VARIABILITY IN UNCONFINED COMPRESSION STRENGTH OF PAVEMENT MATERIALS STABILISED WITH CEMENTITIOUS BINDERS

Greg White, Senior Pavement and Airport Engineer, GHD Pty Ltd's Canberra, Australia.

C. T. (Rajah) Gnanendran, Senior Lecturer, Geomechanics and Pavements, School of Civil Engineering, University of New South Wales' Australian Defence Force Academy.

ABSTRACT

This paper examines the variability of strength in stabilised pavement materials' and some of the causes of such variation. The variation of Unconfined Compressive Strength (UCS) of new quarried materials is compared with that of reclaimed road base, both stabilised with cementitious binders. The effect of binder type (slag-lime blends versus General Purpose Portland cement) on the stabilised material's UCS variability is also discussed. The paper presents the following information and findings from the laboratory testing undertaken.

When conducting laboratory investigations into the strength, modulus and fatigue life of stabilised materials, the inherent variability must be low enough to ensure that meaningful and reliable relationships between the characteristics of interest can be drawn. However, if the variability is not too high, use of reclaimed material would be preferred as it more readily mirrors the actual field conditions.

A review of literature found that typical laboratory prepared and tested samples indicated UCS values to have coefficients of variation ranging between 10 and 25%. This typically increases to around 40% for field cured samples which are cored from actual pavements. The UCS testing conducted in this research produced coefficients of variation of between 10 and 18% for 9 sample batches and this is comparable to those reported in the literature from other laboratory testing programs.

When comparing a new and reclaimed material stabilised with 7% slag-lime binder, the new material had a UCS of around double that of the reclaimed material but also had a higher (about twice the amount of) standard deviation. However, the difference in coefficient of variation in UCS between the two host materials was negligible.

When comparing batches of identical reclaimed material stabilised with different binders (one with 7% slag-lime and one with 3.5% GP cement), the UCS values obtained were very similar. The standard deviation of the GP cement stabilised material is, however, around double and therefore the coefficient of variation is significantly higher (around double). This is thought to be due to the low binder content making it difficult to ensure uniform binder distribution and, therefore, higher variability in the UCS and other properties.

For the remaining laboratory testing program the authors will utilise the reclaimed material stabilised with 7% slag-lime binder as it does not increase the variability above that determined from using a new crushed rock host material and better models the field characteristics of an insitu stabilised pavement material with cementitious binder. Where GP cement is utilised to compare with the slag-lime stabilised materials, 7% binder content will be used to ensure more uniform binder distribution.

INTRODUCTION

The use of cementitious insitu stabilisation as a means of road recycling for rehabilitation has been available in Australia since the 1950s (Vorobieff, 1998). It has been demonstrated to provide benefits when rehabilitating pavements from the points of view of minimising disruption to traffic (by providing a fast construction method), minimising the production of waste materials (by reusing the granular pavement layers), reducing the consumption of precious crushed rock and providing a cost effective method of rehabilitation (around 40% of that of conventional reconstruction) (Vorobieff, 1998a).

When conducting laboratory investigations to support research into the performance of stabilised materials, the variability in the test results must be reasonably low enough to allow reliable conclusions to be drawn regarding their mechanical and physical properties. 'Reasonably low' is a subjective term and in practice, the variability of the results is reduced by careful planning of the testing program and the resulting variability accepted, rather than setting a statistically accepted level and designing the testing program to meet the requirements (Metcalfe, 1994).

An understanding of the variability in material strength and other characteristics used for conformance checking in pavement construction, is essential for engineers involved in the acceptance or rejection of work under contractual arrangements as well as for designers (APSARC, 2000). When constructing with or researching the performance of pavement materials stabilised with cementitious binders, such issues are even more important as the addition of binders can increase the material's variability. Also of importance is an understanding of the processes involved in insitu cementitious stabilisation with slow setting binders as these processes contribute to the material's variability.

CEMENTITIOUS INSITU STABILISATION WITH SLOW SETTING BINDERS

Construction of an insitu cementitiously stabilised pavement consists of proportioning the components, intimate mixing, shaping, compaction and curing (Gordon, 1984). A minimum of 12 hours working time is generally required to allow adequate forming, compaction and trimming of recycled highways to achieve acceptably low roughness counts (Bilaniwskyj, 1994).

There are many types of binders available for insitu stabilisation, including General Purpose (GP) cement, flyash and blast furnace slag. One can use either pure cement or a blend. Flyash and slag have inherent slow setting characteristics (Ray, 1986) but must be blended with lime or GP cement to initiate the required cementitious hydration reaction (AUSTSTAB, 2000).

In warmer regions, cement binders are inappropriate as they cure rapidly and don't allow adequate working time for shaping and compaction (Hodgkinson, 1993). Also, when using GP cement for insitu stabilisation, the heat generated by the cement hydration reaction causes the mix to thermally expand whilst curing, and then as the mix cools, it shrinks and can crack (Williams, 1986). The slow hydration of slag-lime and flyash-lime binders reduces the heat generated and the tendency to shrink and crack upon cooling (Foley *et al*, 2001).

Slag-lime and flyash-lime binders are therefore ideally suited to insitu stabilisation as a means of pavement recycling as they allow the required working times and are also less susceptible to cracking (AUSTROADS, 1998). Before progressing further, an understanding of the theory of variability in pavement materials and the theory of statistical variance is required.

PAVEMENT MATERIAL VARIABILITY

When considering variation in pavement material strength, or any other characteristic, both the actual variation in the produced material as well as that created by the sampling and testing of the material must be considered (Kennedy and Neville, 1976). These two factors are statistically referred to as the 'process variability' and 'measurement variability' respectively (Hogg and Ledolter, 1992). Poor sampling techniques or highly variable methods of measuring the characteristic of interest can induce variations that are not present in the actual material and this could easily be overlooked by engineers who are not familiar with materials testing and do not have a firm understanding of statistical variance. In addition, engineers must remember that the natural variability will mean that at times, however rare, isolated results will be quite different from the representative value of any given material property.

In all manufacturing processes, some variability occurs due to slight differences in the manufacturing process (equipment operation, temperature and raw materials) (Hogg and Ledolter, 1992). The main sources of process and measurement variation in pavement materials, specifically focussing on insitu cementitiously stabilised materials, are discussed below.

Host material

The nature of the host material used for the production of stabilised pavement materials is itself variable. Variability occurs in the particle size distribution, particle shape and strength as well as the material's stiffness from one portion of material source to another, even within a single quarry (White, 1993). As the basis of a stabilised material (comprising over 90% by mass of the final product) the host material's variability is a significant factor in that of the stabilised material.

Binder distribution uniformity

The cementitious binder provides significant strength and stiffness in a stabilised pavement material. It also binds the particles together to provide tensile strength to otherwise granular materials (Vorobieff, 1998). Consequently, the distribution of binder will affect the strength and stiffness, as well as the variability of these properties in a cementitiously stabilised material.

Moisture content

In a similar manner to binder distribution, any difference in moisture content between samples of the material and non-uniformity of moisture within any given sample, will affect the moisture available for cementitious binder hydration, density achieved during compaction and the susceptibility to cracking (Williams, 1986). Obviously, variation in the moisture content and distribution will result in variability in the density achieved, as well as the strength and stiffness of the stabilised material.

Density

The density of pavement layers is affected by the nature of its constituent materials, the moisture content at which compaction is conducted and the nature and magnitude of the compactive effort applied (CPEE, 2002). In addition, for cementitiously stabilised materials, the time between mixing the material and applying the compactive effort also affects the density achieved (Alderson, 1999). As density is a key factor affecting the strength of pavement materials (TSA, 1998), then variation in density will induce a variation in strength and other material properties.

Sampling

The selection of a sample of material from the field, the selection of a sample for testing from the bulk sample taken from the field and the splitting of the sample into sub-samples for testing of multiple specimens can all create variable or inaccurate test results. The sampling and splitting of materials for laboratory testing should be conducted in accordance with Australian Standard 11.41, Method 3, Sampling - Aggregates (AS, 1980) in order to promote repeatable test results.

Sample preparation

The preparation of samples in laboratory testing programs commonly includes determination and measurement of the required binder and water, mixing the host material with binder and water, production of samples by portioning the material into a standard mould and compacting with a drop hammer (or using another compaction method), removal of the sample from the mould, measurement of its height, diameter and weight, and storing it in a standard curing room. All these processes introduce human and natural errors into the sample preparation process which will affect the overall variability of the test results if not controlled and consistent.

Testing

During the testing of the pavement materials, the test protocol and any variations in it will result in variability in the test results. UCS is generally acknowledged to be a test of higher inherent variability than other measures of pavement material strength (Foley *et al*, 2001) because the result is significantly influenced by the random arrangement of course aggregate particles and any minor specimen defects, which significantly affect the result of the sample tested (Holtz and Kovacs, 1981).

STATISTICAL VARIABILITY

The theory of statistical variability is well established and documented. Key aspects of the theory of variability, in the context of UCS of pavement materials, are discussed below.

Lots

A 'lot' is defined as being any amount of work or product that can be considered to be homogenous or uniform from a quality point of view. A lot is also referred to as a 'batch' (Chatfield, 1985). In pavement construction, a lot is often considered to be the work performed in a single day but any significant changes in the weather (say rain commencing) or a change in the supplier of a material (say a difference asphalt batching plant) or even a change in construction crew could warrant a days work being split into numerous 'lots' if the quality of the produced material is affected (CPEE, 2002).

Population and Sample

All the possible values of a certain characteristic within a lot make up the 'population'. In pavement construction work, the population is virtually infinite because of the continuous nature of the product. It is impossible to test the entire population (especially when conducting destructive testing) so a 'sample' of the population is selected for testing. Selection of a suitable sample size for the analysis proposed and getting a sample which is representative of the lot is crucial to obtaining statistically reliable results (Chatfield, 1985).

Distribution of strength results

Pavement material strength (measured as UCS), along with many natural material characteristics, is assumed to be 'normally distributed'. This means that the distribution of strength results for a large sample will be concentrated, symmetrically, around a 'most likely value' referred to as the 'mean'. The rate at which the frequency of results on either side of the mean falls away is characterised by the 'standard deviation' which represents the deviation either side of the mean within which 68% of the population values lie. The frequency of occurrence of normally distributed values are characterised by the following equation (Chatfield, 1985).

$$p(x) = \frac{1}{\sigma \times \sqrt{2\pi}} \times e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

Where:

$p(x)$ = The probability distribution of the variable x.
μ = The mean of the population of x.
σ = The standard deviation of the population of x.

Mean or average

The 'mean' of the population is simply the average value. It is defined as follows (Chatfield, 1985).

$$\mu = \frac{\sum_{i=1}^{n} x_i}{n}$$

Where:

μ = The mean of the population.
x_i = The i'th value in the population.
n =The population size.

Where a sample mean is measured rather than a population mean, $\bar{x}$ is used in place of μ.

Standard deviation

The standard deviation of the population is a measure of the spread of population values. Standard deviation is defined as follows (Chatfield, 1985).

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \mu)^2}{n}}$$

Where:

σ = The standard deviation of the population of x.
μ = The mean of the population.
x_i = The i'th value in the population.
n = The population size.

Or, when a sample's standard deviation is measured rather than that of the population, the symbol s takes the places of σ and the denominator is changed from n to $n-1$. The change to $n-1$ is required because the values being compared to the mean were actually used to determine the mean, rather than the mean being independently known. This means that there are only $n-1$ degrees of freedom rather that n degrees as there were when the population mean is used. μ is also replaced with $\bar{x}$ (Kennedy and Neville, 1976). In this case, the standard deviation of the sample is defined as follows (Chatfield, 1985).

$$s = \sqrt{\frac{\sum_{i=1}^{n} \left(x_i - \bar{x}\right)^2}{n-1}}$$

Where:

s = The standard deviation of the sample of x.
$\bar{x}$ = The mean of the sample.
x_i = The i'th value in the sample.
n = The sample size.

Coefficient of variation

Whilst the standard deviation is an expression of the absolute deviation of the values in a population or sample, the coefficient of variation (C of V) is an expression of the relative deviation (Kennedy and Neville, 1976). It is the ratio between the standard deviation and the mean, expressed as a percentage. The coefficient of variation for a population can be used to compare the variability or values with different means and is defined as follows (Chatfield, 1985).

$$CofV = \frac{\sigma}{\mu} \times 100\ \%$$

Where:

$CofV$ = The population coefficient of variation.
σ = The population standard deviation.
μ = The population mean.

Where the coefficient of variation for a sample is desired, the sample mean and sample standard deviation replace the population values. The C of V allows comparison of the variability of measurements which do not have a similar mean. In the context of this investigation, the variability of UCS for stabilised materials which have different design UCS values (by the use of different host materials, binder types and binder contents) is assessed by comparing the C of V values.

VARIABILITY IN CEMENTITIOUSLY STABILISED MATERIAL'S UCS

Table 1 shows typical coefficients of variation for various test method results for pavement materials.

Test result	Reported C of V (%)	Typical C of V (%)	Reference/s
Californian Bearing Ratio	17-58	25	Ingles and Noble (1975) and Kuhn (1972).
Optimum Moisture Content	11-43	20 for cohesive 40 for granular	Ingles and Nobel (1975), Leach and Goodram (1976) and Sherwood (1970).
Maximum Dry Density	1-7	5	Kuhn (1972), Leach and Goodram (1976) and Sherwood (1970).
Density	1-10	3	Ingles and Noble (1975), Lumb (1974) and Sherwood (1970).
Unconfined Compressive Strength	6-100	40	Otte (1978), Morse (1971) and Stamatopoulus and Kotzias (1975).
Tensile Strength	15-29	20	Kennedy (1978).

Table 1. Coefficient of variation for common pavement material measurements

It is noted that the higher coefficient of variation for UCS testing is related to field constructed, cured and cored samples, whilst the lower values are usually associated with laboratory prepared, cured and tested samples.

A summary of the variability of UCS test results for a variety of stabilised pavement materials with various binder types and contents is presented in Table 2.

Material	C of V (%)	Reference
Cement-Flyash (80-20) at 4% recycled material, lab tested, cored from insitu stabilised pavement	42.1	Andrews and Burgess (1994).
Cement stabilised crushed rock, lab prepared and tested	9.8	TSA (1998).
Flyash-lime (50-50) stabilised crushed rock, lab prepared and tested	7.4	TSA (1998).
Flyash-lime (67-33) stabilised crushed rock, lab prepared and tested	15.7	TSA (1998).
GP cement stabilised (4%) crushed rock	22.0	Symons and Poli (1996).
Blended cement stabilised (4%) crushed rock	12.3	Symons and Poli (1996).
SCM stabilised (4%) crushed rock	8.2	Symons and Poli (1996).
GP cement stabilised (4%) recycled base course	18.8	Symons and Poli (1996).
Blended cement stabilised (4%) recycled base course	14.1	Symons and Poli (1996).
SCM stabilised (4%) recycled base course	12.4	Symons and Poli (1996).
GP cement stabilised (4%) natural gravel	18.5	Symons and Poli (1996).
Blended cement stabilised (4%) natural gravel	13.5	Symons and Poli (1996).
SCM stabilised (4%) natural gravel	23.2	Symons and Poli (1996).
New crushed rock with 5% of various blended binders	3.9-10.5	Haber (1994).

Table 2. Example coefficients of variation for UCS.

Table 2 shows that the C of V for different stabilised materials are generally between 4 and 20% for laboratory prepared and tested samples. For field prepared samples, the variability increases to around 40% which agrees with the typical values suggested in Table 1.

LABORATORY INVESTIGATION

Research is being undertaken to develop reliable and cost effective testing protocols and/or methods for determining modulus and fatigue life models for pavement materials which have been cementitiously stabilised insitu. The subject host material was therefore a reclaimed granular pavement material which was cementitiously stabilised in the laboratory. The quality and uniformity of the reclaimed material was unknown and if high, may have induced excessive variability in the laboratory prepared samples. Therefore, when planning this research, the authors considered whether to use a new quarried pavement material (new fine crushed rock) or the proposed reclaimed road base as the host material.

In order to characterise the performance of insitu stabilised pavement material as accurately as possible, a reclaimed base material (which was originally a crushed rock) was considered to be preferable. However, if the natural variability in the reclaimed material lead to highly variable test results, then a new crushed rock material may have been required to investigate the trends of pertinent performance characteristics. These same questions arose when considering slow setting binders (such as slag-lime and fly ash-lime blends) or GP cement as the stabilising binder. This prompted a laboratory testing program, which was aimed at investigating the comparative variability of stabilised new and reclaimed crushed rock road base, as well as the same host material stabilised with slag-lime and GP cement binders.

Materials

The materials used in the laboratory testing program are described below. It is noted that the particle size distribution curves and moisture content versus dry density plots for the two host materials, referred to below, show that the two host materials were very similar. The Plasticity Index (PI) of the reclaimed material was found to be 2.5 whilst the new quarried material was determined to be 'non-plastic'.

Reclaimed host

The base and sub-base material from the existing pavement of the Barton Highway widening project, 2002, was used as the reclaimed host material in this research. The material was subjectively assessed as being a well graded crushed rock and the host material pavement was estimated to be 10 years old. The materials appeared to be uniform in quality and contained only a small amount of contamination from the original asphalt surfacing and clayey subgrade.

The host material was characterised prior to UCS testing. The particle size distribution (PSD), moisture-density relationship and optimum moisture content/maximum dry density (OMC/MDD) and PI of the material were determined. This was to aid in the sample preparation for UCS testing as well as for comparison with the new quarried host material. The PI of the fines was found to be 2.5. The grading and MC versus DD plots are included in Figure 1 and Figure 2 respectively.

New quarried host

The new host material was an ACT size 20 base gravel sourced from Boral's Hall quarry, about 20 km north of Canberra, ACT. This material was described by the supplier as being a high quality crushed rock with some fines added to provide adequate workability. This material was also tested for PSD and moisture-density relationship prior to UCS testing and the results are shown in Figure 1 and Figure 2. The material was found to be 'non-plastic' due to the inability to perform the Plastic Limit (PL) test.

Slag-lime binder

The slag-lime binder was a blend of Ground Granulated Blast Furnace Slag (or simply 'slag') and lime in a ratio of 85 to 15 by weight. This material was provided by Blue Circle Southern Cement Pty Ltd and is marketed under the proprietary name of 'Stabilment'. This binder was provided in a 20 kg sealed tub and was used within the published three month shelf life. Slag-lime stabilised materials contained 7% (by mass of the dry host material) binder and 5% (by combined mass of the host and binder) water. The binder content of 7% was selected as the upper end of likely binder content practically useable in the field, as well as being high enough to maximise the probability of achieving a bound material, free of stress dependant properties.

GP cement binder

The general purpose (GP) cement used in this investigation was also provided by Blue Circle Southern Cement Pty Ltd. This cement was manufactured at their Berrima works and was provided in a 20 kg sealed tub and used within the recommended three month shelf life. Cement stabilised materials were prepared with 3.5% (by mass of the dry host material) binder and 5% (by combined mass of the host and binder) water. The reduced binder content was adopted to provide a stabilised material of similar UCS and modulus to that expected for the slag-lime binder, based on relationships between UCS and binder type/content published by TSA (TSA, 1995).

Laboratory testing

Testing program

UCS testing was conducted on the samples listed in Table 3 in order to compare the variability in UCS between a new and reclaimed stabilised host material and between materials stabilised with 7% slag-lime and 3.5% GP cement binder. Each sample was named with a 4 part alpha-numeric code as follows.

- The first letter represented the host material (R for reclaimed and N for new host)
- The second letter represented the binder type (S for slag-lime and C for GP cement)
- The third for the batch (A, B and C)
- A number showing the sample number with the batch (3 samples per batch)

Sample No	Host	Binder	Batch
RSA1, RSA2 and RSA3	Reclaimed	Slag-lime	1
RSB1, RSB2 and RSB3	Reclaimed	Slag-lime	2
RSC1, RSC2 and RSC3	Reclaimed	Slag-lime	3
NSA1, NSA2 and NSA3	New	Slag-lime	1
NSB1, NSB2 and NSB3	New	Slag-lime	2
NSC1, NSC2 and NSC3	New	Slag-lime	3
RCA1, RCA2 and RCA3	Reclaimed	GP cement	1
RCB1, RCB2 and RCB3	Reclaimed	GP cement	2
RCC1, RCC2 and RCC3	Reclaimed	GP cement	3

Table 3. Host material, binder and batch details for each sample tested.

Sample preparation

The host material for each batch of three samples was taken from a bulk sample of material and then passed through a 19 mm sieve (with any retained material discarded) and the sample air dried in a 60°C oven for a minimum of 48 hours. The host material was then riffled into three sub-samples of 5 kg mass each. Each sample was weighed to the nearest gram and the required amount of binder and water determined.

The binder was added to the dry host material and mixed by trowel and by hand until visual inspection indicated uniform distribution. Determining the uniformity of the distribution of the GP cement binder was difficult because of the similar colouring of the binder and the host material. The required mass of distilled water was then added and again mixed by trowel and by hand until visual inspection indicated uniform distribution. The sample was then left to sit for 60 minutes.

After 60 minutes of delay, the material was placed and compacted into a 100 mm diameter by 200 mm high cylindrical mould in 5 layers and compacted to standard density. The split mould was then stripped and the sample placed in a plastic bag and cured in a fog room for 28 days. A small sample of uncured material was segregated for moisture content determination. At the end of 28 days curing in the fog room, the sample was removed from the plastic, weighed and dimensions measured prior to testing.

Test method

The test method used for the determination of UCS was based on Australian Standard 1141.51 (AS, 1996). Some modifications were made to suit the testing of cementitiously stabilised materials. An outline of the test method used was:

- A cement-sand-water mix (mortar) was placed on the bottom and top of the rough sample faces to allow uniform application of the load across the sample surface.
- The sample was placed in the test machine and an LVDT and load cell installed to record applied vertical load and displacement.
- The load platen was lowered until it almost touched the top of the sample.
- The load was applied at a controlled displacement rate of 1 mm per minute.
- When the sample visibly cracked the load application was ceased.

A portion of the failed sample was retained for ‘as tested’ moisture content determination and the load-displacement data was collected to determine the stress-strain plot and stress at failure (UCS in MPa). It is also noted that the stress-strain plot was not utilised in the analysis of test results for this investigation, but was incorporated for the determination of the material stiffness and for other analysis forming part of the principal author’s PhD research project.

Test results and discussion

The results obtained from the UCS testing program are shown in Figure 3. The mean and coefficient of variation for the UCS of the various samples from the 27 tests are shown in Table 4, by batch and by theoretically identical host-binder combinations.

Material type	**Batch statistics**			**Overall statistics**		
	Mean (MPa)	**SD** (MPa)	**C of V** (%) (3 samples)	**Mean** (MPa)	**SD** (MPa)	**C of V** (%) (9 samples)
Reclaimed material stabilised with slag-lime	1.59	0.22	13.9	1.59	0.15	9.7
	1.48	0.08	5.2			
	1.67	0.11	6.6			
New material stabilised with slag-lime	3.91	0.39	9.9	3.69	0.37	10.1
	3.68	0.21	5.8			
	3.48	0.47	13.5			
Reclaimed material stabilised with GP cement	2.10	0.39	18.3	2.13	0.38	17.7
	2.16	0.31	14.2			
	2.14	0.57	26.6			

Table 4. Mean, standard deviation and coefficient of variation for each batch and overall.

The UCS test results presented in Table 4 show the UCS of the tested material to be generally between 1.6 and 3.7 MPa. This is considered to be low, but still comparable to that reported in other testing programs such as the GIRD project (Symons and Poli, 1996) and work conducted by TSA (TSA, 1998) for similar host and binder materials.

The results in Table 4 show that the new host material stabilised with slag-lime binder had the highest average UCS whilst the coefficient of variation was very similar for the two slag-lime stabilised materials and significantly higher for the cement stabilised recycled material. The values of coefficient of variation of 5.2 – 26.6% for batches of three samples and 9.7 – 17.7% for materials of 9 samples are comparable to those obtained from previous studies reported in Table 2 for laboratory prepared and tested samples.

Figure 3 illustrates the following general trends in the UCS results:

- New host material provided a higher UCS than the reclaimed material when stabilised with 7% slag-lime.
- The 7% slag-lime and 3.5% GP cement binder resulted in similar UCS values in the reclaimed material.
- The 3.5% GP cement bound reclaimed host material had a higher UCS variability than the other materials.

The mean and standard deviation for each material were used to determine the probability density function for UCS. Figure 4 shows the probability distribution function for the UCS of each binder-host combination. Figure 4 supports the general trends identified from Figure 3.

Effect of host material on variability of UCS

It is clear from Figure 3 and Figure 4 that the UCS of the new host material was significantly higher than that of the reclaimed host material when both were stabilised with 7% slag-lime, at slightly over double the average UCS value. Given the similarity in the particle size distribution and OMC/MDD for the two host materials, the shape of the aggregate particles (which was visually assessed as being more rounded for the reclaimed material) is thought to be responsible for the majority of the higher strength exhibited by the new crushed host. The new material was visually noted to be more angular than the recycled material and angularity is known to contribute to inter-particle friction and therefore UCS when stabilised (Williams, 1986).

Even though Table 4 shows that the new host material had a higher standard deviation, the higher mean combined with the standard deviation produced very similar coefficients of variation for both the new and reclaimed host material when stabilised with the slag-lime binder. Using the chi-square distribution (Chatfield, 1985), the 90% confidence interval of mean and standard deviation was determined for both host materials (when stabilised with slag-lime) and these are shown in Table 5 with the resulting 81% confidence interval of coefficient of variation.

Interval	New host material	Reclaimed host material
90% for mean	3.07 – 4.30 MPa	1.33 – 1.83 MPa
90% for SD	0.27 – 0.64 MPa	0.11 – 0.26 MPa
81% for C of V	6.2 – 20.8 %	6.0 – 19.7%

Table 5. UCS for different Confidence intervals for materials stabilised with slag-lime.

Based on the intervals shown in Table 5, the effect of using a new or reclaimed host material on the variability of UCS is negligible when both are stabilised with 7% slag-lime binder. This implies that reducing variability in test results is not a valid argument for selecting a new crushed rock over a reclaimed material as the host, when investigating the characteristics of a reclaimed and cementitiously stabilised pavement material.

Effect of binder on variability of UCS

It is clear from Figure 3 and Figure 4 that for the reclaimed host material, the UCS of the 7% slag-lime samples are only slightly lower than that for the 3.5% GP cement stabilised samples. The lower binder rate of 3.5% was selected with the aim of achieving a similar UCS for the two materials and this was quite successful.

Table 4 shows that the GP cement stabilised samples had a significantly higher standard deviation than the slag-lime stabilised samples. With a comparable average UCS but a higher standard deviation, the GP cement stabilised material had a significantly higher coefficient of variation. Using the chi-square distribution (Chatfield, 1985), the 90% confidence interval of mean and standard deviation were determined for both host materials (when stabilised with slag-lime) and these are shown in Table 6, with the resulting 81% confidence interval for coefficient of variation.

Interval	GP cement stabilised	Slag-lime stabilised
90% for mean	1.51 – 2.75 MPa	1.33 – 1.83 MPa
90% for SD	0.27 – 0.64 MPa	0.11 – 0.26 MPa
81% for C of V	9.8 – 42.7 %	6.0 – 19.7%

Table 6. Confidence intervals for stabilised reclaimed host material.

Based on the intervals shown in Table 6, the use of 3.5% GP cement binder significantly increases the variability in UCS results when compared to the same material stabilised with a slag-lime binder at 7%. This is thought to have been caused not by the change in binder type, but by the binder content. At 7% by mass of slag-lime binder (which is very light in colour) assessing and achieving uniform binder distribution is relatively easy compared to that for 3.5% of cement binder, which is dark and hard to see when mixed into the host material. Given that the binder was mixed into the host material by hand and completed when the binder was visually assessed as being uniformly distributed, this is considered to be the most likely cause of increased variability in the UCS results. It is therefore considered that 7% is a more appropriate binder content as it reduces the risk of not achieving a uniformly distributed binder (and associated increase in variability). Whilst further testing would be required to confirm this theory, it is expected (based on advice from experienced laboratory technicians) that at binder contents of 5% and above, adequate distribution of binder can be achieved by hand mixing. It is noted that 5% is around the maximum binder content currently being utilised by most road authorities for insitu cementitious stabilisation projects. This binder content will be adopted for all future testing of this nature conducted by the authors and is recommended to other researchers, performing similar testing, as a minimum binder content.

SUMMARY AND CONCLUSIONS

When investigating the characteristics of insitu cementitiously stabilised materials, the use of a reclaimed material is preferred as it more closely reflects the field behaviour of the materials. However, if the variability in the host material causes excessive variation in the results and, in turn, unacceptably reduces the ability to find relationships and correlations between strength, modulus and fatigue life, then using a new crushed rock, in lieu, should be considered.

A laboratory testing program was undertaken aimed at comparing the variability of UCS between:

- Similar new and reclaimed host material when stabilised with the same binder.
- Reclaimed host material when stabilised with slag-lime and GP cement binders.

The coefficients of variation of UCS obtained in this experimental program were typical when compared with those reported in other literature. This is considered to be the result of a well planned and documented testing program and good quality assurance practices. The achieved variability was significantly lower than that achieved for samples which were prepared in the field and cored prior to testing in a laboratory.

The C of V of UCS in the 7% slag-lime bound reclaimed material was 9.7% (81% interval of 6.2-20.8%). The new host material, stabilised with the same binder, had a coefficient of variation in UCS of 10.1% (81% interval of 6.0-19.7%). When the reclaimed material was stabilised with 3.5% GP cement binder, the C of V for the UCS values was 17.7% (with a 81% confidence interval of 9.8-42.7%).

This investigation indicates that the effect of using a reclaimed or a new host material on UCS variability is negligible for the materials selected. However, the effect on binder content on UCS is significant and higher contents (say above 5%) are preferred. The extrapolation of these conclusions to other pavement materials has not been investigated in the research.

For ensuing reliability of laboratory investigations, a 5% binder content and reclaimed host materials will be used. Using 5% GP cement binder will increase the UCS well above that of 5% or 7% slag-lime binder. Whilst not ideal, the cost of having increased UCS values for the GP cement stabilised samples is considered acceptable if it ensures that the coefficient of variation in those samples is restricted to around 10%. It is noted that many stabilisation projects on Australia use lower binder contents than 5% and should therefore expect higher variability than if 5% binder content was used.

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AUTHOR BIOGRAPHIES

Greg White

Greg White is a PhD candidate within the School of Civil Engineering at the University of New South Wales' Australian Defence Force Academy. Greg is also the Senior Pavement and Airport Engineer with GHD Pty Ltd's Canberra Office.

C. T. (Rajah) Gnanendran

Rajah Gnanendran is a Senior Lecturer in geomechanics and pavements within the School of Civil Engineering at the University of New South Wales' Australian Defence Force Academy.

FIGURES

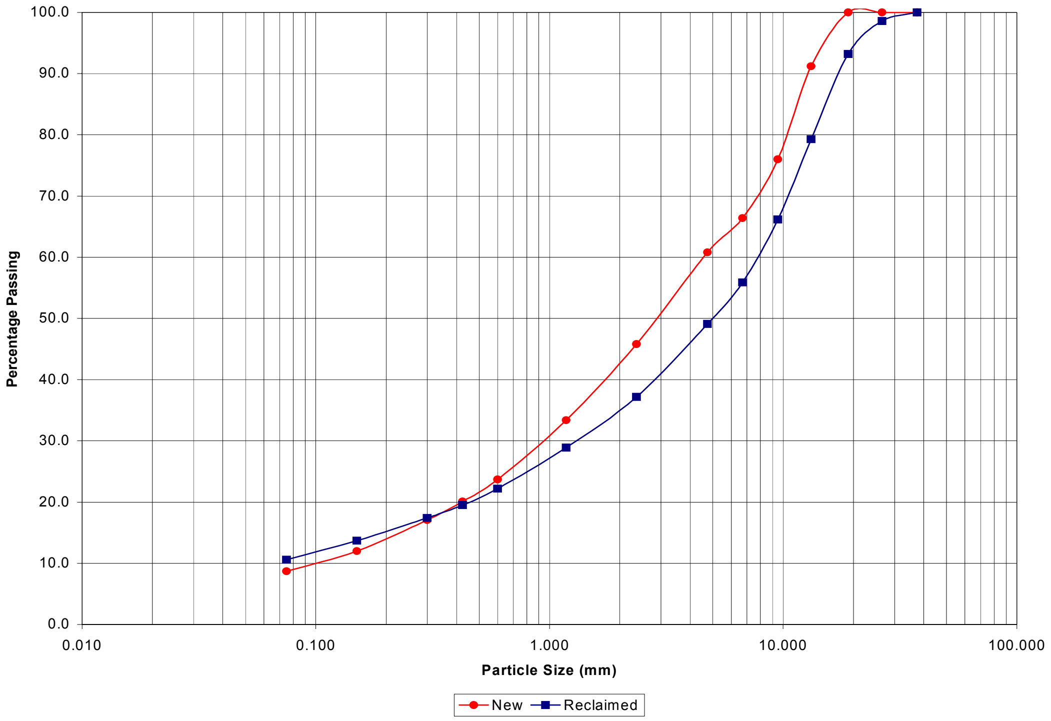

Figure 1. Particle size distribution plots for both host materials.

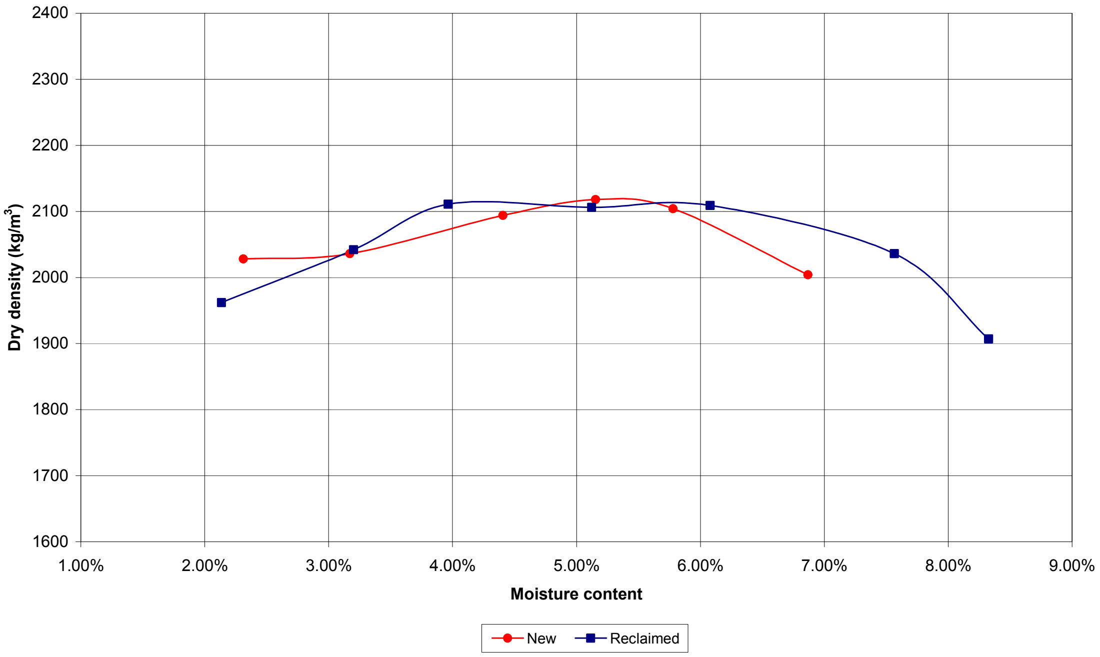

Figure 2. Moisture content – dry density relationships for both host materials.

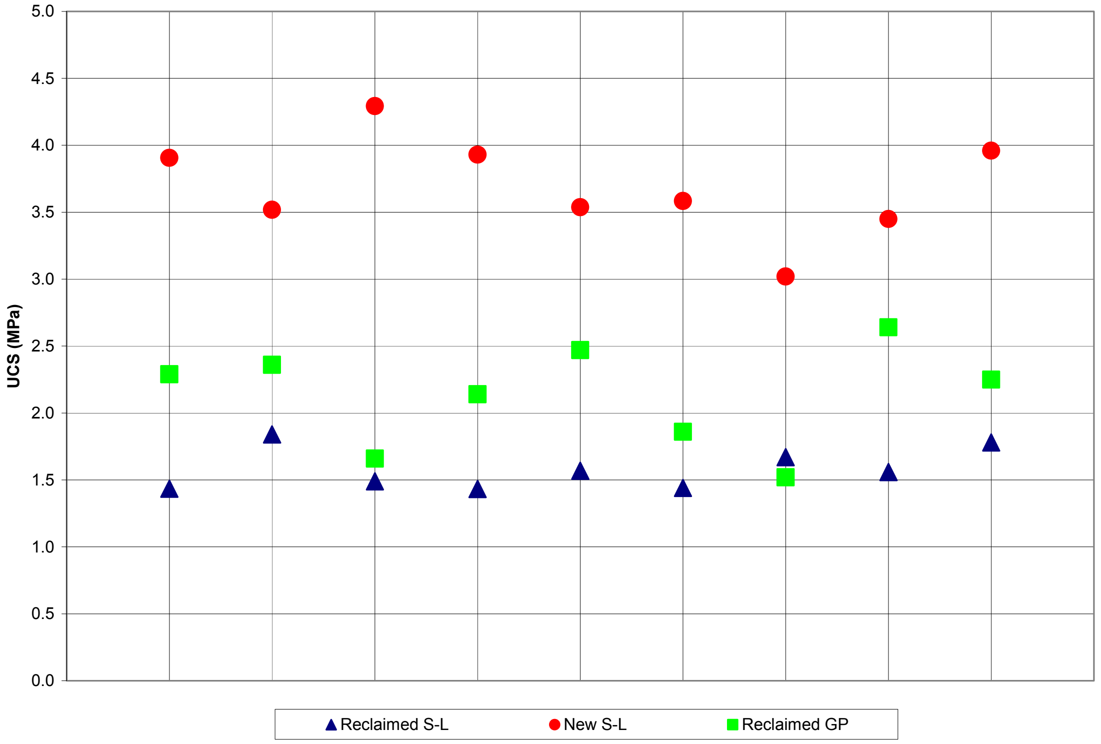

Figure 3. UCS for each sample by material.

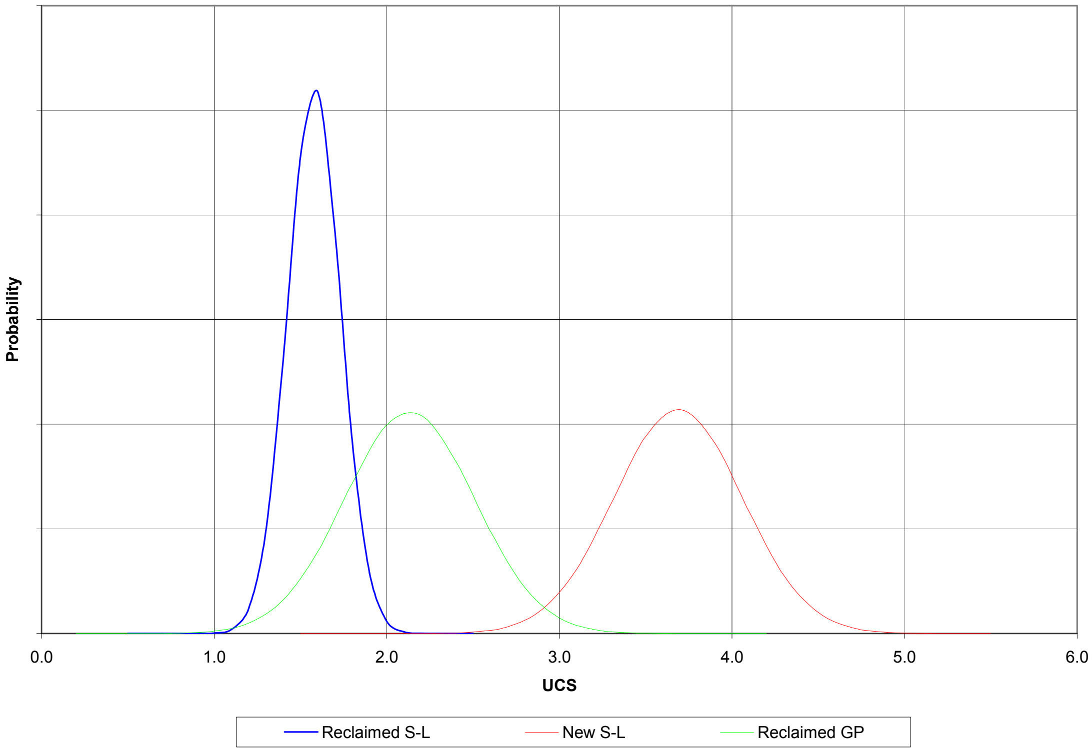

Figure 4. Probability distribution functions for UCS of each material.