Characterisation of Cementitiously Stabilised Pavement Materials – The Australian Experience –

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ABSTRACT: Cementitious stabilisation of pavement materials has a long history of use in Australia and other countries. Since its first recorded attempts in the 1940s, stabilisation has been further developed and now a wide range of binder options exist. The Australian Accelerated Load Facility (ALF) program has allowed advancement of stabilisation material assessment in the field, whilst layered elastic analysis has allowed these materials to be directly considered in pavement thickness design. These circumstances have lead to the desire to improve the laboratory characterisation of these materials. Australian practice has moved towards the use of Indirect Diametrical Tensile testing for strength, modulus and fatigue life determination, using samples prepared by gyratory compaction methods. The development of generic relationships between strength, modulus and fatigue life, which are able to be customised to specific materials by a simple and timely test, are now being investigated.

KEY WORDS: Cementitious stabilisation, Indirect diametrical tensile test, Material characterisation.

1 INTRODUCTION

Stabilisation of pavement materials can be performed in a drum mixer or insitu (Vorobieff, 1998). When performed insitu, either subgrade improvement or improvement of an existing pavement's granular material is generally the aim. Stabilisation of pavement material provides resistance to moisture changes, improvement in the shear and bearing capacity of poor materials and in the case of insitu stabilisation, is a quick method of reconstruction (White and Gnanendran, 2002). Stabilisation offers an economical and quick method of pavement rehabilitation which is also environmentally responsible as many of the binder options include industrial by-products with little other useful function (Chini *et al,* 1996). In the case of insitu stabilisation, the reuse of the existing granular pavement layers provides both a reduction in waste materials as well as avoiding the requirement for new quarried rock products.

With the development of binder options and the improvement of construction technologies and methods over the years, the current most challenging aspect of stabilised pavement materials technology is the characterisation of the material for pavement design. With the availability of layered elastic design tools, these materials require a modulus and fatigue life model for each design scenario (White and Gnanendran, 2002).

This paper presents the Australian development of a method for adequately characterising stabilised pavement materials for use in layered elastic design tools. This is shown by providing a history of the stabilisation technology in Australia and the current state of the technology. The development and contribution made by the ALF project is described as is the research undertaken in Australia. A number of recent studies are described and their contribution to the characterisation of stabilised materials is presented, along with the ongoing and planned future research efforts.

2 HISTORY OF STABILISATION

The use of stabilisation as a means of pavement material improvement has been available in Australia since the 1940s. In these early times, the justification for using the technique was largely economic (Vorobieff, 1998). In the 1990s and into the 21st century, the social expectations and environmental pressures have combined with the economics of this process to return stabilisation to popularity. A summary of the history of pavement material stabilisation in Australia is presented in Table 1.

3 BINDER OPTIONS AND SELECTION

Prior to the 1990s, binders used for cementitious stabilisation were generally restricted to general purpose (GP) cement and lime (Vorobieff, 1997). Since the 1990s, a diverse range of binders has become available and slower setting binders are common. These slower setting binders were required to allow the deep-lift pavement layers to be adequately compacted prior to excessive binder setting and the associated workability loss (Vorobieff, 1997).

In present days, binder options include traditional GP cement and lime, general blend (GB) cements, fly ash, ground granulated blast furnace slag (GGBFS or slag) and double and triple blends of these materials (Vorobieff, 1998). Non-cementitious binders such as bitumen emulsion, foamed bitumen and dry powder polymers are also available. Not all binders are suited to all host materials and careful matching of the binder and host material is essential for successful stabilisation.

The GIRD project was undertaken by the University of South Australia in the 1990s. This project investigated the compatibility and characteristics of cementitiously stabilised pavement materials from around Australia (Symons *et al*, 1996). Twenty Australian binders were investigated with nineteen host materials and tests included Unconfined Compression Strength (UCS), erodability and resilient modulus. The conclusions included the requirements for heavy compaction equipment to achieve the required densities for these materials, the compatibility of host and stabilising agents being good but being material dependent and recommendations for the design of recycled pavements including cementitiously stabilised materials.

The selection of binders for a range of project circumstances and, most importantly, the host pavement material, is provided in Australia through an Australian Stabilisation Industry Organisation (AustStab) guide (AustStab, 2000) as well as an AUSTROADS guide to stabilisation of road pavement materials (AUSTROADS, 1998).

Table 1: Summary of insitu stabilisation history.

Year	**Event**	**Reference**
1944	First recorded attempt at stabilisation in Australia.	Williams (1986)
1944-1950	Insitu stabilisation performed by road contractors on a part-time basis in Australia.	Williams (1986)
1952	First specialist stabilisation contractor entered the Australian market.	Wilmot (1996)
1960s	Mobil Oils purchase Stabilisers Limited and competition became fierce.	Vorobieff (1998a)
1960s	Fierce competition lead to cheaper equipment and unskilled labour being used, which lead to poor work and pavement failures.	CPEE (2001)
1960s	Pavement failures turned Australian road authorities away from insitu stabilisation.	Vorobieff (1998)
1970s	Insitu stabilisation returned to favour slowly and with improved construction success.	CPEE (2001)
1976	First edition of Road Note published which promoted insitu stabilisation.	CPEE (2001)
Late 1970s	Single rotor stabilisers replaced the previously popular triple rotor versions.	Wilmot (1996)
1980s	Local Government adopted insitu stabilisation as an economical means of local road rehabilitation.	Hodgkinson (1991)
1983	Accelerated Load Facilit commissioned and used to correlate lab and field testing of stabilised material performance.	Vorobieff (1997)
1992	CMI RS 500 deep-lift stabilisation equipment, able to stabilise to 500 mm depth, became available in Australia.	Vorobieff (1998a)
1992	Deep-lift stabilisers required slow setting binders to enable enough time before setting to allow adequate compactive effort to be applied.	Wilmot (1996)
Mid 1990s	Supplementary Cementitious Binders (slag-lime and flyash-lime blends) became common, slow setting, binders for stabilisation projects.	Wilmot (1994)
1996	The GIRD project was undertaken to increase the industry's understanding of the behaviour and performance of stabilised materials from all over Australia.	Symons, *et al* (1996)
2001	The Australian industry adopted the Indirect Diametrical Tensile (IDT) test on samples prepared by gyratory compaction as the standard method for characterisation of these materials.	Foley, *et al* (2001a)
2003	A draft test method released in Australia for IDT and gyratory compactor measurement of strength, modulus and fatigue life of stabilised materials.	Yeo, *et al* (2002)

4 FULL SCALE ACCELERATED LOAD TESTING

Cementitious stabilisation of pavement layers has been the subject of a substantial degree of research. One notable contribution in this area was the development of the ALF which has been used to trial stabilised pavements at Cooma, Beerumbeena, Lake Macquarie, Wellington, Erraring and Mulgrave.

The then Department of Main Roads, NSW, developed the ALF in 1983. The ALF now represents the key to Australia's flexible pavement research and consumes approximately $1m annually of AUSTROADS and industry road research funding (Vorobieff, 1997).

The Beerburrum, and Cooma ALF projects were the basis of revising the fatigue life model for mechanistic pavement design used by Queensland's Department of Main Roads in the 1990s (Vorobieff, 1998).

ALF trials conducted at Nabiac and Wellington (Porter, 1992) as well as Cooma (Jameson *et al*, 1995) have confirmed that for deep lift (exceeding 300 mm) stabilisation, the bottom third of the layer has a relative density 5% lower than the upper two thirds. Such a variation in density has been shown to have a significant influence on material modulus, which in turn can impact on pavement life.

In conjunction with laboratory testing to determine material properties affecting fatigue performance, the correlation between laboratory and field performance is expected to be further investigated through use of the ALF.

The ALF program continues in 2005 and 2006 with a project being planned to assess the impact of heavy vehicles with various axle loads on cemented pavement materials. The investigation includes the comparison of strength, modulus and fatigue life determined insitu by the ALF with those determined by laboratory IDT test methods (Yeo, 2004).

5 LAYERED ELASTIC DESIGN PARAMETERS

Australia's primary layered elastic design tool for pavement thickness is CIRCLY. CIRCLY was developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) of Australia (Wardle, 1976). The program was then commercialised and distributed by MINCAD Systems. CIRCLY is now in its fifth version and aircraft pavement (APSDS) and marine port pavement (HIPAVE) versions are also now available.

Like many of its non-Australian equivalents, CIRCLY has the ability to model cementitiously stabilised pavement materials in any design scenario. This is one advantage of layered elastic design tools over the traditional empirical design tools which were developed from full-scale testing of granular pavements and relied on material equivalences to incorporate cemented materials. Like many layered elastic design tools, CIRCLY calculates indicators of damage induced in the modelled pavement by a single load application. This single load damage indicator is then related to an allowable number of load repetitions of the same magnitude. For cementitiously stabilised pavement materials, this relationship is determined for the tensile strain induced at the bottom of the bound layer and is known as the fatigue life model.

Where cementitiously stabilised materials are incorporated into design scenarios, a modulus is required to calculate the modelled damage indicators through the stabilised material and into the underlying layers. A tensile fatigue life model is also required. These material characteristics are discussed in the following sections.

5.1 Modulus

Modulus is a critical factor for the layered elastic behaviour of cementitiously stabilised pavement materials. It is one of the sensitive input parameters into the mechanistic pavement design tool CIRCLY (MINCAD, 1999). The AUSTROADS design guide (AUSTROADS, 1992) requires flexural modulus as the key input for cementitiously stabilised pavement design. Because of the difficulty in determining the flexural modulus directly for these materials, the elastic modulus or the resilient modulus is commonly used as the flexural modulus value.

Whether one measures the flexural, elastic or resilient modulus of a material will depend on which of the many test methods available for modulus determination are used. In this paper, the generic term ‘modulus’ is used to reflect the value used to characterise the material in layered elastic pavement design. There are two main approaches to the determination of a modulus value. Firstly, modulus may be determined by relationship to material strength. Secondly, it may be determined directly from the gradient of the stress-strain relationship plot, under either a monotonic or repeated load regime.

Strength from a monotonic test is often used to estimate the modulus using empirical equations adopted from testing of similar materials (AustStab, 2000). These strength tests are relatively inexpensive, quick and easy to conduct. These tests are therefore popular, but the published relationships between strength and modulus are known to be unreliable across a large range of binder-host combinations and binder contents (Foley *et al*, 2001).

The current Australian empirical relationship for the determination of modulus from UCS is (AUSTROADS, 2004):

$$Modulus = k \times UCS$$

Where k varies from between 1000 and 1250, selected based on the material. No guidance is provided as to which materials should be assigned what k-values within this range.

5.2 Fatigue life

For pavements constructed with cementitiously bound layers, fatigue of the cemented layer will generally govern the performance of the pavement. Fatigue life modelling is therefore critical to the characterisation of cementitiously stabilised materials as it is a key input to mechanistic design. The current Australian fatigue life model for cementitiously bound materials has been critically examined and its validity questioned by researchers with ongoing investigations under way (Foley *et al*, 2001).

AUSTROADS (1997) provides the following fatigue life model for use in mechanistic design:

$$N \quad = (K/\mu\varepsilon)^{12}$$

Where:

N = fatigue life (allowable number of standard axle repetitions).
K = a material constant.
$\mu\varepsilon$ = the horizontal tensile strain induced at the bottom of the layer for single application of static axle load in $\mu\varepsilon$.

The factor ‘K’ is dependent upon the modulus of the material and AUSTROADS (1997) provides values of ‘K’ for typical moduli values. It is noted that often a presumptive value is adopted for the modulus or it is otherwise estimated via a questionable empirical relationship from UCS. This fatigue model has been questioned by researchers, especially when compared to overseas relationships and results from field trials.

Prior to the Cooma ALF trials, the AUSTROADS fatigue model had an exponent of 18 rather than 12 and correspondingly different values of K (Vorobieff, 1998). Many researchers have concluded that the original, as well as the current, AUSTROADS fatigue model is too conservative when compared to field observations. This was particularly evident during the Cooma ALF trial (Vorobieff, 1998a) and Lake Macquarie field trials (Vorobieff, 1998). Andrews and Burgess (1994) and Wilmot and Rodway (1999) also concluded that in-service fatigue lives exceeded those predicted by the previous and current AUSTROADS models, indicating that the lightly bound cementitiously stabilised materials were acting as a somewhat ‘stress dependent’ (not fully bound) material. This has been supported by RLT testing of low binder content cementitiously stabilised materials showing a significant dependence of their modulus on stress levels (Symons *et al*, 1996).

6 VARIABILITY OF LABORATORY PREPARED MATERIALS

When designing pavements with stabilised materials, their characteristics are generally determined in the laboratory. Common parameters for laboratory determination are strength, modulus and less commonly, fatigue life. When determining such parameters for research, or for use in design tools such as CIRCLY, the variability of the measured parameters is of interest.

Variability in stabilised pavement materials comes from:

- Host material.
- Binder distribution uniformity.
- Moisture content.
- Density.
- Sampling.
- Sample preparation.
- Test regimes and parameter measurement.

A study was conducted in Australia by White and Gnanendran (2003) which investigated the variability of these materials and the suitability of the results to allow statistically based analysis of the data.

The laboratory testing program aimed at comparing the variability of UCS between a number of stabilised pavement materials including new crushed rock and reclaimed road base, which would expect to be encountered for stabilisation projects. White and Gnanendran (2003) found that UCS was quite variable for these materials, especially at low binder contents. Further investigations found that the regular shape and consistency of gyratory compacted samples decreased their UCS variability (White and Gnanendran, 2005).

7 INDIRECT DIAMETRICAL TENSILE TESTING AND THE GYRATORY COMPACTOR

An investigation in 2000 and 2001 by AUSTROADS and the Australian Pavement Reference Group into the mechanistic design of pavements with stabilised materials recognised IDT as a potential method for economically obtaining repeatable and reliable moduli and fatigue life results for cementitiously stabilised materials (Foley, *et al*, 2001a).

7.1 Indirect Diametrical Tensile Testing

Based on the recommendations of the 2000 and 2001 investigation, AUSTROADS developed an interim test method for the laboratory characterisation (strength, modulus and fatigue life) of stabilised materials utilising the IDT test method for samples prepared by gyratory compaction (Yeo, *et al*, 2002). The IDT strength is calculated as the stress at breaking whilst the modulus can be determined from the slope of the stress versus strain curve during either a monotonic (strength) test or a sub-maximal (repeated load) test.

7.2 Gyratory Compaction

The genesis of the gyratory method of compaction belongs to the asphalt industry. The gyratory compactor and an asphalt mix design method were developed in parallel in the USA and other countries from 1998 (Oliver, 2003). The benefits of the gyratory compactor for the asphalt industry were that aggregate packing of roller compacted field samples was more closely represented compared to that of Marshall specimens, aggregate degradation during sample preparation was not significant and the ability to prepare samples to varying densities by altering the number of gyrations (Oliver, 2003).

Gyratory compaction was selected for use with the IDT test method for stabilised pavement materials because of its availability as well as its ability to produce samples with flat and uniform ends of consistent dimensions and density (Yeo, *et al*, 2002).

An investigation found that the target moisture content for stabilised pavement materials should be set by the MC-DD relationship for the actual stabilised material rather than arbitrarily adopting a 2% allowance for hydration of the binder as is the current Australian practice (White and Gnanendran, 2005). The study also found that the default vertical pressure (250 kPa) and number of gyrations (75) of the gyratory compactor were unable to achieve densities comparable to those achieved by Standard Proctor compaction for the same materials.

For the materials assessed during this investigation, a 500 kPa vertical pressure and 250 gyrations provided dry densities essentially equal to those obtained by Standard Proctor compaction (White and Gnanendran, 2005).

8 DENSITY AND COMPACTION

The role of density on the strength and modulus of cementitiously stabilised materials is recognised through the specification of density control in many standard specifications for the construction of these materials. With the trend towards IDT methods, the comparative effect of gyratory compaction and Proctor compaction methods is also important. A number of studies have investigated the influence of density on strength and modulus. Many of the investigations, however, utilised different compaction methods to achieve different densities. The contribution of the resulting density difference was often not isolated from the contribution of the different compaction methods.

White and Gnanendran (2005) undertook an investigation which specifically aimed at isolating the influence of density on strength from the compaction method. This isolation was achieved by preparing the same materials at varying densities using the same compaction method and then by preparing samples to the same density using difference compaction methods. The study found that whilst density had a significant impact on strength and modulus, the method of compaction used to achieve that density was not statistically significant. It was concluded that previous studies which found that compaction method had a significant impact of strength/modulus achieved, were likely to be measuring the difference in strength/modulus which resulted from the difference in density that was achieved with each compaction method.

9 IDT STRENGTH VERSUS MODULUS

Although the empirical relationship for estimating the modulus from strength is defined by AUSTROADS, it is commonly accepted that the conversion is material specific. Many studies have been performed in Australia which have measured the strength and modulus of various stabilised materials and found a line of best fit for the data. The authors have specifically investigated the relationships between strength and modulus of a cementitiously stabilised reclaimed host material. This material was stabilised with varying binder types and contents. Each material was tested for IDT strength and IDT modulus at 7, 28 and 90 days after mixing. Linear regressions were performed to provide relationships between the strength and modulus of the materials.

The investigation found that a linear model was able to adequately represent the relationship between strength and modulus. As an example, the relationship between strength and modulus found is detailed below.

$$Modulus\ (MPa) = 1400 + 2600 \times Strength$$

This is not significantly different to the current and previous AUSTROADS (AUSTROADS, 1997 and AUSTROADS, 2004) relationships. There was no statistically significant benefit in adopting a quadratic or more complex model form. The study also found that whilst the measurement of strength is reasonably consistent for identically designed materials, the measurement of modulus from a monotonic IDT test is highly variable. The reliability of the strength versus modulus relationship would be further improved by a measurement of modulus which is more consistent and less variable.

Subsequent studies continue which are investigating the use of repeated load IDT testing for modulus determination of these materials. From preliminary findings, it is considered that the repeated sub-maximal load test is likely to produce significantly less variable moduli values. This would be expected to contribute to less variability in the strength-modulus relationships.

10 IDT FATIGUE LIFE MODELLING

The generic model for fatigue life detailed previously has been found by numerous ALF investigations to be unable to model a range of material performance. With the move towards IDT regimes for cementitiously stabilised pavement material characterisation, a draft method for measuring fatigue life has been developed (Yeo, *et al*, 2002). The test applies a cyclic sub-maximal load (generally 60% to 80% of the breaking load) until failure. Failure is commonly accepted as the point at which the modulus decreases to 50% of the initial value. The only major drawback of the fatigue test is that it can take up to five hours for each sample to be tested and produces up to 1,000,000 data points, which is difficult to manage and analyse.

Investigations continue which aim at developing a generic fatigue life model based on IDT cyclic load testing to relate induced tensile strain to fatigue life. The investigation hopes to provide a method where one or two fatigue tests can be conducted and used to adequately customise the generic model to the specific material of interest.

11 CONCLUSIONS

Cementitious stabilisation of pavement materials has developed greatly in Australia since its first recorded use in 1944. As construction equipment and techniques have improved, the ability to stabilise pavement materials in a consistent and reliable manner has developed. Stabilisation today is an accepted practice in Australia and is a cost effective, environmentally responsible method for rehabilitating failed pavement structures.

With the availability of layered elastic design tools for pavements, such as Australia's CIRCLY, the ability to directly model stabilised pavement materials in thickness design is now available. These layered elastic tools require that cementitiously stabilised materials be assigned a modulus and a fatigue life model. Traditionally, modulus has been determined from a general relationship from strength, which has changed significantly in the AUSTROADS 1992, 1997 and 2004 design guides. The fatigue life model has traditionally been customised to a specific material by the material's modulus and has also changed significantly since 1992.

Since 2000, Australian practice and research has been moving towards IDT testing of gyratory compacted samples for these materials. An IDT based test has been developed for the measurement of strength, modulus and fatigue life. The results to date have suggested that the IDT methods are viable and with further refinement, should provide a suitable method for the characterisation of these materials in a timely and cost effective manner, for both research and project based purposes.

The IDT test methods continue to be progressed and improved. The measurement of strength and modulus is relatively well proven and the fatigue characterisation remains the greatest challenge. Whilst the strength and modulus tests are inexpensive and quick enough to allow use on a project basis, fatigue life measurement is less so. Work continues to develop a generic model which can be customised to any particular material through the use of strength, modulus or some other easily measured material parameter.

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