : 19460

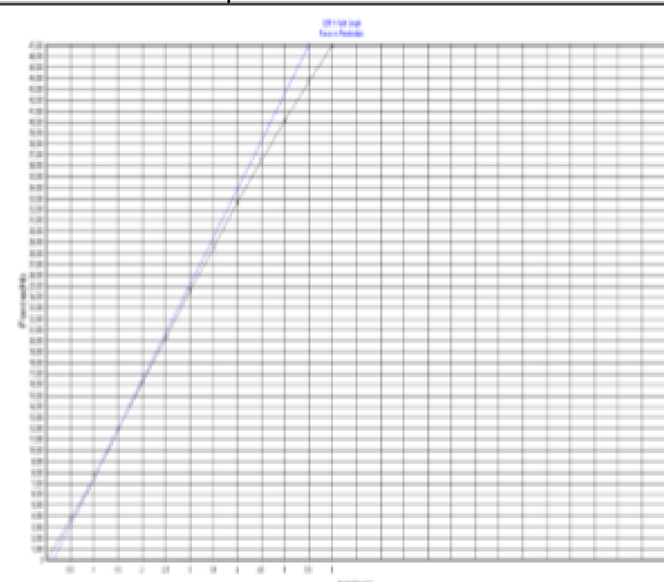
Document Code RF39-12

California Bearing Ratio Report (1 Point)

Client :	CONSOLID (COD)	Report Number:	BN5227 - 3/1
Address :	PO Box 595, Cleveland, QLD, 4163	Report Date :	14/12/2016
Project Number :	BN5227	Order Number :	-
Project Name :	SOIL STABILISATION	Test Method :	Q113C
Location:	Laboratory Testing , Banyo	Page 1 of 2	

Sample Number :	BN11546	SAMPLE LOCATION
Date Sampled :	30/11/2016	Comparative Testing
Date Tested :	30/11/2016	CONSOILD 2%
Sampled By :	Matthew Rheinberger	Type 2.5 Roadbase
Sampling Method :	AS1289.1.2.1 - Clause 6.2	
Material Source :	Hanson - Ferny Grove Quarry	Lot Number :
Material Type :	Type 2.5 Roadbase	Test Number :
Remarks :		

Moisture Method :	Q102A
Maximum Dry Density (t/m³) :	2.168
Optimum Moisture Content (%) :	8.0
Compactive Effort :	Standard
Nominated Percentage of MDD :	100
Nominated Percentage of OMC :	100
Achieved Percentage of MDD :	100
Achieved Percentage of OMC :	94.0
Dry Density Before Soak (t/m³) :	2.176
Dry Density After Soak (t/m³) :	2.178
Moisture Content Before Soak (%) :	7.5
Moisture Content After Soak (%) :	7.5
Density Ratio After Soak (%) :	100
Field Moisture Content (%) :	3.7
Top Moisture Content - After Penetration (%) :	8.0
Total Moisture Content - After Penetration (%) :	7.8
Soak Condition :	Soaked
Soak Period (days) :	4
Swell (%) :	0.0



CBR Surcharge (kg) :	4.5	Bearing Ratio 2.5mm (%) :	160
Oversize (%) :	-	Bearing Ratio 5.0mm (%) :	210
Oversize Material Replaced (%) :	No	**CBR Value (%) :**	210

Site Selection :	-
Soil Description :	Type 2.5 Roadbase

NATA

Accredited for compliance with ISO/IEC 17025.

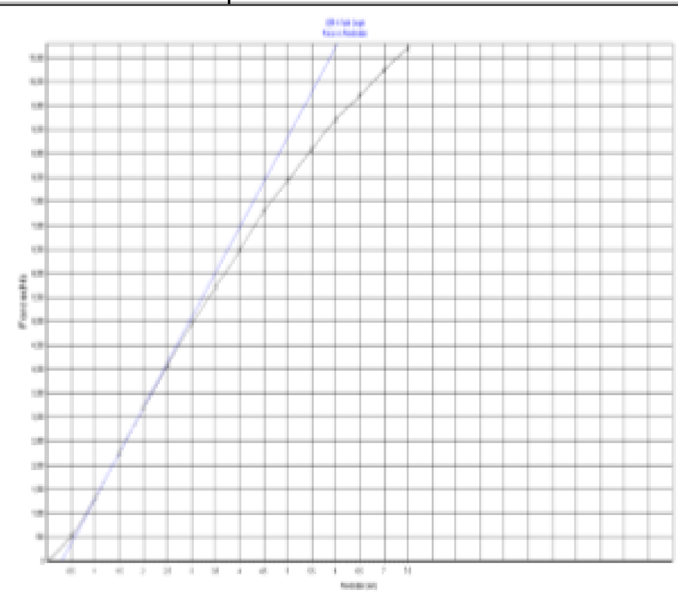
APPROVED SIGNATORY

Paul Shaw - Senior Technician

California Bearing Ratio Report (1 Point)

Client :	CONSOLID (COD)	Report Number:	BN5290 - 2/1
Address :	PO Box 595, Cleveland, QLD, 4163	Report Date :	20/07/2018
Project Number :	BN5290	Order Number :	
Project Name :	Qld Rail	Test Method :	Q113C
Location:			Page 1 of 2

Sample Number :	BN13761	SAMPLE LOCATION	
Date Sampled :	1/07/2018	test pits 1 to 5 Mixed	
Date Tested :	12/07/2018	Control	
Sampled By :	Client Sampled		
Sampling Method :	As Received		
Material Source :	Client Supplied	Lot Number :	No Additive
Material Type :	product Testing	Test Number :	
Remarks :	Sample compacted and cured for 4 days prior to test		



Moisture Method :	Q102A
Maximum Dry Density (t/m³) :	1.173
Optimum Moisture Content (%) :	24.5
Compactive Effort :	Standard
Nominated Percentage of MDD :	100.0
Nominated Percentage of OMC :	100.0
Achieved Percentage of MDD :	99.8
Achieved Percentage of OMC :	101.0
Dry Density Before Soak (t/m³) :	1.171
Dry Density After Soak (t/m³) :	
Moisture Content Before Soak (%) :	24.8
Moisture Content After Soak (%) :	
Density Ratio After Soak (%) :	
Field Moisture Content (%) :	16.1
Top Moisture Content - After Penetration (%) :	
Total Moisture Content - After Penetration (%) :	
Soak Condition :	Unsoaked
Soak Period (days) :	
Swell (%) :	0.0

CBR Surcharge (kg) :		CBR 2.5mm (%) :	34
Oversize (%) :	0	CBR 5.0mm (%) :	42
Oversize Material Replaced (%) :		**CBR Value (%) :**	**42**

Site Selection :	Client Selected
Soil Description :	Gravelly Silt - Dark Brown

NATA

Accredited for compliance with ISO/IEC 17025 - Testing

APPROVED SIGNATORY

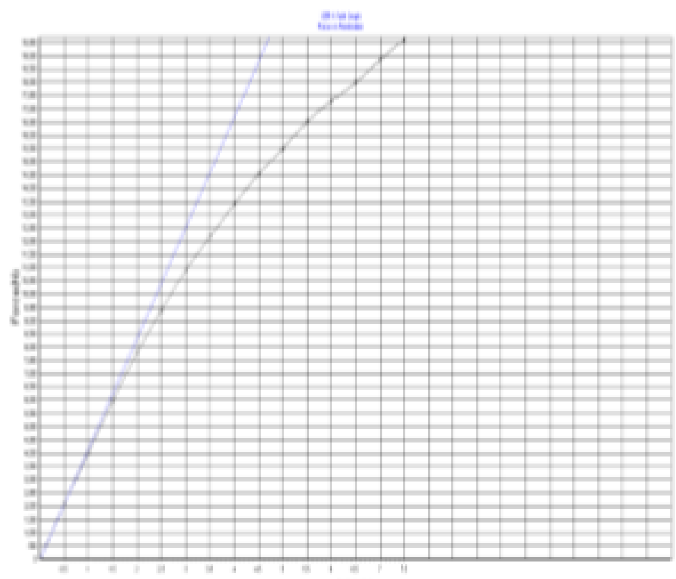
David Sankey - Laboratory Manager

California Bearing Ratio Report (1 Point)

Client :	CONSOLID (COD)	Report Number:	BNS290 - 2/1
Address :	PO Box 595, Cleveland, QLD, 4163	Report Date :	20/07/2018
Project Number :	BNS290	Order Number :	
Project Name :	Qld Rail	Test Method :	Q113C
Location:			Page 2 of 2

		SAMPLE LOCATION
Sample Number :	BN13762	test pits 1 - 5 Mixed
Date Sampled :	1/07/2018	With Additive
Date Tested :	12/07/2018	
Sampled By :	David Sankey	
Sampling Method :	As Received	
Material Source :	Client Supplied	Lot Number : 2
Material Type :	Product testing	Test Number :
Remarks :	Sample compacted and cured for 4 days prior to test	

Moisture Method :	Q102A	
Maximum Dry Density (t/m³) :	1.242	
Optimum Moisture Content (%) :	26.1	
Compactive Effort :	Standard	
Nominated Percentage of MDD :	100.0	
Nominated Percentage of OMC :	100.0	
Achieved Percentage of MDD :	100.1	
Achieved Percentage of OMC :	100.0	
Dry Density Before Soak (t/m³) :	1.243	
Dry Density After Soak (t/m³) :		
Moisture Content Before Soak (%) :	26.1	
Moisture Content After Soak (%) :		
Density Ratio After Soak (%) :		
Field Moisture Content (%) :	16.1	
Top Moisture Content - After Penetration (%) :		
Total Moisture Content - After Penetration (%) :		
Soak Condition :	Unsoaked	
Soak Period (days) :	0	
Swell (%) :	0.0	
CBR Surcharge (kg) :		CBR 2.5mm (%) : 72
Oversize (%) :	0	CBR 5.0mm (%) : 78
Oversize Material Replaced (%) :		**CBR Value (%) : 78**



Site Selection :	Client Selected
Soil Description :	Gravelly Silt - Dark Brown + Consolid

NATA

Accredited for compliance with ISO/IEC 17025 - Testing

APPROVED SIGNATORY

David Sankey - Laboratory Manager

USC AUSTRALIA

The University of the Sunshine Coast

APPENDIX F:

Engineering Competencies Evaluation (ECE)

Preview & review

ENG402 Engineering Project 2

Final Project Report & Oral Defence (Review)

Student name: Shaun Callanan

Student ID: 1075125

Project title: Further Investigation into the efficacy of a Soil Stabilisation product for use within Australian Pavement Design

Academic supervisor: Adrian McCallum

Table 2. 6: Engineering Competencies – Statements & Evaluations (Assessments)

	Demonstration of attainment (A brief summary of how, where and when you have applied a Competency)	Self-Evaluation (scale: 1–5)	Supervisor's or Assessor's Evaluation (scale: 1–5)
PE1 KNOWLEDGE AND SKILL BASE			
PE1.1 Comprehensive, theory-based understanding of the underpinning natural and physical sciences and the engineering fundamentals applicable to the engineering discipline	I have used the principles of geotechnical/mechanics of materials engineering to research the properties of materials treated with stabilisation product Consolid including strength, bearing capacity, and permeability. This can be seen in the lit review	4	4
PE1.2 Conceptual understanding of the mathematics, numerical analysis, statistics and computer and information sciences which underpin the engineering discipline	After testing, I used several statistical methods to compare and analyse the data gained by the previous studies and future results. This, with the addition of computer analysis (Microsoft excel) provided the results and discussion	4	4
PE1.3 In-depth understanding of specialist bodies of knowledge within the engineering discipline	This project required a certain knowledge of both the pavement design and geotechnical engineering disciplines. This included soil stabilisation and soil strength and was discussed in the lit review	4	4
PE1.4 Discernment of knowledge development and research directions within the engineering discipline			
PE1.5 Knowledge of contextual factors impacting the engineering discipline			
PE1.6 Understanding of the scope, principles, norms, accountabilities and bounds of contemporary engineering practice in the specific discipline	I have applied the appropriate project management skills required to ensure smooth project delivery. This is evident from my project program found in the appendices.	5	5
PE2 ENGINEERING APPLICATION ABILITY			
PE2.1 Application of established engineering methods to complex engineering problem solving	A variety of engineering methods obtained throughout my University studies were used to analyse situations. Results from research were assessed and compared to other geotechnical and pavement design theory to ensure any complications were addressed immediately.	4	4
PE2.2 Fluent application of engineering techniques, tools and resources	I have applied adequate engineering tools to achieve the desired results. These tools have	4	4

	been chosen through possessing the relevant engineering knowledge. If errors or unrealistic results occurred, the material testing methods and engineering tools were changed to suit.		
PE2.3 Application of systematic engineering synthesis and design processes			
PE2.4 Application of systematic approaches to the conduct and management of engineering projects			
PE3 PROFESSIONAL AND PERSONAL ATTRIBUTES			
PE3.1 Ethical conduct and professional accountability	I used my proficient communication skills I learnt throughout my studies to deliver information correctly and professionally. All work including site visits and testing was conducted to a professional engineering standard.	5	4
PE3.2 Effective oral and written communication in professional and lay domains			
PE3.3 Creative innovative and proactive demeanour			
PE3.4 Professional use and management of information	I applied the newest and most relevant sources of information throughout the project to assist and support conclusions and arguments. Any material or data obtained from someone else's work such as Hayden Curran's was acknowledged appropriately.	4	5
PE3.5 Orderly management of self, and professional conduct	All contact including emails, meetings, phone calls were recorded in a diary for future reference and can be found in the appendices. Performance was assessed throughout the project duration to ensure all work was completed at an acceptable standard.	5	5
PE3.6 Effective team membership and team leadership			
	TOTAL	39	39

Student signature: Shaun Callanan 26/10/2018

Academic advisor's comments and recommendations
Shaun appears to have delivered a high-quality research project that builds valuably upon existing knowledge

Academic Advisor signature: Adrian McCallum 26/10/2018

APPENDIX G – PROJECT POSTER

2018 Final Year Project – University of the Sunshine Coast

ENG402 School of Science & Engineering

Shaun Callanan

Adrian McCallum Supervisor

In association with AustraBlend, Pavement management services, SES soil aggregate & concrete testing

Further Investigation into the efficacy of a soil stabilisation product for use within Australian pavement design

Abstract

The Consolid system is a non-traditional soil stabilisation process aimed at strengthening a natural material for use as a pavement sublayer. The product has been used throughout the past 30 years however thus far never in Australia. Previous laboratory studies and field tests evaluating the product have been conducted by students from the University of the Sunshine Coast. Results from these investigations determined the Consolid system's ability to improve the resilient modulus of pavement sublayer materials.

The objective of this investigation is to examine the long-term performance of the product and provide additional support to previous studies for its incorporation into Australian pavement design. In 2016, a section of pavement subject to heavy vehicle loads at Bracalba Quarry was treated with Consolid for testing purposes. Site inspections and Falling Weight Deflectometer testing have been conducted and will continue until project completion. Moisture instrumentation was installed within construction and have remained in place. Past data was accessed and compared against environmental conditions and material properties.

Figure 1: Bracalba Quarry trial site

Figure 2: Final layer of treatment after compaction

Methodology

- Moisture Sensors - Moisture sensors were installed by Pacific data systems measuring dielectric, electrical conductivity, and temperature
- Falling weight deflectometer - FWD testing is being performed to determine the structural capacity of the pavement and its layers
- Laboratory testing - Laboratory tests have been conducted by SES services determining the California Bearing Ratio and Unconfined Compressive Strength of Consolid stabilised soil (brown gravelly silt)
- Visual inspections - Visual inspections are being undertaken throughout the investigation to identify possible potholes, cracks, deformation, and overall visual structure of the pavement.

Figure 3: Trial site approx 2 years after treatment

Figure 4: Temperature readings

Figure 5: Electric conductivity readings

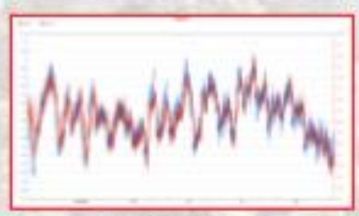


Figure 6: Dielectric readings

Visual inspections have shown the pavement to be in good condition with no visible defects or signs of degradation. Following completion of this investigation, it is expected that long-term results will continue to show merit for the use of Consolid within Australian pavement design through providing the benefits of; increased strength, reduced permeability, and in-situ stabilisation